The Canada Country Study:

Climate Impacts and Adaptation

NATIONAL SECTORAL VOLUME

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Environment
Canada

Canada

This is a component report of the Canada Country Study: Climate Impacts and Adaptation. In addition to a number of summary documents, the first phase of the Canada Country Study will produce six regional volumes, one volume comprising twelve national sectoral reports, and one volume comprising eight cross-cutting issues papers. This is The Canada Country Study – Volume VII: National Sectoral Volume.

For further information on the Canada Country Study (CCS), please contact the Environmental Adaptation Research Group in Toronto, Ontario at 416-739-4436 (telephone), 416-739-4297 (fax), or indra.fungfook@ec.gc.ca (e-mail).

Ce rapport est une partie composante de L'Étude pan-canadienne sur les impacts et l'adaptation à la variabilité et au changement climatique. En plus de quelques documents sommaires, la première phase de L'Étude pan-canadienne produiront six tomes régionaux, un tome comprenant douze rapports nationaux au sujet des secteurs sociaux et économique, et un tome comprenant huit papiers concernant les questions intersectorielles. Ce rapport est L'Étude pan-canadienne – Tome VII: Questions Sectorielles.

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TABLE OF CONTENTS

Acknowledgments ii
List of Tables v
List of Figures viii
List of Appendices ix
Message from the Minister x
Executive Summary xi

1 Climate Change and Variability: Impacts on Canadian Water 1
by: Nancy Hofmann and Linda Mortsch, Simon Donner, Kirsty Duncan, Reid Kreutzwiser, Suren Kulshreshtha, Andrew Piggott, Shirley Schellenberg, Bill Schertzerand and Michel Slivitzky

2 Impacts of Climate Change and Variability on Unmanaged Ecosystems, Biodiversity and Wildlife 121
by: John C. Anderson, Ian Craine, Antony W. Diamond, and Roger Hansell

3 Canadian Inland Wetlands and Climate Change 189
by: Thomas A. Clair, Barry G. Warner, Richard Robarts, Henry Murkin, John Lilley, Linda Mortsch, Clayton Rubec

4 Implications of Global Climatic Change for Canadian Agriculture: A Review and Appraisal of Research from 1984 to 1997 - Volume 1: Synthesis and Research Needs 219
by: M. Brklacich, C. Bryant, B. Veenhof and A. Beauchesne

5 Canada Country Study: Climate Impacts and Adaptation - Fisheries Sector 257
by: Brian J. Shuter, Charles K. Minns, and Henry A. Regier

6 The Impact of Climate Change on Canadian Forests 319
by: Rica Saporta, Jay R. Malcolm, and David L. Martell

7 Canada Country Study: Climate Impacts and Adaptation - Energy Sector 383
by: Gilles Mercier

8 Canada Country Study: Climate Impacts and Adaptation - Transportation Sector 405
by: Jean Andrey and Adam Snow

9 Canada Country Study: Climate Impacts and Adaptation - Built Environment Sector 449
by: W. Alan Dalgliesh

10 Canada Country Study: Climate Impacts and Adaptation - Insurance Sector 483
by: Mark W. Baker

11 Canada Country Study: Climate Impacts and Adaptation – Health Sector 501
by: Kirsty Duncan, Tee Guidotti, Weiping Cheng, Komali Naidoo, Ginger Gibson, Laurence Kalkstein, Scott Sheridan, David Waltner-Toews, Shauna MacEachern and John Last

12 Impacts of Climate Change on Recreation and Tourism 591
by: Geoffrey Wall

LIST OF TABLES

1.1 Canadian Precipitation Records 13
1.2 Canadian Drought Episodes 14
1.3 Precipitation trends* in Canada 15
1.4 Changes in Temperature and Precipitation 1988 (Annual) for various regions in Canada based on GCM $2xCO_2$ Scenarios 19
1.5 Comparison of seasonal GCM precipitation scenarios for the Great Lakes-St. Lawrence Basin ($2xCO_2$ / $1xCO_2$) 20
1.6 Monthly Precipitation Change for various GCM Scenarios for the Grand River Basin (%) 20
1.7 Great Canadian Floods 25
1.8 Canadian Climate Impact Assessments on Hydrology: A Review of Scenarios, Methods, and Impacts 31
1.9 St. Lawrence Flows at Montréal - Historical and $2xCO_2$ Conditions (Monthly flows in cubic meters per second) 33
1.10 Moisie River hydrologic impacts of various climate change scenarios 34
1.11 GCM Impacts on the Great Lakes by Scenario 37
1.12 Summary of hydrologic impacts from Canadian studies using various climate change scenarios 53
1.13 Cropped Area and Irrigation in Canada, by Province 57
1.14 Interactions of British Columbia Fisheries with Changes in Local Climate 59
1.15 Fisheries Impacts in the Great Lakes 61
1.16 Summary of Navigational Impacts In Canada 67
1.17 Summary of Gaps/ Limits in Research 75
1.18 Estimated Costs of Adaptation in Water Resources Management in Canada's Current Climate and Trends under Climate Change 77
1.19 Comparison of Average International Water Prices, 1986 89
1.20 Specific Adaptations for Changes to the Hydrologic System 94
3.1 Occurrence of peatlands and wetlands in the provinces and territories in Canada 196
3.2 Wetland functions and values 197
3.3 Model projections for increased temperature and precipitation 202
4.1 Overview of Literature Searches, Databases Searched 229
4.2 Estimated Impacts of Climatic Change Scenarios on Selected Agro-climatic Properties 231
4.3 Estimated Impacts of Global Climatic Change on Grain Crops 235
4.4 Estimated Impacts of Global Climatic Change on Oilseed, Forage and Potato Yields 237
4.5 Estimated Impacts of Global Climatic Change on Land and Production Potential 239
4.6 Estimated Impacts of Global Climatic Change on the Agricultural Economy 241
4.7 Adaptation of Canadian Agriculture to Global Climatic Change 243
5.1 Probable impacts of climate-induced changes in fish ecology on fisheries 263
5.2 An overview of Canadian commercial fisheries giving landed catch and landed value statistics for 1990 and 1994 268
5.3 Production statistics for the Canadian aquaculture industry in 1994 268

5.4 Profile of recreational fishing by residents and non-residents in Canada for 1990 270
5.5 Canadian subsistence and native fisheries: estimates of the number of fishers and the annual harvest for each fishery 271
5.6 Potential Impacts of Climate Change on Ecosystem Productivity in both Estuaries and Coastal Marine Waters 276
5.7 Potential effects of a warmer, drier climate on annual average volume-specific productivity of lake ecosystems in central Canada 279
5.8 Summary of studies that either demonstrate a link between measures of population production and thermally suitable habitat or use such a link to forecast effects of climate change 282
5.9 Habitat use over the life cycle of common Pacific salmonids 282
5.10 Summary of observed/predicted/possible changes in zoogeographic boundaries of species 285
5.11 Potential interactions between existing ecosystem stresses and expected elements of climate change 288
5.12 Examples of biological impacts of climate change by region 292
5.13 Regional examples of impacts of climate change on fisheries 293
5.14 Classification of adaptation options for Canadian fisheries 294
7.1 Crude Oil Reserves 386
7.2 Primary Energy Demand by Region (Petajoules) 389
7.3 Available Estimates of Climate Change Impacts on Energy Demand 396
8.1 Resources Devoted To Transport 409
8.2 Employment in the Transportation Sector 409
8.3 Gross Domestic Product 410
8.4 Road Network 1975 411
8.5 Road Network 1995 411
8.6 Traffic Volumes 1990 411
8.7 Road Network, 1995, By Province/Territory And Jurisdictional Responsibility 411
8.8 Motor Vehicle Data 412
8.9 Bus Operating Revenues Including Subsidies 412
8.10 Bus/Transit Passenger Statistics 413
8.11 Transit Fleet 413
8.12 Operating Revenues for Large For-Hire Trucking Companies 414
8.13 For-Hire Trucking Fleet, 1994 414
8.14 For-Hire ($1 million +) Trucking Operating Revenues, By Region, 1995 414
8.15 Trucking Freight Statistics for Large For-Hire Operators 414
8.16 Aircraft, 1993 415
8.17 Air Operating Revenues 415
8.18 Air Passenger Statistics 415
8.19 Air Freight Statistics 416
8.20 Mainline Track 416
8.21 Rail Equipment 416
8.22 Rail Operating Revenues 417
8.23 Rail Freight Statistics 417
8.24 Rail Passenger Statistics 417

8.25 Shipping Operating Revenues 418
8.26 Shipping Freight Tonnage 418
8.27 Total Freight By Region 419
8.28 Shipping - Top Three Freight Commodities In 1994, By Region 420
8.29 Marine Passenger Statistics 420
8.30 Pipelines, 1993 420
8.31 Sensitivities of Transport Activities to Weather Conditions 422
8.32 Summary of IBI Group Report 423
8.33 Ice Road Season for Crossing the Mackenzie River at Norman Wells 426
8.34 Transportation Accidents, 10-Year Averages 429
8.35 Number of Road Traffic Collisions, 1995, by Weather Condition 429
8.36 Average Annual Navigation Costs - Canadian Fleet 433
9.1 Regional distribution of Capital Expenditures in Canada, 1993 454
9.2 Sectoral distribution of Capital Expenditures in Canada, 1993 454
10.1 Top Ten Insurers 486
10.2 Change in Annual Damage Potential 493
10.3 Total damage projections 493
11.1 Number of days per year with ozone levels in excess of the one-hour air quality objective of 82 ppb 517
11.2 Number of Canadian deaths due to excessive heat and excessive cold for the years 1965-1992 521
11.3 Weather variables used in the mortality study 523
11.4 Climate change scenarios used in this study 523
11.5 Regression analysis for days above threshold for Montreal 526
11.6 Regression analysis for days above threshold for Toronto 526
11.7 Characteristics of offensive air masses: Montreal, Ottawa and Toronto 527
11.8 Estimates of total present-day mortality attributed to weather during the summer 1958-1988: Montreal and Toronto 528
11.9 Estimates of total present-day mortality attributed to weather during the summer 1958-1988: Montreal, Toronto and Ottawa 528
11.10 Estimates of future Canadian mortality in summer attributed to weather using the threshold approach 530
11.11 Estimates of future Canadian mortality in summer attributed to weather using the synoptic approach 530
11.12 Comparison between the present and scenarios: percent of days above the threshold or within an offensive synoptic category 531
11.13 Canadian and U.S. death rates from selected causes 532
11.13 Number of Canadian deaths due to (1) lightning and (2) storms and floods for the years 1965-1992 533

LIST OF FIGURES

1.1 Inter-relations and inter-connections between water and numerous other sectors 8
1.2 Two Water Systems 9
1.3 Diagram of the hydrological cycle 10
1.4 Annual Total Precipitation for Canada 12
1.5 Annual Precipitation in the Great Lakes Basin (1860-1990) 16
1.6a Snow cover for the current climate for the northwestern portion of the Bay of Quinte Watershed 18
1.6b Snow cover for the $2xCO_2$ climate scenario for the northwestern portion of the Bay of Quinte Watershed 18
1.7 Annual average runoff for Canada 23
1.8 Trends for Bow River, Alta. peak spring runoff and regional spring temperature departures 26
1.9 Discharge Trends of the St. Lawrence River (at Cornwall) (1861-1994) and at Ville de Lasalle (1955-1994) 27
1.10 Seasonal and Annual Runoff (5-year Moving Averages) for the St. Mary’s River, NS 27
1.11 Quarter-monthly levels (IGLD 1985) at Montreal Harbor - Jetty No. 1 for the 1930s under present regulation conditions for Lake Ontario (plan 58D) and chart datum 32
1.12 Mean Annual Lake Levels 36
1.13 Summary of hydrological impacts in Canada 52
1.14 Differing levels of Research 78
1.15 Arnstein’s Ladder of Citizen Participation 82
2.1 Major pathways through which climate may affect waterfowl populations 152
3.1 Wetlands in Canada 193
3.2 Wetland Classes in Canada 195
5.1 Relative amounts of land and water in Canada 265
5.2 Percentage of the area of each province that is covered by lakes – annual runoff by province 267
5.3 Relative importance of direct and indirect effects of climate change for different aquatic ecosystems and different geographical regions of Canada 290
5.4 Effects of geographic/economic scale on net gain (benefits minus costs) arising from effects of climate change on society and the role adaptation might play in mitigating the more negative outcomes 298
7.1 GHG Emissions by Source 390
8.1 Theoretical Framework of the Impacts of Climatic Change on Great Lakes Commercial Navigation 432
8.2 Indirect effects of climate change on transportation 436
10.1 Simple Model of the Property and Causality Insurance Sector 485
11.1 Maximum temperature vs. mortality for Montreal 525

LIST OF APPENDICES

2A Common and Scientific Names of Some Species Referred to in the Text 188
4A Glossary of Terms Used in the Chapter 256
6A Common and Scientific Names for the Species Referred to in the Text 377
7A Energy Production – Impacts and Adaptation 402
7B Energy Transmission – Impacts and Adaptation 402
7C Energy Demand and Use – Impacts and Adaptation 403

Message from the Minister of the Environment

Climate change is one of Canada's biggest challenges as we head toward the millennium. If we meet that challenge, it will ensure the continued health of our planet. Otherwise future generations may suffer.

We know that the science on climate change is sound. Scientists from around the world agree that our climate is warming at an increasingly rapid rate because of higher volumes of greenhouse gases entering the atmosphere.

The Canada Country Study provides another important piece of knowledge on how climate change could impact our communities across the country. Not only does it alert Canadians to what scientists expect will happen, it suggests ways in which Canadians can adapt to changes in climate. The Study also provides a critical perspective for charting Canada's future.

The Canada Country Study helps us understand how to capitalize on economic opportunities and enhance our social well-being as we face this challenge. In some cases, we have the answers. In others, further study and consultation is required to forge the best strategies. Much work remains to be done.

Overcoming the problem of climate change will require a concerted effort. It is imperative that Canadians are well-informed when preparing to respond to the potential impacts of this phenomenon. Once Canadians understand the implications, I am confident that they will take action to safeguard our environment, health and economy for the benefit of our children and grandchildren.

I would like to thank the many individuals who have contributed to the Canada Country Study. Through your efforts, Canadians are better informed about how they can take greater responsibility in ensuring our continued prosperity.

Christine S. Stewart

Executive Summary

INTRODUCTION

The scientific and technical results of the assessment phase of the Canada Country Study (CCS) are published in eight volumes - six regional volumes (Arctic, Atlantic, Ontario, Pacific and Yukon, Prairies, and Québec), a national sectoral volume consisting of twelve papers and a cross-cutting issues volume consisting of eight papers. The current document - the Executive Summary - provides a digest of the material in the twelve sectoral papers in the national sectoral volume (agriculture, built environment, energy, fisheries, forestry, human health, insurance, recreation and tourism, transportation, unmanaged ecosystems, water resources and wetlands).

The Issue of Climate Change

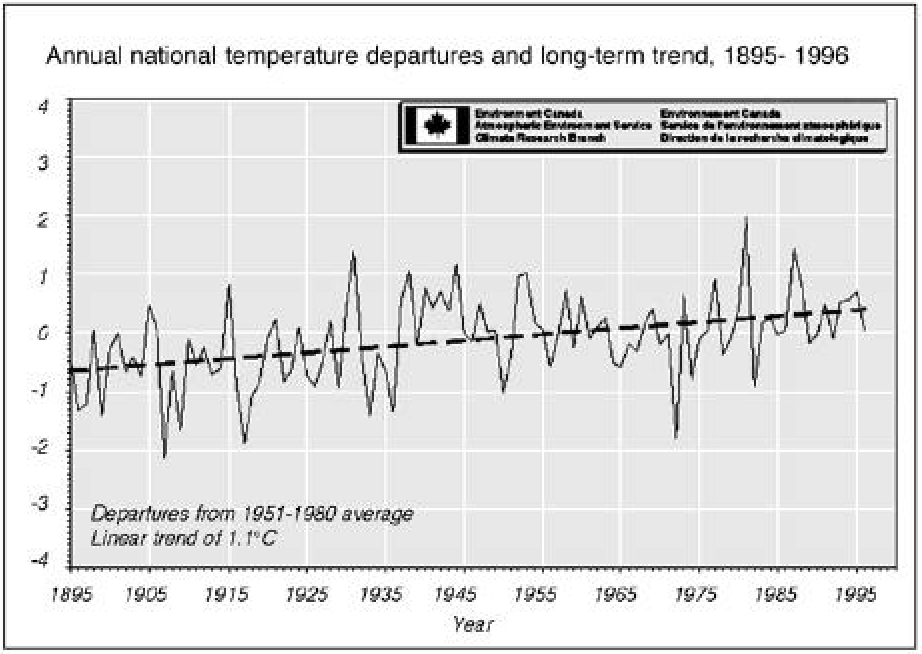
The Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report concludes that the balance of evidence suggests a discernible human influence on global climate. Human activities are increasing the atmospheric concentrations of greenhouse gases and these changes are projected to lead to regional and global changes in climate and climate-related parameters such as temperature, precipitation, soil moisture and sea level.

In order to understand how the world's climate may respond, sophisticated computer models called general circulation models (GCMs), are used to simulate the type of climate that might exist when global concentrations of greenhouse gases are doubled from pre-industrial levels. As the initial focus has been on providing a state-of-the-art assessment based on existing scientific and technical literature, the results of the CCS are not based on a single climate scenario. Instead, it includes the range of scenarios used as a basis for the various papers and reports appearing in the scientific literature. In general, the main model scenarios used come from one of five GCMs which have been developed in Canada, the United States or the United Kingdom: CCC92 – Canadian Centre for Climate Modelling and Analysis 2nd generation model; GFDL91 – Geophysical Fluid Dynamics Laboratory model (US); GISS85 – Goddard Institute for Space Studies model (US); NCAR93 – National Center for Atmospheric Research model (US) and; UKMO95 – UK Meteorological Office model.

When interpreting the results presented here, based on these scenarios, the reader should be aware that confidence is higher in the hemispheric-to-continental projections of climate change than in the regional projections, where confidence remains low. It is also worth noting that the majority of the identified changes in climate and, therefore, the identified impacts, are projected to occur over the next century, and that the average rate of warming would probably be greater than any seen in the last 10,000 years. Furthermore, although future, unexpected, large and rapid climate system changes (as have occurred in the past) are difficult to predict, future changes may also involve "surprises".

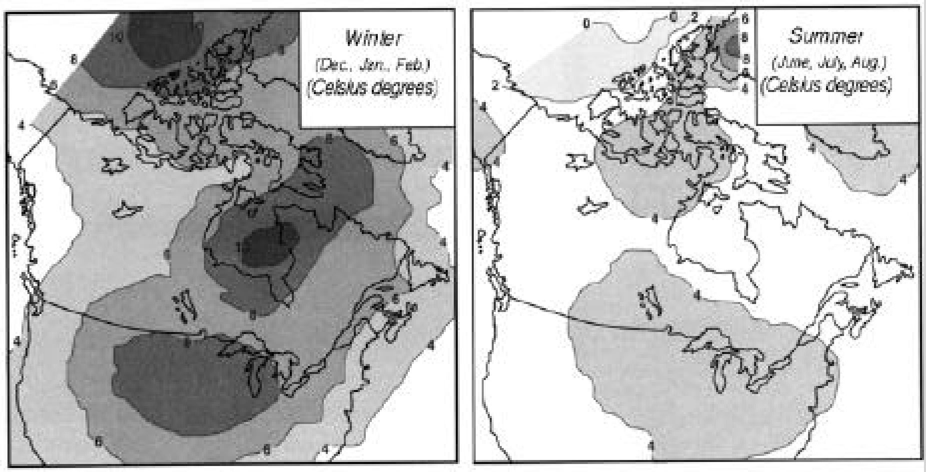
IMPACTS OF CLIMATE CHANGE

In structuring this executive summary, results are organized into impacts of climate change and adaptation to climate change for each of the twelve sectors individually. Virtually all sectors within Canada are vulnerable to climate change to some degree and these projected impacts are such that the status quo will not be an option. Taken individually, responses to any one of the impacts identified may be within the capacity of a particular region or sector. The fact that they are projected to occur simultaneously and in concert with changes in population, technology, economics, and other environmental and social changes, however, adds to the complexity of the impact assessment and the choice of appropriate responses. Furthermore, our climate is variable and Canadians and the economy react to it on different temporal and spatial scales. As such, all of the impacts are expected to exhibit significant regional variations which would have implications for distributional changes in social welfare and the choice of appropriate responses.



CCC GCM2 2xCO$_2$ temperature projections for Canada for winter and summer seasons

Climate changes wil not be distributed uniformly. For a doubling of carbon dioxide concentrations, GCM2 projects an increase of 3.5C in the earth's average annual temperature but shows more substantial warming over much of Canada, particularly in winter.



Model	*Winter*	*Summer*
GFDL 91 - Geophysical Fluid Dynamics Laboratory GCM.	*2-6°C*	*2-3°C*
GISS 85 - Goddard Institute for Space Studies GCM.	*2-14°C*	*1-2°C*

The literature of climate change impacts and adaptation shows wide disparity in the amount of research that exists relevant to any given natural system or socio-economic sector in Canada. In addition, relatively little attention has been given to a comprehensive examination of positive impacts or possible opportunities. The CCS, being based on the existing scientific and technical literature, reflects this disparity.

Water

Water is essential to many economic and societal functions in Canada including: municipalities, industries, manufacturing, recreation, navigation, and hydro-electric generation. Water is also a critical, limiting factor in the existence and distribution of our natural ecosystems. Climate change is expected to lead to an intensification of the global hydrological cycle and this will cause major impacts on regional water resources. Relatively small changes in temperature and precipitation, together with the effects on evapotranspiration and soil moisture, can result in relatively large changes in the magnitude and timing of runoff and the intensity of floods and droughts.

Hydrological impacts: Some of the generalized hydrological impacts in Canada based upon climate change scenarios include: increases in annual precipitation for most regions; increases in the intensity of local precipitation events; increases in evapotranspiration due to higher air temperatures; changes in runoff and streamflow across Canada; decreases in lake levels; decreases in groundwater levels; decreases in soil moisture in southern Canada; reductions in the ice cover season and; reductions in the extent of permafrost.

Impacts on water use: Hydrological impacts also have important implications on the natural environment and how humans use water. Rural water use conflicts may increase, as growing demands for irrigation may not be met as water supplies decrease due to increases in potential evapotranspiration. Decreased lake levels and lowered streamflows may reduce the amount of fish habitat. Increased water temperatures and reduced dissolved oxygen may impair many fish species. Lowered lake levels and flows will likely cause reductions in hydroelectric power generation capabilities, increase energy costs, and affect the cargo carrying capacity of commercial vessels. However, warmer winter temperatures may allow a longer shipping season by reducing the amount of ice cover in navigation channels. Municipal water consumption, particularly lawn watering activities, will likely increase as air temperatures rise. Changes in precipitation rates may increase the potential breeding sites for vectors which carry diseases. Floods or intense precipitation events may cause overflows of combined storm and sewage systems leading to water contamination such as outbreaks of *Cryptosporidium*.

Ecosystems, Biodiversity, Wildlife and Wetlands

Ecosystems contain the Earth’s reservoir of genetic and species diversity. The occurrence and association of plants and animals in the natural environment depend, to a great extent, on climate. As such, projected changes in climate could have significant implications for natural ecosystems in Canada. Small variations in climate, such as a 1.0ºC to 2.0ºC in mean annual temperature can have significant repercussions for the characteristics and functions of natural ecosystems. The composition and geographic distribution of many ecosystems will shift as individual species respond to climate change. However, some ecosystems may remain unstable for several centuries as the changing climate continues to impose new limits and opportunities.

Terrestrial: Plant and animal species, adapted to existing climatic conditions, would be affected through projected changes in temperatures, habitat loss or degradation, changes in food abundance or availability, and changes in predation rates, competition, parasites and diseases. A real concern is the capacity for terrestrial species to be able to survive when the rate of climate change is anticipated to be both faster than the ability of terrestrial ecosystems to adapt and migrate, and faster than any experienced in the last 10,000 years.

Under climate change, the boundaries of existing plant, animal species, insects, and soil microbes can be expected to shift to higher latitudes and/or higher elevations, while the invasion of southern species into Canada is also likely. This reflects an expected northward shift in the ecoclimatic regions of Canada as well as a change in their relative size and composition. For example, the tundra area could shrink by more than a third of its current size under projected changes in climate, so that it would be confined mainly to the islands north of the mainland, and its vegetative content would likely alter to reflect snow cover and soil moisture changes. High Arctic Peary caribou and muskoxen may become extinct, while mainland caribou would come under significant stress.

With increases in air temperatures, plant growth should increase in those areas where the current climate is a limiting factor. Satellite data have provided evidence of an overall increase in terrestrial photosynthetic activity in Canada from 1981-1991 in marginal areas extending in a wide band from the Yukon and British Columbia southeastward to the Great Lakes, then northeastward to Labrador. A warmer, drier climate is also expected to substantially increase the number of wildfires and area burned in Canada, with obvious consequences for wildlife and the associated ecosystems.

Wetlands: Wetlands currently cover 14% of Canada’s land mass and are a critical resource providing habitat for species (including some of Canada’s rare, threatened, or endangered ones), storage for atmospheric carbon, nutrient and mineral cycling, water purification, and natural flood control. Climate change could result in the conversion of semi-permanent wetlands from open-water dominated basins to vegetated areas, and wetland salinity could increase significantly.

Hydrology is a key factor in determining wetland ecology. Lowered water levels in wetlands can alter both the quality and quantity of waterfowl habitat. A 3.0ºC increase in temperature could result in a 39% decline in the number of wet basins in Canada’s parkland region, despite increased precipitation; the impact is expected to be less severe in the grassland region. There is some possibility that prairie wetlands could expand northward offsetting some of the anticipated loss in other parts of the region.

Much of Canada’s peatland area is underlain by sporadic to continuous permafrost. A climatic warming of 2.0ºC would shift the boundaries of this underlying permafrost northward and increase the depth at which permafrost occurs, with the result that most of the current peatland regions would have only sporadic permafrost underlying, with major consequences for their ecology and biogeochemistry. It may also renew peat accumulation in subarctic regions of Canada although degradation of southern peatlands may be much faster than northward migration and the total area of Canada’s peatlands will likely decrease.

Aquatic: Freshwater habitat for some key aquatic wildlife including salmonids could be lost in parts of Canada. Inland aquatic ecosystems will be influenced by climate change through altered water temperatures, flow regimes and water levels. Many species in inland lakes and streams, where not land locked, are likely to shift northward by about 150 km for every 1°C rise in temperature. In terms of water quality, decreased lake levels, lowered streamflow, increased water temperatures and reduced dissolved oxygen may reduce the available habitat for fish. For instance, cold-water species near their southern limits such as brook trout may be replaced by warm-water species.

Reduced sea ice thickness and extent, and sea level rise under climate change, will result in mixed impacts. Some species such as the sea otter could benefit from being able to expand into new areas while others such as seals may decline due to reduced sea-ice expanses for breeding and feeding. The polar bear is particularly of concern; it could become extinct through starvation if the Arctic Ocean becomes seasonally ice free for a long enough period. Some large breeding colonies of seabirds are at risk due to rising sea level, including colonies of Common Murre and Northern Gannets in Newfoundland.

Agriculture

In Canada, an important dimension to the relationship between climate change and agriculture is the wide range of conditions for agricultural production between different regions. There has been considerable research into the possible implications of climate change scenarios for agro-climatic conditions in all regions of Canada, except southern British Columbia. These studies have considered several climatic change scenarios and have examined the implications of altered climates for wide range agro-climatic properties, including the growing and frost free seasons, and seasonal values for temperature, growing degree days, corn heat units, precipitation and moisture deficits. The implications for thermal regimes have been investigated more thoroughly than the implications for moisture regimes.

All of the global climatic change scenarios and studies suggest warming for most of Canada. Impacts of climate change on agriculture will be most directly reflected through the response of crops, livestock, soils, weeds, and insects and diseases to the elements of climate for which they are most sensitive. Soil moisture and temperature are the climate factors likely to be most sensitive to change across large agricultural areas of Canada. Longer frost free seasons more conducive for commercial agriculture are expected under climate change. For the Prairies, Ontario and Quebec, most estimates suggest an extension of three to five weeks. Results relating to moisture regimes show estimated precipitation changes ranging from decreases of about 30% to increases of 80%. Despite favourable potential impacts in terms of longer and warmer frost free seasons and of greater precipitation, most climate change scenarios also imply important increases in potential evapotranspiration. This will lead to larger seasonal moisture deficits in all regions of Canada, with the severest situations anticipated for Ontario.

Land capability: Impacts on agricultural land potential north of 60º are generally considered to be insubstantial in nature. However, the Peace River region and northern agricultural areas in Ontario and Québec are expected to see some expansion of the land area suitable for commercial crop production. The physical potential for fruit and vegetables could expand beyond current southern locations in Québec, Ontario, and British Columbia.

Crop development: Research has focused on impacts on grain crops, including grain corn, spring and winter wheat, oats and barley. Warmer frost free seasons are expected to increase the rate of development of grain crops, reducing the time between seeding and harvesting by up to 3 weeks in most regions for spring-seeded cereals and coarse grains. In northern regions, the shorter maturation time would reduce the risk of frost-induced crop injury.

Yields: Most of the research reviewed predates the more recent generation of crop development and productivity models which take into account the potential benefits of increased CO_2 levels on crop yields. As a result, these studies probably overestimate the negative effects of climate change on crop yields. In the Prairies, spring-seeded cereal yields are expected to decrease by up to 35% in the west and increase by up to 66% in the east. Ontario and Québec would experience similarly variable results except that northern areas could anticipate increased grain production, especially for corn. In both the Atlantic region and British Columbia, increased grain yield potential is foreseen, but realization is likely to depend on increased irrigation and the availability of land. Oilseed yields may be generally reduced in Canada due to crop moisture stress, although possibly offset by northern expansion of the area capable of such production.

Agricultural Trade: Canada is a major producer of agricultural products on an international scale, and therefore changes occurring abroad may have as significant an influence on Canadian agriculture as changes in domestic production prospects. Major changes, whether these be positive or negative, in Canada's agricultural production capacity will be bound to have consequences within and beyond its national borders.

Fisheries

Fisheries are important sources of food, sport and employment in Canada. In 1994, the total Canadian commercial catch was 1,070 k-tonnes primarily from the oceans with a landed value of $1.78 billion. Aquaculture is a rapidly growing sector in competition with commercial fisheries. In 1994, production reached 54 k-tonnes of fish, mainly salmon, valued at $300 million. For fish, the temperature tolerance zones for survival, growth and reproduction are species-specific characteristics. Each species exhibits a characteristic preferred temperature and preferred temperatures range from values below 10ºC to values above 25ºC. Given the importance of temperature in shaping the vital activities of fish, the responses of freshwater and marine populations to changes in water temperatures under climate change fall under two broad categories: changes in fish production in a particular area and changes in fish spatial distributions. Under a warmer, drier climate in Canada, the following impacts on Canadian fisheries are possible:

Pacific marine: Lower and more variable sustainable harvests from southern salmon populations are expected. Pacific cod abundance is also likely to be reduced. Higher, more consistent sustainable harvests are anticipated from northern salmon populations, with sockeye salmon most affected.

Atlantic marine: A decrease in overall sustainable harvests from coastal and estuarine waters is projected due to decreases in freshwater discharge and consequent declines in ecosystem productivity. Widespread changes in sustainable harvests, locations of fishing grounds, and gear efficiencies for many species could occur due to complex and likely unpredictable changes in the water current systems that shape offshore marine habitats and migration patterns.

Arctic marine: Increases in sustainable harvests for most fish populations are likely, due to increased ecosystem productivity as shrinking ice cover permits greater nutrient recycling.

Southern freshwater: There could be decreases in sustainable harvests for many fisheries due to declining water levels in lakes, declining flow rates in streams, and reductions in nutrient loading and recycling for many lakes and streams on the Canadian Shield. Of the overall sustainable harvest, the proportion comprising cold water fish will be reduced, including species such as trout, pickerel, whitefish, and grayling.

Northern freshwater: There will be increases in sustainable harvests for most fish species, due to longer, warmer growing seasons and relatively small changes in water levels. Potentially, there will also be an increase in the diversity of fish species that can be harvested sustainably due to increases in the diversity of thermal habitats available to support new species expanding their ranges from the south.

Forestry

Forests have long played an important role in Canada's economy and culturally they help define our social identity. Of Canada's 417.6 million ha of forested land (42% of the total land area), 119 million ha are managed for timber extraction while another 50 million ha are protected from harvesting through legislation. The forest ecosystem supports 1 in 15 jobs and over 200,000 wildlife species found in Canada. Forest responses to climate change can be classified as either direct changes induced by the increased concentrations of greenhouse gases, or indirect changes such as changes to temperature and precipitation.

Forest regime: Canada's forests sequester significant quantities of carbon due to the slow rate of soil organic mass decomposition. Increased temperatures would increase the rate of decomposition, as well as increases in the vegetation growth rates or net primary productivity. The fact that the climate is projected to change faster than forests can adapt or migrate suggests that our forest ecosystems will be in a state of transition in response to the changing climate, with primarily negative impacts. Furthermore, Canadian forests could experience more frequent and severe storms and wind damage in coastal areas, drought stress due to the redistribution of precipitation patterns, and an increase in frequency and severity of fire.

Shifts northward (and to higher altitudes) in the current ranges of individual forest species and species associations are expected. The boreal forest is expected to undergo an extensive reduction in size, with grasslands and temperate deciduous species expected to invade from the south. Northern expansion of the boreal forest will be curbed by poor soil, permafrost and lower solar radiation rates. Forest structure of the Pacific northwest is expected to remain similar to the present with richness in species diversity compensating for individual species migration. Wildlife habitat and natural reserves could suffer due to a lack of connectivity and the disturbance in the equilibrium between habitat and climate created by climate change.

Forest industry: With forests maladapted to the projected changes in climate, large areas of forest decline are anticipated. Salvage harvesting of these areas could increase the potential harvest for a period of time; however, at some point, there could be a timber shortage because new forested areas in the north will not be maturing fast enough to offset the losses in southern areas. As such, losses due to forest decline and modified fire and insect regimes, as well as drought stress in some areas, could challenge the adaptive capacity of the industry. This seems likely to be the case where long-run sustainable yield levels are considered. As a consequence, the overall impact on the Canadian forest industry is expected to vary by regions. For example, in the Mackenzie Basin area, yields from all stands of commercial lumber, both softwood and hardwood, are anticipated to decline by 50% as a result of the projected changes in climate.

Energy

In general, the sensitivity of the energy and transportation sectors to climate change is relatively low, compared to that of agricultural or natural ecosystems. The capacity for adaptation through management and normal replacement of capital is expected to be high. However, activities in these sectors would be susceptible to a rapid rate and sudden changes in climate, as well as changes in the frequency or intensity of extreme weather events.

Energy demand: Space conditioning demand profiles could alter to reflect lower heating needs in winter, but higher air conditioning needs in summer. An overall decline in energy needed for space conditioning is generally foreseen across the country, although in Québec, an overall increase is possible. For Ontario, overall space conditioning energy demand may decrease, but peak energy demands could rise. Changes in energy demand for other purposes are also expected. In the Prairies, for example, energy use will decrease for transportation, but increase for irrigation, grain drying, and harvesting.

Supply - Hydro-electricity: Hydro-electric generation potential is sensitive to changes in water availability and river flow regimes. As such, regionally differentiated changes in hydro-electric generation potential are expected, reflecting projected regional increases (e.g., Labrador and northern Québec), and decreases (e.g., Ontario, the Prairies, and southeastern British Columbia) in water availability and flows. Transmission lines may be subject to more storm-related outages should projected changes in extreme events occur. Electricity-driven industry (for example, aluminum production) could be particularly affected as a result.

Supply - Fossil fuels: Offshore oil and gas operations should benefit from reduced hazards such as sea ice and perhaps icebergs, but could be subject to more intense and frequent extreme storms. Any savings on the costs of offshore platforms would be partially offset by increased costs for coastal facilities subject to more severe wave activity. Pipeline costs in the Arctic are likely to be more expensive due to the need to address increased permafrost instability. Costs for ice-breaking tankers should be reduced. Uncertainties are still high enough, however, that the positive impacts cannot be incorporated into current design while negative impacts have to be included due to the conservative approach adopted by industry for frontier activities. As a consequence, there may be an increased cost for frontier oil and gas operations in the short term. For coal mining operations, increased erosion and landslides may be a concern in some areas, such as British Columbia.

Transportation

Land-based: It is expected that overall costs would be reduced due to shorter and/or less harsh winters (more efficient engine operation, less warm-up time, shorter snow removal seasons although with greater amounts during the winter season in some areas of the country). This is particularly applicable for the southern half of the country. In the North, however, such as in the Mackenzie Basin, winter transportation costs may be raised due to a reduced length of season for ice roads. Increased permafrost instability will likely lead to increased maintenance costs for existing all-weather roads and rail-beds.

Marine: The shipping season could lengthen for areas currently characterized by sea ice for all or part of the year, such as Hudson Bay and the western and central Arctic, and marine design needs related to sea ice may be relaxed. Sea-level rise will generally contribute to deeper drafts in harbours and channels, but will be associated with significant damage to coastal support infrastructure in Atlantic and Arctic Canada. The potential of increased storm activity has raised concerns regarding the necessity of increased navigational aid support.

Freshwater: Although longer open-water seasons will result, projected reduction of water levels will generally translate into significant, negative impacts for commercial navigation on major rivers and lakes, such as the Great Lakes - St. Lawrence River system. On the Mackenzie River, the barge season would lengthen by as much as 40%, but navigation would be more difficult with the lower water levels.

Air: The impacts on air travel have not been rigorously investigated, but decreased engine efficiency is anticipated. For smaller craft, longer seasons for the operation of float planes are likely, with conversely shorter seasons for snow and ice landing strips.

Built Environment

The built environment includes homes, buildings, roads, railways and engineering structures such as dykes and pipelines. Impacts from climate change on the built environment could include changes in construction requirements, land stability (e.g., landslides and permafrost), and the frequency and intensity of floods and other extreme events.

Construction Season: The length of the summer construction season is expected to increase while the length of the winter season decreases. While an advantage for southern Canada, a shortened winter season in the North will create difficulty for access (winter roads) and heavy construction since only then can heavy equipment operate safely without disturbing sensitive tundra areas.

Permafrost: Increased frost heave, thaw settlement and slope instability will negatively affect the structural integrity and design of northern construction including pipelines. Foundation conditions will change in the North as permafrost thaws, with differential settlement leading to changes in the integrity of structures, or even collapse of buildings. Utility lines and pipelines could rupture. Mining operations might become easier, but waste dumps, tailings dams, and water diversion channels would require increased and expensive maintenance.

Snow: Cost savings from projected decreased snow loadings on buildings and structures could be offset by increased wind and rain loadings and increased freeze/thaw cycles. Foundation instability may result from projections of increased winter rainfall, increased freeze/thaw cycles and drier summers.

Flooding and Other Extreme Events: Although there remains considerable uncertainty regarding projections of changes in flooding and other extreme events, the implications, should these changes occur, warrants consideration of the impacts. The flooding of low-lying homes, docks and port facilities as well as stresses on water distribution and sewage systems caused by projected increases in sea level, extreme rain/snow fall, and spring ice jams on rivers is a major concern. Particularly vulnerable to changes in extreme events are transmission lines (e.g., wind and ice loading) and bridge piers and dams (changes in flood levels and ice jams). Increased density of population and possessions means the target of extreme events will be greater in future so that losses would be higher even without climate change. Premature structural failure due to deterioration over months and years could be accelerated where increased occurrences of such things as hours of sunshine, temperature extremes, and frequency of combined wind and rain are anticipated.

Insurance

It is anticipated that any change in the frequency or severity of such extreme events will alter demands on insurance for claim payments. This in turn affects insurance coverage and premiums under the traditional industry actuarial approach of “the past is the key to the future”. Of serious concern is the possibility that abrupt climate change, resulting in more frequent claims disasters, could produce higher and more frequent claim payments before adequate reserves are built up. Thus the traditional industry approach would not have enough time to take such changes into account.

Property insurance: Property insurance is most likely to be directly affected (either restrictions in insurance coverage or steep price increases) and stronger building codes are being advocated as one means of reducing sensitivities. Among the consequences of these implications to insurance coverage may be greater public or personal responsibility to deal with natural disasters such as flood, drought, and wind storms. Also of concern is that the availability and costing of insurance will have ramifications for the viability of existing and new enterprises.

Crop insurance: Any sudden changes in the frequency or severity of extreme weather events affecting the occurrence of hail, drought, frost and excessive moisture would affect the industry. In the Prairies, it is anticipated that premiums in the agricultural sector may need to increase, with changed availability and eligibility criteria possible. Such restructuring may challenge the financial viability of agriculture and other sectors.

Marine insurance: Climate change with its possible effects on coastlines, pack ice, amount and time of ice breakup and other oceanic effects would affect the merchant fleets and the marine insurance companies that service them.

Human Health

Climate change is likely to have wide-ranging and mostly adverse impacts on human health. Direct risks involve climatic factors which impinge directly on human biology. Direct health impacts of climate change include:

Heat stress: It has been suggested that an increased frequency and severity of heat waves may lead to an increase in illness and death, particularly among the young, the elderly, the frail and the ill, especially in large urban areas. A comprehensive empirical study, which examined the potential impacts of climate change on human heat-related mortality for ten cities in Canada, found that if temperatures warm as expected under $2xCO_2$ conditions, urbanized areas in southeastern Ontario and southern Quebec could be impacted. An “average” summer in the year 2050 could result in a range of 240 to 1140 additional heat-related deaths per year in Montreal, 230 to 1220 in Toronto, and 80 to 500 in Ottawa, assuming no acclimatization to increasing temperatures.

Indirect health impacts of climate change include increases in some air pollutants, pollens and mold spores, malnutrition, increases in the potential transmission of vector-borne and water-borne diseases, and impacts on public health infrastructure.

Air pollution: Respiratory disorders and allergy problems will be accentuated as heat and humidity increases, although fewer high-particulate-concentration occurrences in areas such as southern Ontario and Québec, and the Fraser Valley may reduce some smog events.

Extreme weather events: Projected increases in the frequency and severity of extreme weather events, although currently somewhat uncertain, are of concern as these changes could increase deaths, injuries, infectious diseases (e.g., contaminated runoff affecting water supplies) and stress-related disorders, as well as other adverse health effects associated with social disruption and environmentally-forced migration.

Disease vectors: It has been suggested that western equine encephalitis, eastern equine encephalitis, St. Louis encephalitis and the snowshoe hare virus would expand their ranges in Canada in response to climate change. It has also been suggested that malaria may extend northward into Canada. One study, however, noted that in temperate countries, continued and increased application of control measures, such as disease surveillance and prompt treatment of cases would probably counteract any increase in vectorial capacity. Other mosquito-borne diseases that may extend northward into Canada with climate change include dengue and yellow fever. Tick-borne diseases such as Lyme disease and Rocky Mountain Spotted Fever, may also extend their geographic distribution under climate change.

Environmental contamination: Health disorders related to environmental contamination, water contamination by bacteria (e.g., *Bacillus anthracis*), viruses, protozoa (e.g., *Giardia lamblia, Cryptosporidium, Leptospira*) and parasites is likely to increase under climate change. Any effects of climate change on Canadian nutrition are likely to be associated with the effects on foods brought in from other countries. Food imports are likely to be associated with increases in outbreaks of some viral, parasitic and bacterial diseases, such as hepatitis A.

Public health infrastructure: There are likely to be an increased number of environmental refugees under climate change. These refugees may bring with them disease agents that are not endemic to Canada. The current Canadian public health infrastructure is also not organized to cope with changes amongst fiscal, agricultural, transportation and energy policies and how they impact health.

Recreation and Tourism

Tourism: Tourism destinations which rely primarily upon their natural resource base to attract visitors, such as mountains and coasts, are likely to be more at risk to climate change than those destinations which depend upon cultural or historical attractions.

Water-based recreation: Since most forms of recreation are enhanced by the presence of water, any changes in water quantity or quality due to climate change is likely to affect outdoor recreation. Sea level rise caused by climate change will affect coastal communities dependent on recreational activities. Beaches, marine wetlands, built structures and potable fresh water supplies may be affected. Fluctuating water levels can impact marinas and recreational boating activities on the Great Lakes.

Natural areas: Climate change may modify many ecosystems on which outdoor recreationalists depend on. This has implications for the amount of land devoted to parks and other natural areas the size of each individual park, park selection and designation, and boundary delineation. Climate change impacts will also affect management practices such as the content of interpretive programs, the protection of endangered species, and the determination of appropriate recreational activities.

Winter: Downhill ski areas will likely experience diminished quantities and reliability of snowcover with associated curtailments of the operating seasons of many ski areas. Ski areas may have to rely increasingly on artificial snow-making technology to retain a viable season length. Other winter activities such as cross-country skiing, snowmobiling, ice fishing and other activities dependent on snow or ice are likely to be impacted negatively.

Summer: Projections of increases in temperature may lengthen the summer sports seasons across Canada (e.g., the golfing season in Québec may be extended by up to 3 to 4 weeks). The reliable camping season in Ontario is extended under several climate change scenarios, sometimes by as much as 40 days. Hunting game and waterfowl and bird-watching are also likely to be impacted as wildlife may be displaced due to habitat loss or increased competition.

ADAPTATION TO CLIMATE CHANGE

There are several points that must be kept in mind when considering the extent to which adaptive strategies should be relied upon. In the first place, adaptation is not without cost and, therefore, its implementation will divert scarce natural and financial resources away from other productive activities. Canadians spend billions of dollars annually adapting to our current climate, including its variability. In addition, our climate results in a myriad of social and environmental disruptions to which we also must adapt, the "costs" of which are for the most part unknown. Adapting to changing climate will likewise "cost" Canadians, but calculating these costs will be exceptionally difficult. It is expected, however, that increases in these potential costs could be reduced if information on changes, their impacts, and viable response options was available in a timely manner (proactive opportunities) and if supportive and informative institutional and financial mechanisms were also available.

Secondly, the economic and social costs of adaptation are expected to increase the more rapidly climate change occurs. Thirdly, although many opportunities exist for technological and behavioural adaptation, uncertainties exist concerning potential barriers and limitations to their implementation. Fourthly, uncertainties exist about the efficacy and possible secondary effects of particular adaptive strategies. Fifthly, in addition to climate change, Canadians will also be dealing with major changes in technology, the economy, markets, products, and population demographics over the next century. Our adaptive responses should be integrative, not addressing simply one change but recognizing the broad spectrum of potential changes.

Finally, information on adaptation options is, in general, less often available and where it does exist, it is often subjective in nature. Interpreting a region's or sector's adaptive capacity must include rigorous research on social and cultural acceptability, as well as research on the necessary institutional and financial mechanisms to manage the change.

Water

Canadians spend close to a billion dollars in the water resources sector adapting to current climate conditions. These adaptations include the construction of dams, sewers, drainage ditches, floodways, and others. Adapting to climate change will likely increase these expenditures considerably.

Methods of adapting, in addition to increasing the capacity of the existing water infrastructure , include: the use of insurance coverage, government subsidies and disaster relief to pay for damages; bearing personal financial losses; improving public awareness concerning both the impacts of climate change and adaptation strategies; improving knowledge of water and climate linkages through further research in areas such as evapotranspiration, permafrost, groundwater, northern regions and small lakes; introducing nonstructural approaches to reducing the impacts such as instituting integrated water resource management, encouraging sub-watershed planning; continuing and improving water conservation programs (e.g., behavioural change); improving zoning and building permit process; implementing water demand management (e.g., water pricing); and structural approaches such as reducing pollution; increasing municipal water supply infrastructure; making marginal changes in the construction of infrastructure (e.g. incorporate climate change scenarios); implementing more floodproofing; constructing new dams, levees, dikes, and reservoirs; continuing and improving water conservation programs (e.g. toilet dams, building code changes); and implementing natural channel design.

Ecosystems, Biodiversity, Wildlife and Wetlands

There is considerable doubt over how specific unmanaged ecosystems will respond to climate change, especially if the amount of change is towards the high end of current projections. There is, however, no guarantee that the structure and function of future ecological communities in Canada will remain the same under the projected climate change. Humans could find it necessary to minimize the negative effects on ecosystems arising not only from climate change but also from other human-related stressors such as the acidification and long-range transport of toxic substances.

If wildlife populations decline steeply and are evidently at risk of extinction, management efforts may need to become increasingly more intrusive. Adaptation options to be considered include: creation of more and larger protected areas, connected by corridors; implementation of transplantation programs; selective breeding of parts of the population best adapted to the new climate and; off-site storage of genetic material, making up an increasingly aggressive field of “salvage ecology”. Additional adaptations could include: protecting future key areas, such as areas that are likely to be flooded, and managing at a landscape level so that human activities such as forestry and agriculture can be integrated with the overall habitat considerations.

Agriculture

The assessment of adaptation strategies has mainly focused on the Prairies or the current climatic boundary of Canadian agriculture (where appropriate soils may be a limiting factor). Adaptive measures at the farm or local level that have been identified include: switching to different cultivars or introducing higher value field crops, increased use of irrigation, and diversification of farming mix to include more livestock. At the regional or national level, approaches could include: altered subsidy structures to reflect actual climate risk, crop assistance programs linked to soil conservation, and strengthened rural education programs to encourage sustainable land use practices.

Forestry

The adaptability of the forestry sector is dependent on the industry ability and willingness to adapt to whatever species do prevail as a consequence of climate change, to salvage-cut dying stands, to plant cut areas with species better adapted to the altered climate, and to move to locations where resources are more plentiful. Confidence in the industry’s ability to adapt is, in part, a reflection of the expectation that future impacts will be simply extensions of the types of conditions currently dealt with - that is, same problems, different locations and extent. Adaptation, in addition to considering the social and environmental costs, will have to address such important issues as: increasing forest landscapes to reduce fragmentation, managing stands and landscapes to reduce crown and large area fires, and developing ways to maintain landscape corridors.

Fisheries

Fisheries adaptation options that would respond to climate change have, for the most part, been used previously in response to other environmental or use changes and each has limitations, typically assuming orderly change. As such, considerations in the development of adaptation options include: recognition of the possibility of an increased rate of change and the potential of surprises; need for close ties with sustainable ecosystem use objectives; need for responses at the local level to minimize negative impacts and maximize gains while aiming for a net gain overall; robust management regimes which balance long and short term views; and an ecosystem-centred “no regrets” approach wherein all stresses are reduced.

Energy

Historically, the energy industry has been able to adapt fairly successfully to changes in supply and demand, and to tackle new challenges such as the search for oil and gas under ice-covered waters through innovation. As a result, the adaptation capacity of the energy sector is considered to be high, particularly if the projected changes occur relatively slow and if the industry is not faced with surprises. Altered design criteria, energy conservation, and the use of alternatives (such as solar and wind) are among the expected adaptive responses.

Built Environment

In many existing cases, the current margin of safety built into the National Building Code will likely be sufficient to maintain safe and economical structures, given good workmanship and materials. Some upgrading and/or moving of facilities and structures (such as riverine flood control systems), although costly, may be necessary. In order to limit further development in damage-prone areas, strengthening of land use planning regulations may be necessary. Where new construction is involved, altered design criteria and siting to reflect changing climate conditions should be implemented. Particular emphasis should be given to structural safety under extreme weather situations, energy conservation, and the minimization of life cycle costs of buildings and structures. For addressing coastal retreat due to sea-level change, coastal zone management that weighs the relative merits of engineering and natural should be part of adaptive strategy considerations.

Insurance

Weather modification activities such as cloud seeding in the Prairies have been funded by the industry to try to reduce hail damage and payouts by the insurance industry. Research has been funded into improving building materials, methods and lobbying for improved building codes in Canada to reduce risks. Individual insurance companies may change terms of coverage by: limiting the number of policies written and dollar coverage provided in a specific geographic area, reducing policy limits, increasing deductibles, changing payment terms, changing rules as to what risks can be covered, withdrawing from the market entirely and, spreading the risk through reinsurance.

Human Health

Gradual physiological acclimatization of populations, the use of air conditioning, and an adequate hot weather warning system may reduce heat-related morbidity and mortality in the future. Although climate change may extend the range northward of various vectors such as malaria, a responsive Canadian health infrastructure may be able to prevent a large increase in number of actual disease cases.

Recreation and Tourism

Recreationalists have a substantial potential to adapt to climate change since their participation is a result of choice and, although choices are not unconstrained, a great deal of flexibility is involved. Participants may be able to substitute or shift recreational activities and locations without a great deal of loss in the quality of their recreation.

The industry may be able to adapt by diversifying the types of recreational activities to ensure that investments in property and infrastructure generate incomes for much of the year. Examples include the construction of water slides that take advantage of existing ski lifts in the summer, provision of golf courses, hiking trails and swimming pools, construction of condominiums to build a reliable year-round clientele, and the addition of multi-functional facilities (e.g., combinations of recreational and conference facilities). Such strategies can reduce the seasonality of recreational enterprises and provide more reliable employment thereby strengthening surrounding communities and take advantage of possible increases in the length of summer under climate change.

Transportation

Climate is an important consideration in transportation activities. Transport industries, government agencies, and the Canadian public expend considerable effort and substantial sums of money (hundreds of millions of dollars annually) to reduce the risk of delay or incident due to inclement weather. No comprehensive inventory of these various adaptations exists, however, and the effectiveness of many of these measures is largely unknown.

SCIENCE GAPS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Geographic Focus: Conduct studies in regions lacking attention in the necessary scientific research. Among those identified are: Eastern Arctic, British Columbia interior, the central Prairies, Northern Ontario and Labrador, and urban areas and their infrastructure.

Water: Generate more plausible scenarios of extreme events for hydrologic and river basin sensitivity analyses; use deterministic models to assess the hydrologic impacts of climate change; improve estimation of evapotranspiration rates related to vegetation changes due to climate change; conduct empirical analyses of climatological and ecological processes in high-elevation mountainous areas to improve knowledge of impacts on snow accumulation processes under climate change; assess impacts of El Niño and La Niña events on Canadian runoff/streamflow; assess impacts of climate change on water quality, small lakes, lake ice and groundwater in Canada; conduct more research on water resources uses and adaptation for agriculture, fisheries, recreation and tourism, hydrological power, commercial navigation, municipal water supply and human health and; identify methods to include climate change information into long-term water resources planning and management.

Ecosystems, biodiversity and wildlife: Continue and expand long-term multi-disciplinary monitoring and research on fundamental ecological conditions and trends in Canada; improve understanding of changes in basic physical parameters of oceans such as water temperature, salinity and ocean currents; improve life histories knowledge of fish and other marine organisms to understand impacts of climate change and variability; conduct long-term experiments on the effects of elevated CO_2 on ecosystems such as grasslands, tundra and forests; continue study of plant-herbivore and other trophic-level interactions under increased CO_2 conditions; improve understanding of the mechanisms regulating biogeochemical cycling and biological productivity; determine effects of soil feedbacks and biological interactions between different organisms on direct ecophysiological effects of changes in climatic variables; improve knowledge of natural patterns of genetic diversity in Canada; determine the diversity and sensitivity of soil microbes and nonvascular plants to climate change; conduct integrative studies of ecosystem-level behaviours and; improve understanding of the overall effects of climate on wildlife population dynamics.

Wetlands: There are still major gaps in our understanding of wetlands and their likely responses to climate change. Wetlands lag behind other ecosystems in being adequately modelled and are often excluded from global models of the effect of climate change. Research is needed on the hydrogeochemical processes of wetlands and on inter-relationships between water levels and wetland vegetation and areal responses. Simulations of habitat changes associated with climate change are needed to understand the potential changes in wetland numbers and quality and the impact on waterfowl production and biodiversity. Work also needs to be done in establishing the area, depths and types of peatlands as well as their carbon storage capabilities and their responses to climate change especially of methane and carbon dioxide. Climate models should be used in conjunction with other models such as those for precipitation, runoff and groundwater to assist in estimating consequences of climate change for wetlands in Canada and the functions and values they provide.

Agriculture: Standardize research utilizing a common set of climatic and crop productivity models for all regions of Canada to generate more easily comparable results in terms of climate change impacts on crop yields; further assessment of the economic impacts of climate change at various agricultural scales (e.g., farm, regional, national) and for different crop and livestock operations; improve the understanding of farm and agricultural adaptation by effectively integrating agro-climatic indicators which farmers identify as important in their decision-making into the climate change scenarios and; determine the implications of climate change on Canadian agriculture in the context of changing global agricultural commodity markets.

Fisheries: Conduct comparative studies of aquatic ecosystems and fish populations across latitudinal and altitudinal gradients; increase understanding of factors determining fish distributional patterns; improve life-history knowledge of salmonids which are especially vulnerable to climate change; monitor biological responses and ecological climate indicators in representative aquatic ecosystems with significant fisheries; improve understanding of linkages between climate and variations in marine productivity; improve understanding of roles of nutrient, light, thermal and mixing regimes in freshwater ecosystems in determining fish productivity; improve basic knowledge of Arctic marine and freshwater biota life histories and productivity levels; assess impacts of sea level rise and river discharge declines in estuaries; improve estimates of ecosystem and fishery carrying capacities; improve measures and valuations of subsistence and native fisheries.

Forestry: Improve knowledge of the relationship between climate and tree growth in order to better predict physiological climate thresholds for mature trees; improve knowledge on the carbon, methane, and nitrogen cycles and the interaction between the soil ecosystem's physical (e.g. surface albedo, temperature profile) and biological processes (e.g. nutrient cycling, decomposition) in order to improve current biological models; standardize and improve monitoring to include data on species composition, the rate and location of deforestation, improved measurements of hydrological interactions; forest biomass growth, mortality, and disturbance would contribute to better vegetation and carbon sequestering models; improve the interaction of climatic and biological models by establishing links through biochemical processes to better simulate carbon and nitrogen cycling; develop models which include non-climatic factors to determine the role which climate change will play in affecting future forest management practices and; develop models of ecotones and their responses to climate change to describe the transition phase of climate change, and the continual and compounded changes in atmospheric conditions and their dynamic relationship to ecological processes.

Energy: Improve knowledge of regional distribution and intensity of climate change since Canada's climatic diversity has direct impacts on how energy is produced, transmitted and used; assess the sensitivity of energy supply and demand to climate change; focus research more on adaptation measures rather than mitigation measures for the energy sector; improve cost estimates of impacts and adaptation measures; utilize a more integrated approach in research, addressing technological, social and economic issues between sectors.

Transportation: Conduct more detailed impact analyses on the implications of climate change on all dominant models of transport in Canada (automobile travel, trucking, rail, air, coastal marine); further address the issue of extreme weather events and impacts on transportation safety; determine impacts of climate-induced changes in regional economies and settlement patterns on transport demand and; inventory and evaluate the various adaptations available for the transportation sector.

Built environment: Improve collection and analyses of climate design data needed for the construction industry, especially wind-driven rain, solar radiation, snow loads and extreme weather events; assess impacts of climate change on energy efficiency (insulation) and energy use (air conditioning, space heating) of buildings; improve understanding of changes in permafrost due to climate change and impacts on building foundations, infrastructure and existing and new construction and ; improve knowledge of extreme weather events to reduce damage through more resistant building designs and avoidance of high-risk regions.

Insurance: Improve understanding of the potential effects of climate change on the property and casualty industry in Canada; improve predictions on how climate change will affect the number of catastrophic weather events, including associated landslides and snow avalanches; develop better models to determine the impacts of climate change (higher temperatures and severe weather) on mortality rates in Canada.

Human health: Improve data collection on geographic trends in the distribution and abundance of insect vectors of disease in Canada; improve surveillance and monitoring of the distribution and abundance of anopheline mosquitoes that carry malaria and the migration of deer mice that carry the hantavirus; determine the impacts of climate change on human behaviour such as the use of air conditioning, increase in aggressive actions.

Recreation and Tourism: Assess the implications of climate change for natural area designation and management; assess the means by which recreational provisions can be diversified to reduce vulnerability; assess how alternative recreational opportunities are evaluated by potential participants; evaluate the role of extreme weather events in influencing recreational provision and; assess the importance of climate vs. non-climate variables on the location and types of recreational activities; assess current lengths of operating seasons, their temporal and spatial variability, and the associated economic viability of recreation businesses.

CHAPTER ONE

CLIMATE CHANGE AND VARIABILITY: IMPACTS ON CANADIAN WATER

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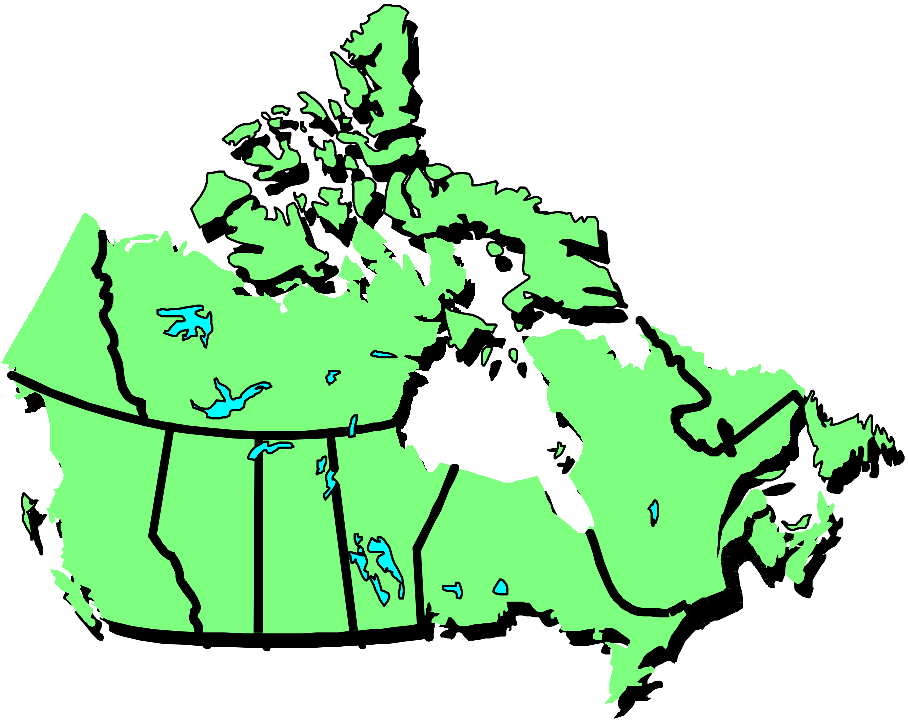

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EXECUTIVE SUMMARY

Water is essential to all life. For humans, water also plays a central role in many economic and societal functions including municipal, industrial, commercial, recreational, navigational, hydroelectric, and agriculture uses. In many parts of Canada there are existing conflicts over this resource (which will be exacerbated by climatic changes). Recommendations have been forwarded by researchers urging governments to improve the current management of water. Climate change impacts, both positive and negative, on water resources in Canada are extremely important.

This summary of climate change and water describes the following: (1) hydrological impacts, (2) impacts on water uses, (3) potential adaptation responses, and (4) gaps requiring research.

Hydrological Impacts

<u>Precipitation</u>

- increases in annual precipitation for most regions
- changes in the form of seasonal precipitation (e.g., less snowfall, more winter rainfall)
- more intense local precipitation events

<u>Evaporation/Evapotranspiration</u>

- increases in evaporation/evapotranspiration due to higher air temperatures

<u>Runoff/Streamflow</u>

- increases and decreases in runoff/streamflow across Canada depending on the region and climate change scenario
- earlier spring freshet runoff and lower maximum runoff

<u>Lake Levels</u>

- lower levels in the Great Lakes
- earlier seasonal maximum levels and less amplitude

<u>Thermal Structure of Lakes</u>

- increased water temperatures of lakes may disrupt thermal stratification patterns and may inhibit lake turnover

<u>Groundwater</u>

- groundwater recharge and levels are likely to decline
- baseflow of rivers may decrease with negative impacts on surface water quality

<u>Soil Moisture</u>

- decreases in soil moisture in southern Canada; summer deficits in southern Ontario and Saskatchewan

Ice Cover

- lake ice cover is expected to be reduced or eliminated on the Great Lakes and smaller lakes
- shorter duration of the ice cover season

Permafrost

- northward movement of permafrost boundaries and permafrost areas reduced

Hydrologic Variability

- hydrologic variability may increase with higher incidences of extreme events, e.g., large flood events, longer summer droughts

Water Quality

- higher water temperatures and lower runoff may reduce water quality in lakes and streams

Wetlands

- wetland areas reduced due to lower water levels and wetland functioning may be negatively affected
- impaired water quality

Impacts on Water Uses

These hydrological impacts have important implications on the natural environment and the ways in which humans use water.

Agriculture

Climate change impacts upon agriculture will be both positive and negative. Some areas of Canada will enjoy a longer growing season due to increased temperatures; however, the increased evapotranspiration and decreased soil moisture may reduce crop yields in many regions. Irrigation use, particularly in the Prairies, will likely increase, as will rural water use conflicts will increase.

Fisheries

Climate change will affect both water quantity and quality which has significant implications for fisheries habitat. In terms of water quantity, lowered lake levels and decreased streamflow may reduce the available habitat for fish. Changes in stream discharge may affect spawning. In terms of water quality, increased water temperatures, and reduced dissolved oxygen may impair habitat for many species. For instance, cold-water species may be replaced by warm-water species.

Recreation and Tourism

Lower water levels may cause marinas to be "high and dry", expose beaches, and reduce canoeing opportunities. Winter recreation activities such as skiing, icefishing and snowmobiling may be negatively affected by less consistent snowfall and icecover.

Hydroelectric power

Lowered lake levels on the Great Lakes will cause reductions in hydroelectric power generation capabilities and increased costs.

Human Health

Extreme hydrologic events are hazardous to human health. Floods or intense rainfall may cause overflows of combined storm and sewage sewers leading to the contamination of water (e.g., *Cryptosporidium* has been caused by contaminated drinking water). Similarly, excessive amounts of precipitation create breeding sites for insects and rodents that carry diseases.

Navigation

Climate change may cause a decline in water levels in the Great Lakes and thus ships could carry less cargo and more trips would be required to transport the same amount of cargo. The viability of certain ports may also come into question. However, climate change may benefit navigation by allowing a longer shipping season. Warmer winter temperatures will limit the amount of ice cover in the navigation channels.

Municipal Water Supply and Demand

Higher air temperatures will cause increases in municipal water consumption. In particular, lawn watering activities are expanded. Under climate change scenarios, water consumption will likely increase while streamflow may be reduced; there may be water demand-supply mismatches.

Adaptation

Canadians have spent close to a billion dollars in the water resources sector adapting to current climate conditions and climate variability. These adaptations include the construction of dams, sewers, drainage ditches, etc. Adapting to climate change will likely increase these expenditures. Methods of adapting include the following:

Share the Loss
- insurance
- government subsidies and disaster relief

Bear the Loss
- "you are on your own"

Research
- increased knowledge of water-climate, linkages e.g., evapotranspiration, permafrost, groundwater, northern regions, and small lakes

Education
- education concerning impacts: public awareness and participation
- education concerning adaptations: water conservation

Modify the Events, Prevent the Effects, Avoid the Impacts

Nonstructural Approaches: These include: integrated water resource management; subwatershed planning; water conservation programs (e.g., behavioural change); zoning and building permits process; and demand management or water pricing.

Structural Approaches: These include: reduction of pollution; increased municipal water supply infrastructure; incorporating climate change scenarios in floodproofing, new dams, levees, dikes, and reservoirs; and improve water conservation programs (e.g., toilet dams, building code changes); and implement natural channel design.

Gaps Requiring Research

Some of the gaps in understanding of the effects of climate change in hydrology, water resources and adaptation are summarized below.

Hydrology

- Climate changes that alter the frequency and magnitude of extreme events are more significant from a hydrologic, water resources management and adaptation perspective than changes in the mean. At present, the spatial resolution of GCMs do not allow development of scenarios of the extreme precipitation events critical for generating extreme floods and associated impacts. Scenarios of extreme events for hydrologic and river basin sensitivity analysis are needed.
- There are no Canadian impact assessments using the most recent GCM runs with the effects of aerosol cooling. There are few assessments using transient GCM scenarios.
- There is a lack of regional hydrologic impact assessments of climate change scenarios on watersheds in the Eastern Arctic and Atlantic Canada.
- High-elevation, mountainous areas need more empirical assessment of climatological and ecological processes since the potential for changes in air temperature and increases and/or decreases in snow accumulation due to climate change will have significant hydrologic and water resources implications.
- Better evapotranspiration estimation methods are needed to answer questions related to vegetation changes due to climate change and vegetation response to CO_2 enrichment and water resources impacts. Some evapotranspiration models have leaf area indices and stomatal resistance variables which can be modified to simulate new/different vegetation response under climate change.
- There have been no Canadian studies relating runoff/streamflow variability and trends to ENSO (El Niño or La Niña) events.
- Empirical relationships between temperature and precipitation and runoff, and/or the water balance approach have been the primary methods used to assess the hydrologic impact of climate change; only a few studies have used deterministic models or process-related models. Impacts are most frequently reported in annual and monthly changes that are not detailed enough for water resources management and planning.
- Limited research has been conducted concerning the impact of climate change on small lakes.

- Little is known about potential changes in frequency of occurrence or variability in lake hydrodynamical responses under a changed climate or how it would impact on ecosystem components.
- Of particular concern for water quality and habitat are projections that warmer climates can result in reduced frequency of buoyancy-driven water column turnovers. In warmer latitudes, periods of stratification may be enhanced. In colder high latitudes, the frequency of overturn is likely to increase. This is could result in significant environmental impacts since spring and fall turnovers are important for nutrient distribution and oxygenation of lake water. The processes and implications need to be explored.
- There has been limited modeling of the effect of future climatic change in Canada on lake ice. The limited ice research in Canada is often attributed to the lack of nationally consolidated data. Individual lakes may be used as regional climate indicators or remote sensing of lake ice cover may be used as a method to detect climate change on a national or global scale.
- There is limited knowledge of the groundwater resources in Canada; there is less knowledge of the effects of climate change on groundwater quantity and quality. Considerable research will be required to understand the potential impacts of climate change on groundwater resources, how these impacts might translate to societal concerns, what adaptation strategies might be applied to these concerns, and how these strategies might be implemented.
- Water quality impacts of climate change has received little research attention. Primarily research has focused on temperature and dissolved oxygen effects in large lakes while other water quality parameters such as nutrients and toxics have not been studied. Riverine and small inland lake effects have also not been assessed. More research is needed to determine the effect of precipitation, evapotranspiration and runoff changes on physical limnology, water chemistry and biology of lakes.

Water Resource Uses and Adaptation

Many of the results on impact assessments are based on expert judgment. Although expert judgment plays an important role in identifying potential impacts, more studies need to be undertaken to provide empirical evidence of climate change impacts.

Agriculture

- More research is needed on water conservation methods, including reducing the use of irrigation, and enhancing on-farm retention
- Considering climate change in agricultural policy-making and planning is necessary

Fisheries

- Studies have focused upon the Great Lakes and British Columbia fisheries; little is known about the northern, inland and small lake fisheries.
- More monitoring for current conditions is needed

Recreation and Tourism

- Limited studies related specifically to water recreation and winter recreation
- no assessment of tourism implications

Hydroelectric Power

- Only studied in Great Lakes and Quebec (no studies in British Columbia)

Human Health

- Limited research has been conducted concerning human health and climate change
- No research on water quality change and human health

Navigation

- The limited research is this area has focused upon the Great Lakes, with some work in the North (Mackenzie) and Maritimes

Municipal Water Supply

- Few studies have been completed concerning municipal water (except Prairies) and reservoir operation.
- There is a need for research to assess the degree to which demand-side management of water supply, economic instruments and improved management of water infrastructure can mitigate the impacts of climate change and what further strategies need to be implemented and at what cost.
- Appears to be little municipal interest in planning for climate change (e.g., only one example found).

General

- Identification of methods to include climate change information into long-term water resources planning and management
- Case studies of adaptation assessments
- Require quantification of the costs of adaptation to current climate variability and climate change.

INTRODUCTION

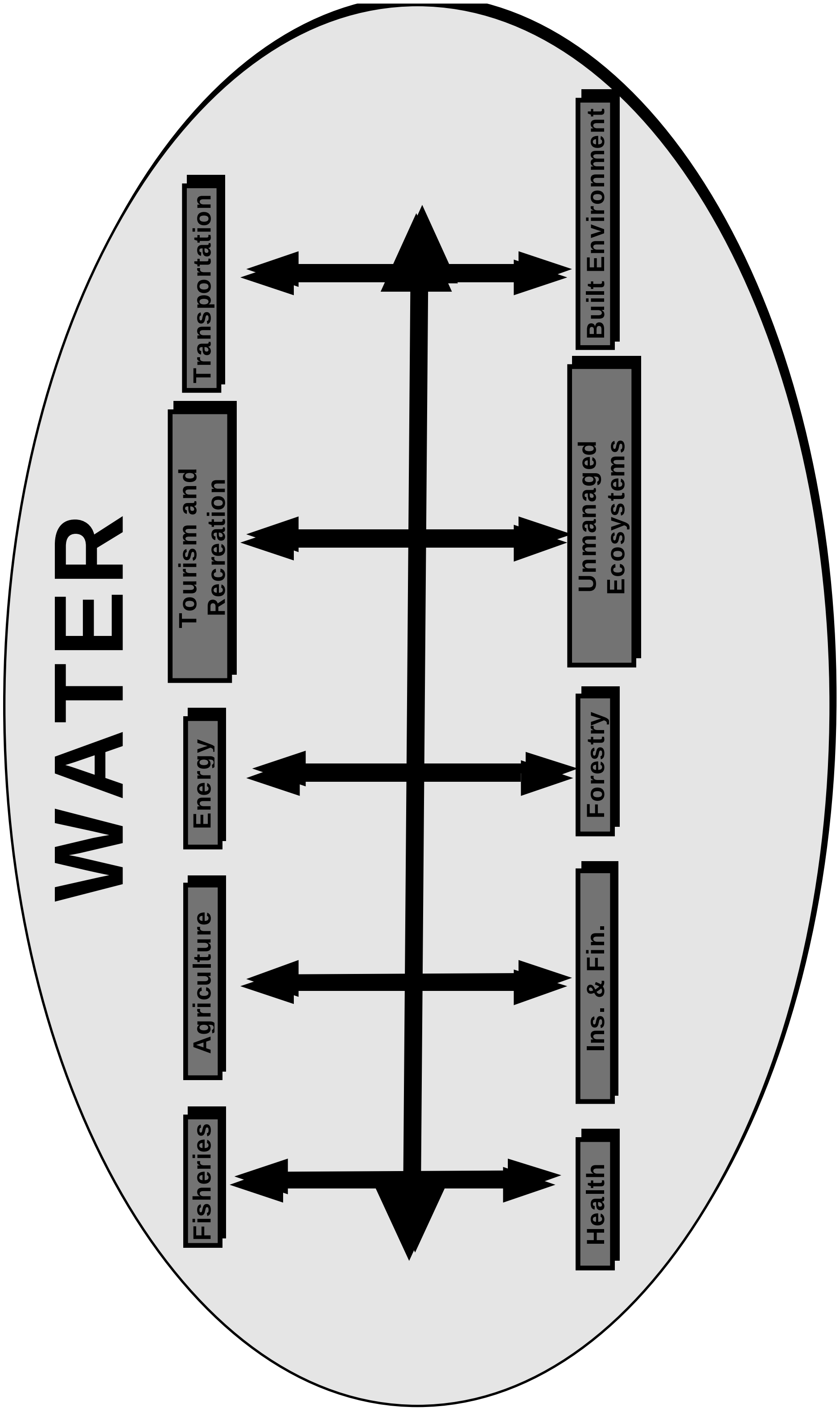
Water the Unifying Agent

Water is essential for all forms of life on Earth. Our society and nature rely on water directly and indirectly. Water is related to all other sectors in the Canada Country Study (CCS) and there are connections between many of the other sectors e.g., tourism and fisheries (Figure 1.1).

Water Systems

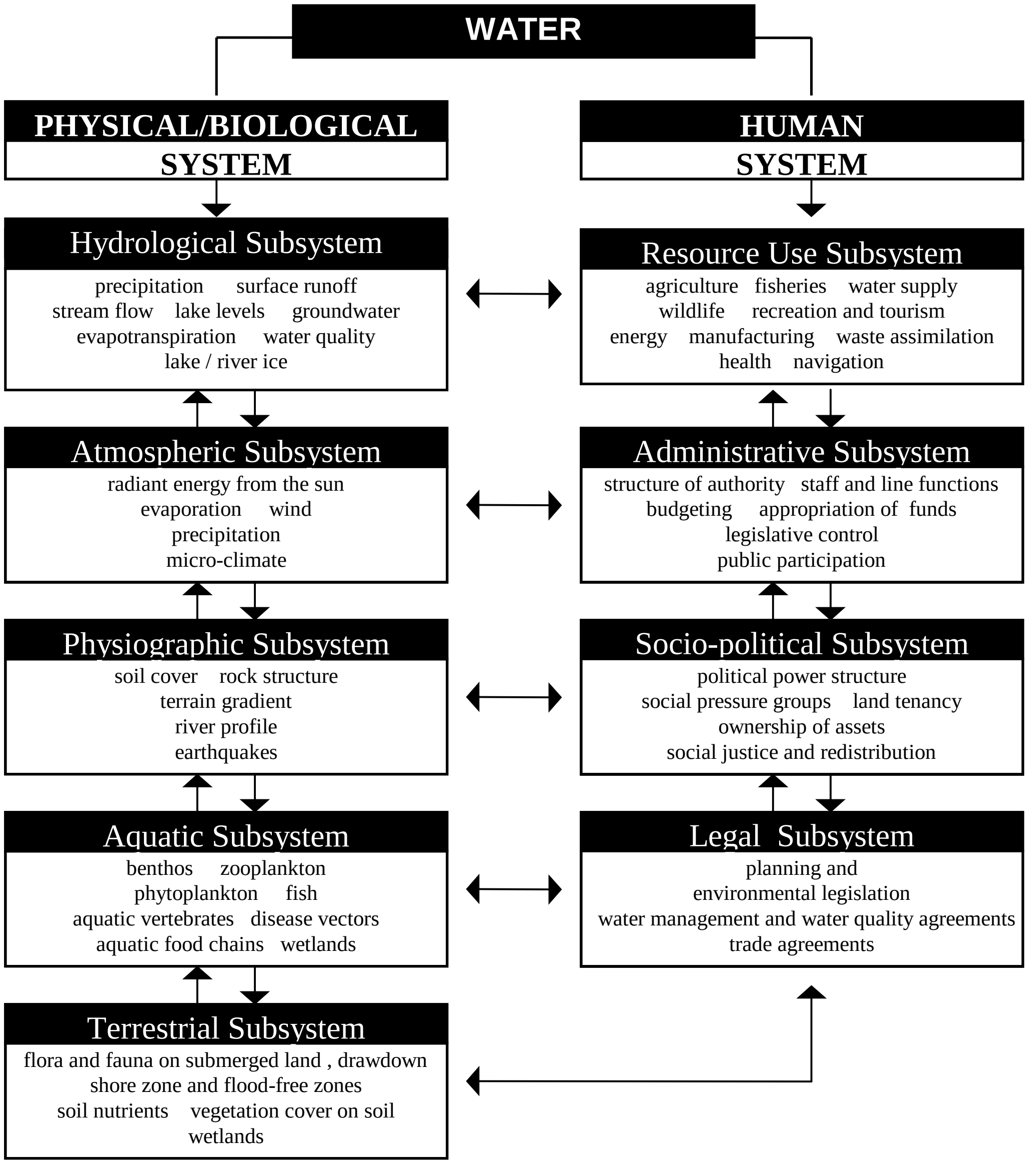
For the purposes of this Water Sector synthesis, water is divided into two main systems (Figure 1.2). One is the physical/biological system which includes the atmospheric, hydrological, physiographic, aquatic and terrestrial subsystems. Another is the human system which consists of resource use, administrative, socio-political, and legal subsystems.

Figure 1.1: Inter-relations and inter-connections between water and numerous other sectors.



The first part of this Water Sector synthesis entitled *Hydrology: Climate Change and Variability* focuses on the Hydrological Subsystem (Figure 2.2) with some discussion of the Atmospheric Subsystem. The Fisheries Sector discusses the Aquatic Subsystem and the Terrestrial Subsystem will be examined in numerous sectors including Agriculture and Forestry. The Human System is addressed in the *Water Resources: Climate Change and Variability* and *Adaptation: Climate Change and Variability* sections of this Chapter.

Figure 1.2: Two Water Systems

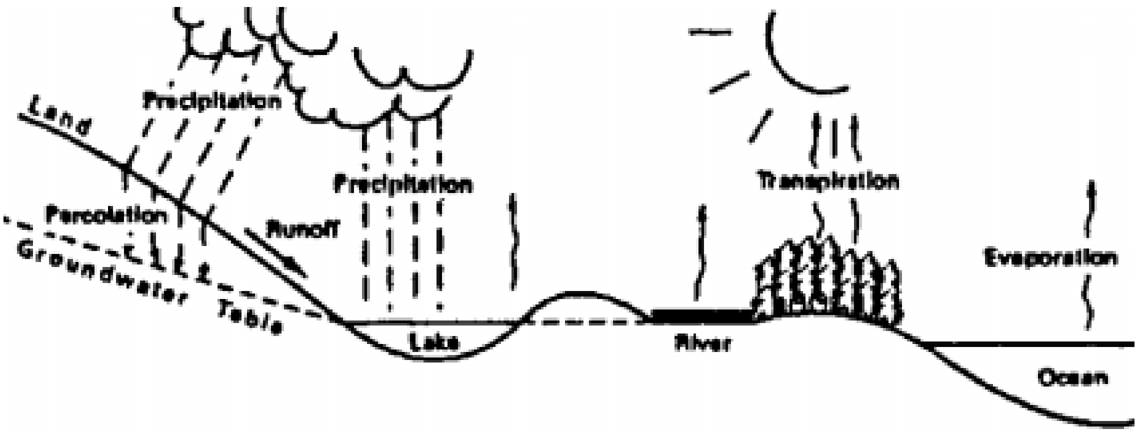


(Adapted from McDonald and Kay, 1988, 192)

HYDROLOGY: CLIMATE CHANGE AND VARIABILITY

Figure 1.3 shows the key components of the hydrological subsystem and the atmospheric subsystem described in the previous section. The hydrological cycle and its components will be used to discuss the impacts (e.g. first order) of climate variability and change in this synthesis. As shown in the diagram, facets of the hydrological cycle are inter-linked. For example, an impact on precipitation affects groundwater supply and streamflow; changes in evaporation affect soil moisture, streamflow, and lake levels. General Circulation Model (GCM) simulations show an enhanced global hydrological cycle due to an increase in temperature; the impacts of these changes are discussed in this synthesis (IPCC, 1996, 23).

Figure 1.3: Diagram of the hydrological cycle



Source: adapted from Sanderson, 1996

Hydrologic Terms:

Precipitation: Precipitation in the form of rain, snow, and hail comes from clouds formed when water vapour condenses. Precipitation in Canada is high on the Pacific and Atlantic and low in the interior and the Arctic.

Evaporation: As water is heated by the sun, its surface molecules become sufficiently energized to break free of the attractive force binding them together, *evaporate* and rise as invisible vapour in the atmosphere.

Transpiration: Water vapour is also emitted from plant leaves by a process called transpiration. Every day an actively growing plant *transpires* 5 to 10 times as much water as it can hold at once.

Surface Runoff: Surface runoff is that part of the precipitation that does not evaporate or transpire but drains across the land surface into creeks, rivers, lakes, and eventually the oceans.

Percolation: Surface water moves downwards, or percolates, through cracks, joints, pores in soil and rocks until it reaches the water table where it becomes groundwater.

Groundwater: Surface water which moves through the soil to reach the water table and eventually discharges into lakes and rivers. The groundwater table is the level to which water will rise in an open well.

(adapted from Environment Canada, 1990)

This synthesis for the CCS presents the current knowledge of variability and extremes, trends and climate change impacts on:

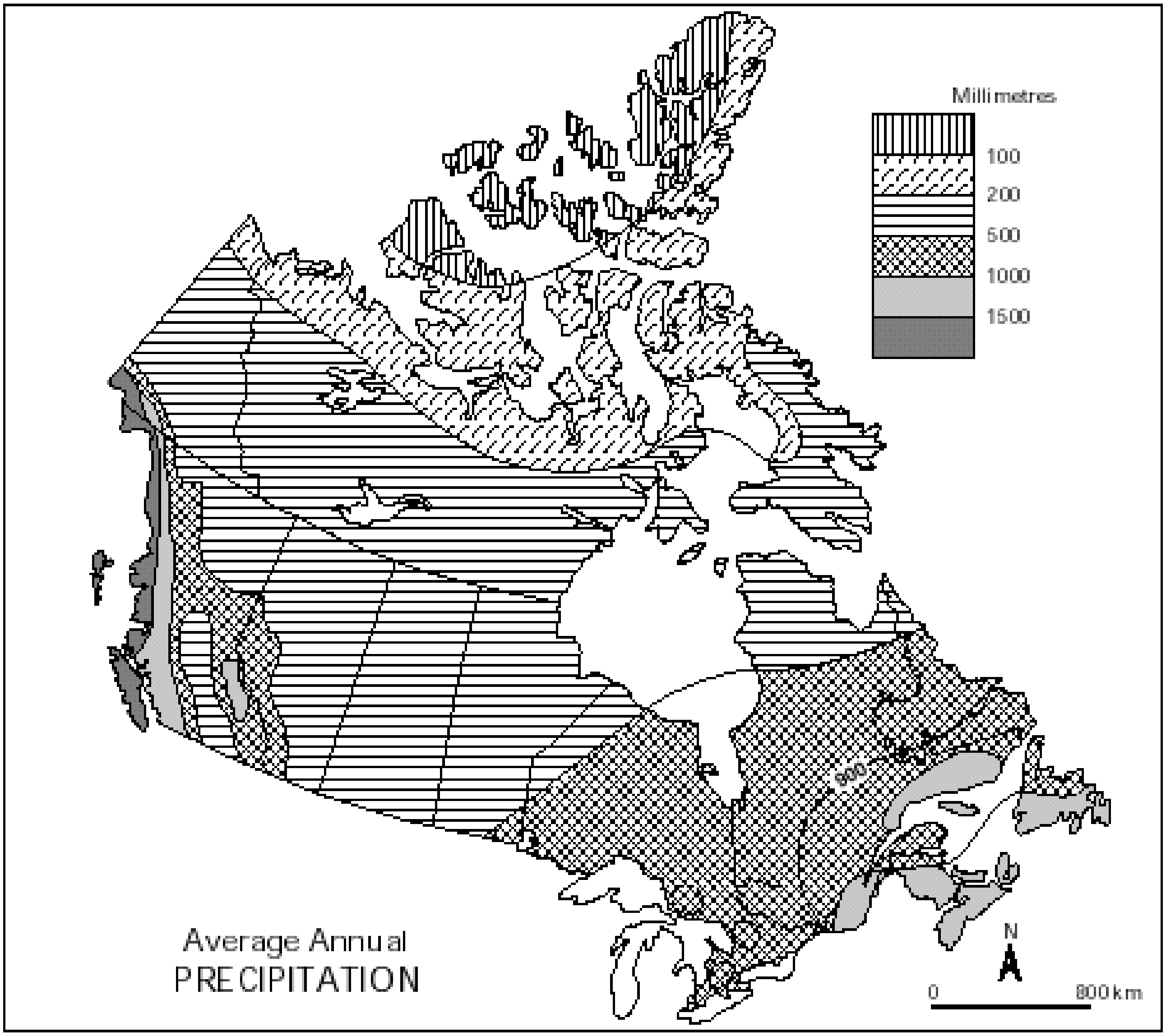
- Precipitation,
- Evapotranspiration,
- Surface Flows (Streamflow/Runoff),
- Lakes,
- Groundwater,
- Water Quality,
- Wetlands, and
- The Frozen Regime.

Precipitation

The temporal and spatial distribution of precipitation is a major determinant of habitability of land for humans (Rogers, 1994) and the development of characteristic biophysical systems. The distribution of precipitation is variable across Canada (see Figure 1.4). These regional differences are due to the size of and heterogeneity in the Canadian landscape and the diverse weather systems which influence the nation. For example, the coastal regions of British Columbia receive the highest precipitation primarily in the winter. Meanwhile, the Prairie region has less precipitation due to the "rain-shadow effect" of the Rockies. The Arctic region also receives little precipitation. Eastern Canada receives an even seasonal distribution of precipitation. In an eastward progression from the eastern Prairies in Winnipeg (500 millimetres (mm)) through Ontario and Québec to Halifax, Nova Scotia (1500 mm), precipitation increases by 40 mm/100 kilometres (km) in a southeast trend. The Atlantic region receives a significant amount of precipitation (Phillips, 1990).

Canada is a cold country. In winter, large portions of the country have precipitation in the form of snow which is stored on the ground. Snow accumulation over the winter has significant implications for hydrology, wildlife, vegetation, and socioeconomic activity.

Figure 1.4: Annual Total Precipitation for Canada



Precipitation Variability and Extremes

Precipitation is also extremely variable seasonally, interannually, and interdecadally. Table 1.1 lists the record extreme high and low precipitation events.

Table 1.1: Canadian Precipitation Records

Event	**Statistics and Location**
Most precip. in 24 hours	489.2 mm, Uclulet Brynnor Mines, BC, 1967
Most precip. in 1 month	2235.5 mm, Swanson Bay, BC, 1917
Most precip. in 1 year	8122.6 mm, Henderson Lake BC, 1931
Highest avg. annual precip.	6655 mm, Henderson Lake, BC
Highest avg. annual snowfall	1433 cm, Glacier Mount Fidelity, BC
Most snowfall in 1 month	535.9 cm, Haines Apps, No. 2, BC, 1959
Most snowfall in 1 day	118.1 cm, Lakelse Lake, BC, 1974.

(Phillips, 1990)

Drought is an extended period of dry weather that lasts longer than expected or than normal and leads to measurable losses (crop damage, water supply shortages (Phillips, 1990). Droughts have occurred throughout the country with significant economic, environmental and social impacts (see Table 1.2). Extreme events, higher intensity rain interspersed with more severe periods of drought, are expected to become more frequent under climate change scenarios with their attendant socioeconomic impacts and costs (IPCC, 1996; Whetton *et al.*, 1993). Climate changes that alter the frequency and magnitude of extreme events are more significant from a hydrologic, water resources management and adaptation perspective than changes in the mean.

Variability: An example - the Great Lakes Basin

Figure 1.5 illustrates the variability in annual precipitation in the Great Lakes Basin from 1860-1990. Two extreme dry periods occurred in the 1930s and in the 1960s. Overall, the 1900-1940 period was much drier than the 1940-1990 period; the mean annual precipitation increases by approximately 50 mm in the later period. The standard deviation (a measure of variability) increases from 50 mm to 71 mm during this period.

Past Trends in Precipitation

In an analysis of the past 40 years of precipitation data for stations across Canada, Gan (1991) found that there was no apparent spatial pattern to precipitation trends; they were scattered. However, there were stations (up to 10%) with increasing precipitation during spring and summer and up to 10% of stations with a downward trend in winter.

Table 1.3 summarizes the annual and seasonal precipitation trends for regions of Canada (Mekis and Hogg, 1997). There is a significant increase in total annual precipitation for most regions of Canada; snow also shows a significant upward trend. The Great Lakes/St. Lawrence Lowlands are the exception; there are significant declines in annual and spring snowfall. North of 55 degrees latitude, spring, summer, fall and annual snowfall increases.

Climate Change Impacts on Precipitation

Table 1.2: Canadian Drought Episodes

Year	Event
1805	scorched potato crop in the Red River Area
1816-9	almost continuous drought and hordes of grasshoppers on the Prairies
1846	complete crop failure in the Red River Area
1862-4	low river levels on the Red River; seed grain imported from the USA
1868	Prairie crop fails; plague of grasshoppers
1890s	9 years of drought force farm abandonment
1933	grasshopper plague and drought result in the smallest wheat crop in Saskatchewan since 1920
1936	sever heat stress in Ontario reduces crop yields by 25%
1936-8	recurrence of drought on Prairies a national emergency
1961	the worst drought year this century for Prairie wheat
1963	severe Ontario drought drastically cut soybean and corn production
1967	extensive drought from Peace River to Southern Manitoba
1973	record warm summer and local drought hurt potato and apple production in Ontario
1977	severe drought in southern Alberta and western Saskatchewan
1978	extensive central Ontario drought
1979-80	two poor wheat and pasture years on the Prairies, estimated loss to national economy $2.5 billion
1983	southern Ontario drought described as the worst this century
1984	drought in southwestern Nova Scotia dried up many streams and wells
1985	southeastern Prairies received 1/2 normal amounts of rain, insect infestations, forest fires in British Columbia cost $300 000 million (firefighting costs and timber losses)
1988	extensive drought across the Prairies, Ontario and Quebec cost $1.8 billion in damages; worst British Columbia interior drought in 60 years
1989	worst summer drought in Nova Scotia in over 40 years affects water supplies, increases number of forest fires

(Phillips, 1990; Koshida, 1992)

Climate change due to an “enhanced greenhouse effect” has the potential to change precipitation form, amount, timing, distribution, intensity and duration, and extremes. The circulation of the oceans and the atmosphere are linked to temperature gradients around the globe; thus, global changes in temperature would affect global circulation patterns. Such changes, for instance, would shift the position of major storm tracks and the regions receiving precipitation (Environment Canada, 1995).

Globally, average precipitation generally increases in 2xCO_2 scenarios but the regional implications are more uncertain because small-scale processes are not captured in the GCM parameterization (IPCC, 1990). Many regions of Canada experience more precipitation (e.g., northern Canada) in 2xCO_2 scenarios while others receive less (e.g., southern Canada). Projected changes in annual precipitation based on 2xCO_2 scenarios used in various climate impact assessments are summarized in Table 4. It illustrates that precipitation increases in almost every region of the country but there are also discrepancies amongst the different GCM models for the same region.

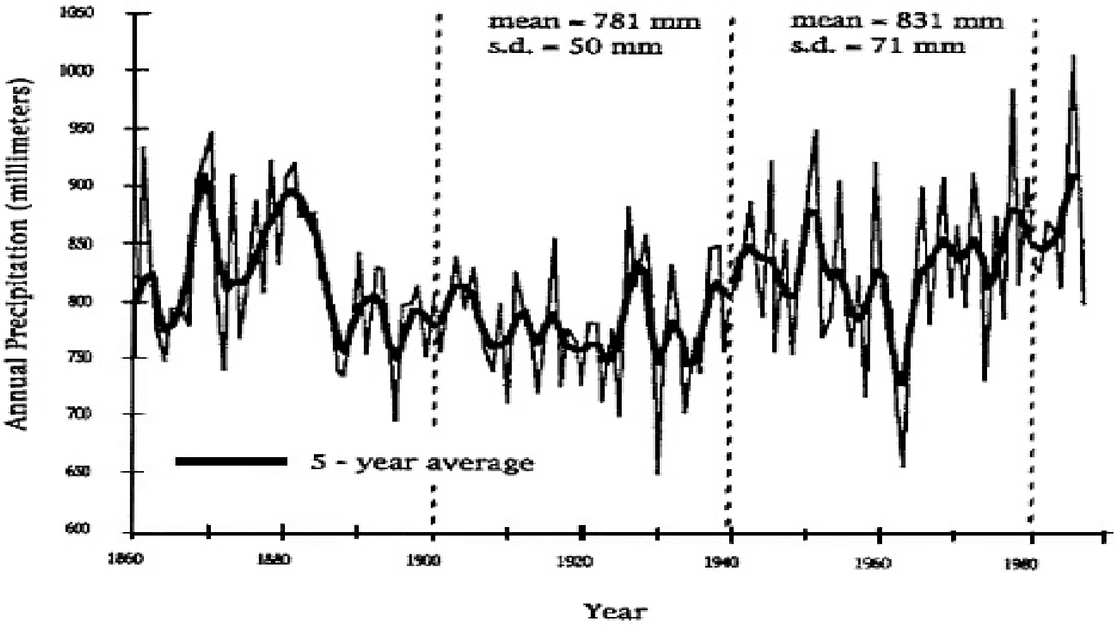
Warming of cold northern regions has the potential to increase precipitation, particularly in winter (Rouse *et al.*, 1997). The continental interior, the Prairies, becomes drier particularly in summer and winter in many GCM scenarios. Isaac and Stuart (1992) demonstrate a close correspondence between higher than normal precipitation and above-average daily temperatures in the current climate.

Table 1.3: Precipitation trends* in Canada (Mekis and Hogg, 1997)

		Annual			Winter			Spring			Summer			Autumn		
NAME	Period	Total	Snow	Rain	Total	Snow	Rain	Total	Snow	Rain	Total	Snow	Rain	Total	Snow	Rain
I. Atlantic Canada	1895-96	0.5	**2.7**	-0.5	0.7	**2.2**	-1.8	0.5	**3.6**	-1.0	0.5	-	0.4	0.1	**5.3**	-0.3
II. Great Lakes / St. Lawrence Lowlands	1895-95	**1.1**	**-1.8**	**2.2**	-0.3	-1.5	2.6	1.0	**-3.8**	**2.6**	1.1	-	1.1	**2.6**	-0.1	**2.9**
III. Northeastern Forest	1918-96	**2.4**	**4.3**	**1.3**	**3.1**	**3.0**	6.2	**2.5**	**4.6**	0.5	**1.7**	-	**1.6**	**2.6**	**6.2**	0.9
IV. Northwestern Forest	1938-96	**1.9**	**0.8**	**2.4**	-2.7	-3.1	-	0.6	1.2	0.1	**3.0**	-	**3.0**	**3.5**	**5.4**	2.2
V. Prairies	1895-95	0.5	1.5	0.1	**2.4**	**2.1**	-	0.9	1.2	0.8	-0.4	-	-0.4	0.5	0.3	0.6
VI. South BC Mountains	1895-95	**1.4**	**2.0**	0.9	**2.4**	**2.7**	1.4	**1.6**	0.8	**2.5**	1.0	-	1.0	0.8	2.0	-0.1
VII. Pacific Coast	1898-95	**0.9**	1.9	**0.8**	0.7	2.1	0.6	0.1	-4.5	0.2	**1.9**	-	**1.9**	1.2	9.6	0.0
VIII. Yukon/North BC Mountains	1939-95	**3.0**	**4.8**	1.6	**5.8**	**5.6**	-	**4.9**	2.8	**7.3**	0.2	-	0.1	**3.9**	**5.3**	2.6
IX. Mackenzie District	1927-96	**1.2**	**1.3**	1.1	1.6	1.5	-	0.2	1.0	-1.3	1.0	-	1.3	1.9	2.2	1.6
X. Arctic Tundra	1948-96	**5.1**	**9.5**	-1.1	5.6	5.9	-	**7.7**	**9.2**	-2.7	0.5	**13.9**	-1.4	**7.4**	**11.3**	0.3
XI. Arctic Mountains & Fjords	1948-96	**2.4**	**3.3**	0.2	0.3	0.4	-	**6.2**	**6.1**	-	2.1	**11.5**	-1.2	1.5	0.8	5.2
>55 °N	1948-95	**2.3**	**4.7**	-0.3	2.3	2.2	-	**3.8**	**3.9**	3.5	-0.2	**13.2**	-1.2	**4.2**	**6.5**	0.7
Canada	1948-95	**1.7**	**2.2**	**1.4**	-0.1	0.1	-0.7	**2.6**	1.2	**4.0**	0.9	**12.2**	0.5	**3.4**	**5.3**	**2.1**

*Unit: (mm change / mean) over 10 years
If mean < 5 mm, trend not computed
Highlighted fields: Trend is significant
Gray area: Residuals are correlated (Durbin-Watson test failed)

Figure 1.5: Annual Precipitation in the Great Lakes Basin (1860-1990) (Nuttle, 1993b, 5)



Increases in precipitation do not necessarily mean that regions of Canada will become “wetter”. Higher evaporation losses due to the warmer temperatures could make many areas drier, even with increased precipitation (Environment Canada, 1995).

Studies suggest that the incidence of more intense, local rain storms will increase at the expense of the gentler but persistent rainfall events in climate change scenarios (Mitchell and Ingram, 1990; Noda and Tokioka, 1989). Experimental results from Danard and Murty (1988) indicate that in 2xCO_2 scenarios precipitation amount increases and the centre of lows deepen. Lambert (1995) found that the total number of extratropical winter cyclones would be reduced particularly in the Northern Hemisphere in the CCC GCMII 2xCO_2 scenario but the frequency of intense cyclones increases. Baroclinic activity may be lessened because of the reduced north-south (meridional) temperature gradient but increased cyclone intensity may be due to the higher humidity of the atmosphere.

With warmer winter temperatures more precipitation will fall as rain instead of snow and as a result more immediate direct runoff can occur. Also, when rain falls on snow, the snowcover changes including a reduction of snowcover and increases in ice density and ice layers. The intensity, timing and magnitude of spring runoff will be affected (Wittrock and Wheaton, 1992).

Accumulation and storage of winter precipitation, as snowcover, has an important role in the hydrology of many regions of Canada. In particular, less runoff occurs in the winter because precipitation is stored in the snowpack. The spring melt leads to a large peak flows, the spring freshet, that has important hydrological, water quality and ecological effects. Higher winter temperatures not only affect the form of precipitation but decrease the snowpack accumulation;

leading to an earlier disappearance of the snow pack and shortening of the length of the snowcover season (Boer *et al.*, 1992, Brown *et al.*, 1994). An impact assessment of the Bay of Quinte, Ontario watershed demonstrates the change in the duration and amount of snow cover from current conditions to a $2xCO_2$ scenario. Snowpack was modeled for a 5-year period for current climatic conditions (1983-1987) and the CCC GCMII $2xCO_2$ scenario in the northwestern portion of the basin (see Figure 1.6a and 1.6b, respectively). Clearly in the $2xCO_2$ scenario, snowpack is much smaller and intermittent; it is almost non-existent in some years. Under current climate conditions, significant snowpack typically remains for over four months.

In a $2xCO_2$ Limited Area Model (LAM) scenario, the climate response for the United States Rocky Mountains include increased cool season precipitation and increased annual air temperature (Giorgi *et al*., 1994 in Williams *et al*., 1997). However, empirical evidence suggests that warming at lower elevations may result in the advection of increased water vapour to higher elevations and more orographic precipitation as snow leading to a short-term reduction in air temperature at higher elevations (Barry, 1990; Williams *et al*., 1997).

High-elevation areas need more empirical assessment of climatological and ecological processes since the potential for increased snow accumulation has significant hydrologic and water resources implications.

In southern Ontario, winter lake-effect storms are formed as cold, Arctic air sweeps across the relatively warm lakes and gains moisture and warmth from the water. They are most numerous from November to January along the eastern shores of the Great Lakes before significant ice cover occurs. Snowfall is highly localized downwind of the lake. The longer the distance the air mass travels, the greater the moisture and warmth derived from the lake. The greater the temperature difference between the lake and air the greater the potential for snow showers (Wong, 1994). The longer open-water season on large lakes in $2xCO_2$ scenarios will increase the lake-effect storm season.

Figure 6a & 6b: Snow cover for the current climate (a) and 2xCO_2 climate scenario (b) for the northwestern portion of the Bay of Quinte Watershed (Walker, 1996)

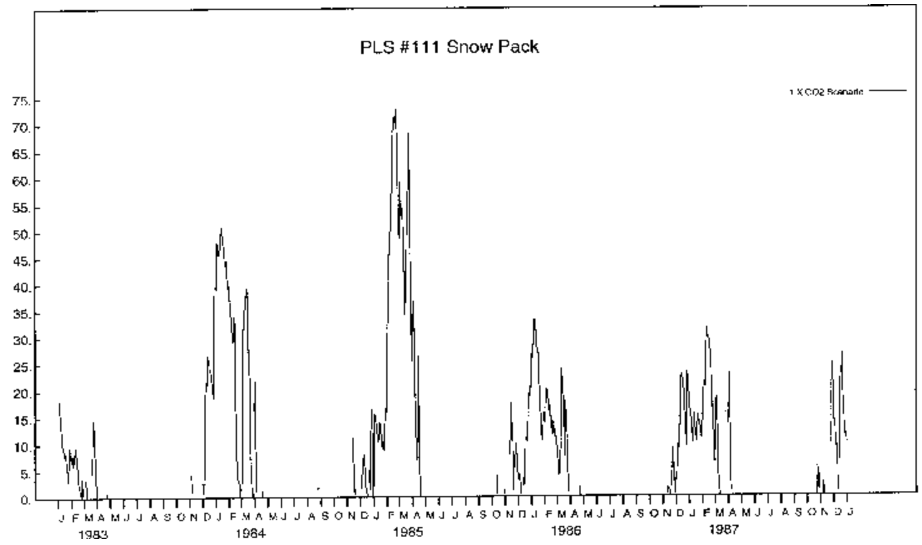


Figure 1.6a

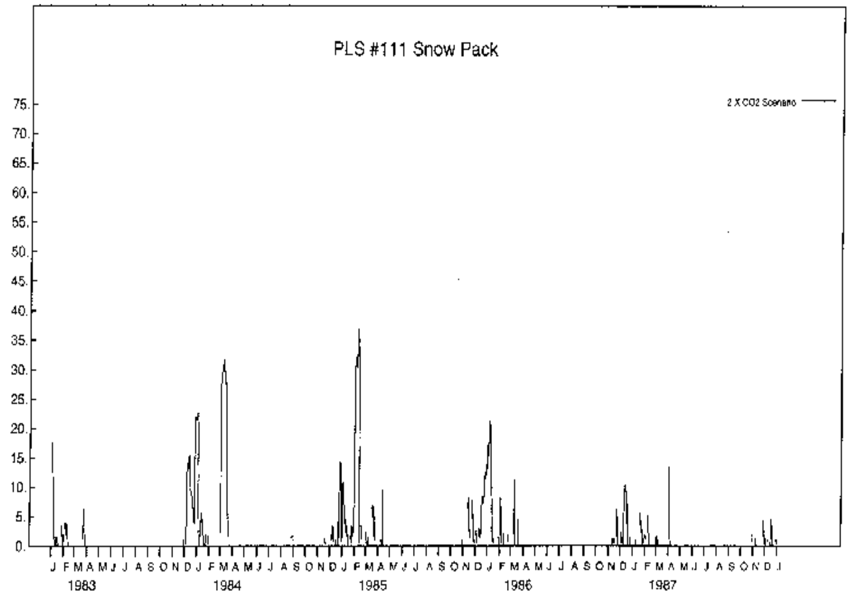


Figure 1.6b

GCM Precipitation Scenarios: Influence of Temporal and Spatial Scale

Table 1.4 summarizes the annual precipitation and temperature changes from GCM scenarios used in climate impact assessments for regions across Canada. Annual precipitation increases in most scenarios. When a seasonal time scale is used, differences in the precipitation scenarios of the GCMs are more apparent for the Great Lakes-St. Lawrence Basin (Table 1.5). Precipitation is also more variable across different portions of the basin (see Table 1.5).

Table 1.4: Changes in Temperature and Precipitation (Annual) for various region in Canada based on GCM 2xCO$_2$ Scenarios

Region	Temp. Change (°C)	Precipitation Change (%)	GCM	Study
Western Canada	+2.5 +4.4	+18 +19	GFDL/80 GISS/84	Haas and Marta (1988); S. Sask. R.
	+2.8 +4.5	+48 +10	GFDL/80 GISS/84	Zaltsburg (1990), Wilson Creek, Manitoba
	+2.2 +4.4 +3.0 +6.7 +4.6	+18 +19 +8 +7.5 +19	GFDL/80 GISS/84 OSU/88 GFDL/87 GISS/87	Cohen (1991); Sask. River
	+4.6 +6.2 +2.8	+11 +2 +6	GISS GFDL OSU	Nkemdirim and Purves (1994), Old Man Basin
Central Canada	+4.7 +5.3 +5.7	+1.9 +0.4 -6.3	GISS GFDL CCC	Sanderson and Smith (1990); Grand River
	+3.1 to 3.7 +4.3 to 4.8	+0.8 +6.5	GFDL/80 GISS/84	Cohen (1986; 1987b); Great Lakes
	+4.3 to +4.7 +5.7 to -+7.2 +3.2 to +3.5	-7 to +18 -4 to +7 +5 to +8	GISS GFDL OSU	Croley (1990); Great Lakes
	+3.5 +4.7	+17.5 +15	GFDL/80 GISS/84	Singh (1988); James Bay
	+4.2	-7.1	CCC	Morin and Slivitzky (1992) Moisie River
Atlantic Canada	+4.0 +4.0 to 4.7	-2 to -3 +5.9 to +7.5		Saulesleja (1989); Maritimes, Nfld/Labr.
Northern Canada	+2 to 3.5	+54	UKMO/83	Ripley (1987)

(modified from Nuttle, 1993a, 8; Nkemdirim and Purves, 1994; Croley, 1990)

Table 1.5: Comparison of seasonal GCM precipitation scenarios for the Great Lakes-St. Lawrence Basin ($2xCO_2$ / $1xCO_2$)

GCM	General Comments	Winter	Spring	Summer	Autumn
CCC	Wetter in spring and winter in N-NW part; drier in S part in summer and autumn	Wetter in N and NW parts; drier in SW parts (0.9-1.2)	Sharp rise in precip. as move N (0.9-1.4)	Generally drier than normal except for NE part (0.8-1.1)	Sharp drop in precip. as move S; increase in N part (0.7-1.3)
GISS	Wettest of all GCMs; wetter as move N (all seasons, esp. winter and summer) Sharp drop in autumn precip.	Progressively wetter as move N (1.0-1.2)	Wetter as move NE (1.0-1.1)	Increase in precip. as move N. (1.0-1.3)	Sharp decrease in precip. as move NW-SE (0.7-1.2)
GFDL	Very wet winter; drier in spring, summer, and autumn (esp. NW parts)	Sharp rise in precip. throughout the basin (1.1-1.3)	Precip. increases as move NW-SE (0.95-1.2)	Sharp decrease in precip. throughout basin (0.7-0.9)	Precip. declines in NW from L. Superior; increase in precip. in SE part (0.8-1.1)
OSU	Precip. increases as move SE-NW in winter and autumn	Precip. increases as move SE-NW (1.0-1.2)	Precip. decreases as move NE-SW (0.9-1.1)	Decrease in N part; increase in S portion (0.9-1.1)	Sharp increase as move SE-NW (1.0-1.3)

(Mortsch and Quinn, 1996, 905)

Table 1.6:
Monthly Precipitation Change for various GCM Scenarios for the Grand River Basin (%)

Month	GISS	GFDL	CCC
J	10.0	15.0	2.0
F	12.0	0.0	10.0
M	11.5	10.0	2.0
A	11.1	10.0	7.5
M	7.1	10.0	2.5
J	9.0	10.0	-5.0
J	8.1	-20.0	19.0
A	-3.1	-10.0	-18.0
S	-14.0	-15.0	-28.0
O	-9.0	0.0	-23.0
N	2.0	-5.0	-35.0
D	-11.5	0.0	-9.0
Mean	1.9	0.4	-6.3

(Sanderson and Smith, 1993, 17)

Table 1.6 shows the variability and changes in monthly precipitation for various GCM scenarios for the Grand River Basin in southern Ontario. There is little consensus in precipitation effects. In comparison to the $1xCO_2$ scenario, the $2xCO_2$ precipitation for the GISS scenario increased throughout the year except September, October and December; for the GFDL scenario, it decreased in the summer months; and for the CCC scenario, precipitation decreased in the autumn and summer.

The uncertainty in the precipitation scenarios (e.g., temporal and spatial distribution of rain and snow) make it difficult to make sound, reliable hydrologic impact assessments for water resources management and planning. GCMs simulate the general, global precipitation patterns reasonably well but they do not represent regional climates very well. They are even poorer at finer scale processes such as large lake effects (snow in the lee of large lakes) and complex topographic effects (e.g., British Columbia) which are important to regional hydrology (McBean *et al.*, 1992).

Evaporation / Evapotranspiration

Evapotranspiration is the loss of water to the atmosphere through evaporation from the Earth's surface and the transpiration of plants. Evapotranspiration is not a directly measured meteorological parameter; it may be estimated using other common climatological parameters. In general, evapotranspiration increases with temperature. Evapotranspiration is affected by insolation, humidity, wind speed, surface characteristics, soil moisture and advection effects. Much of the precipitation that falls on the surface of Canada returns to the atmosphere. In Ontario, almost two-thirds returns to the atmosphere. Phillips (1990) shows that mean annual lake evaporation across Canada is greatest in the dry Prairies (as much as 1,000 mm/year) while lowest evaporation occurs in the extreme north, averaging around 100 mm/year.

Evaporation Trends

Twenty years (1970-1990) of data for the Experimental Lakes Area (ELA) in northwestern Ontario illustrate the relationship between temperature and evaporation in small boreal lakes and streams. During this period, air temperature increased by 1.6ºC, precipitation decreased and average annual evaporation increased by approximately 50%. Evaporation increased by an average of 35 mm/1ºC increase in annual air temperature or 68 mm/1ºC increase in summer air temperature (Schindler *et al.*, 1990; Schindler *et al.*, 1996). For the twenty-year record, evaporation increased by an average of 9 mm/year.

Climate Change Impacts

Given that the $2xCO_2$ GCM scenarios suggest higher air temperatures for most of Canada, evaporation and evapotranspiration is also expected to increase. Although many areas of Canada can expect increased precipitation, ironically, in most cases climate change leads to less water availability (Schindler, 1996). Even when precipitation remains constant, higher air temperatures, longer ice-free and freeze-free seasons, and a longer growing season contribute to an extended period of evaporation and transpiration. Increases in the evaporation: precipitation ratio will likely occur. Unless the rise in temperature and increases in evapotranspiration are accompanied by substantial increases in precipitation or significant decreases in plant stomatal resistance from higher concentrations of atmospheric CO_2 declines of lake levels, streamflows, wetland levels, soil moisture, and groundwater levels are likely (Schindler, 1997; Marsh and Lesack, 1997; Croley, 1990; Hartmann, 1990b; Poiani *et al.*, 1996; Sanderson and Smith, 1993).

There are a variety of methods for estimating evapotranspiration. Energy balance and aerodynamic methods require numerous input variables such as humidity, radiation, and wind speed to simulate evaporation rates (Smith and McBean, 1993). Croley (1990) used bulk aerodynamic techniques for estimating evapotranspiration for the Great Lakes Basin and combined GCM ($1xCO_2$ and $2xCO_2$ ratios and differences) estimates of humidity changes and momentum coefficients for wind speed changes with current climate measurements for input variables. Estimates of changes in evapotranspiration are limited by the quality of the GCM input; for example, winds are suspect. Simpler empirical techniques generally require only one variable, typically temperature, to estimate evapotranspiration.

Thornthwaite's (1948) empirical technique has been used frequently in climate impact assessments (Coulson, 1997; Cohen, 1986; Sanderson and Smith, 1993; Cohen *et al.,* 1989; Zaltsberg, 1990). This technique is very practical because only one climate variable, temperature, is needed. Since the most accurately simulated climate variable produced by the GCMs is temperature, this technique has particular appeal for the estimation of evapotranspiration (Smith and McBean, 1993).

Both empirical and aerodynamic techniques have been utilized to estimate the effect of climate change scenarios on evapotranspiration. In the Great Lakes Basin, Cohen (1986), Sanderson (1987) and Croley (1990, 1992) found that evapotranspiration significantly increases due to warming in climate change scenarios. A similar increase in evaporation was noted in British Columbia (Coulson, 1997), Mackenzie Basin (Soulis *et al*., 1994), the Prairies (Cohen *et al.*, 1989; Byrne *et al.,* 1989; Nkemdirim and Purves, 1994; Zaltsberg, 1990) and the Grand River (Smith and McBean, 1993). Cohen (1987) found that evaporation is also sensitive to wind speed scenarios.

Sanderson and Smith (1993) applied Thornthwaite's empirical technique and three climate change scenarios to the Grand River watershed and found a 20-30% increase in potential evapotranspiration and a 13-16% increase in actual transpiration and an average evapotranspiration increase of 16.7% in the Basin for these scenarios. Higher evapotranspiration offsets higher precipitation in climate change scenarios for the Great Lakes Basin, Mackenzie Basin and other areas (Croley, 1990; Cohen, 1987b; Soulis *et al*., 1994).

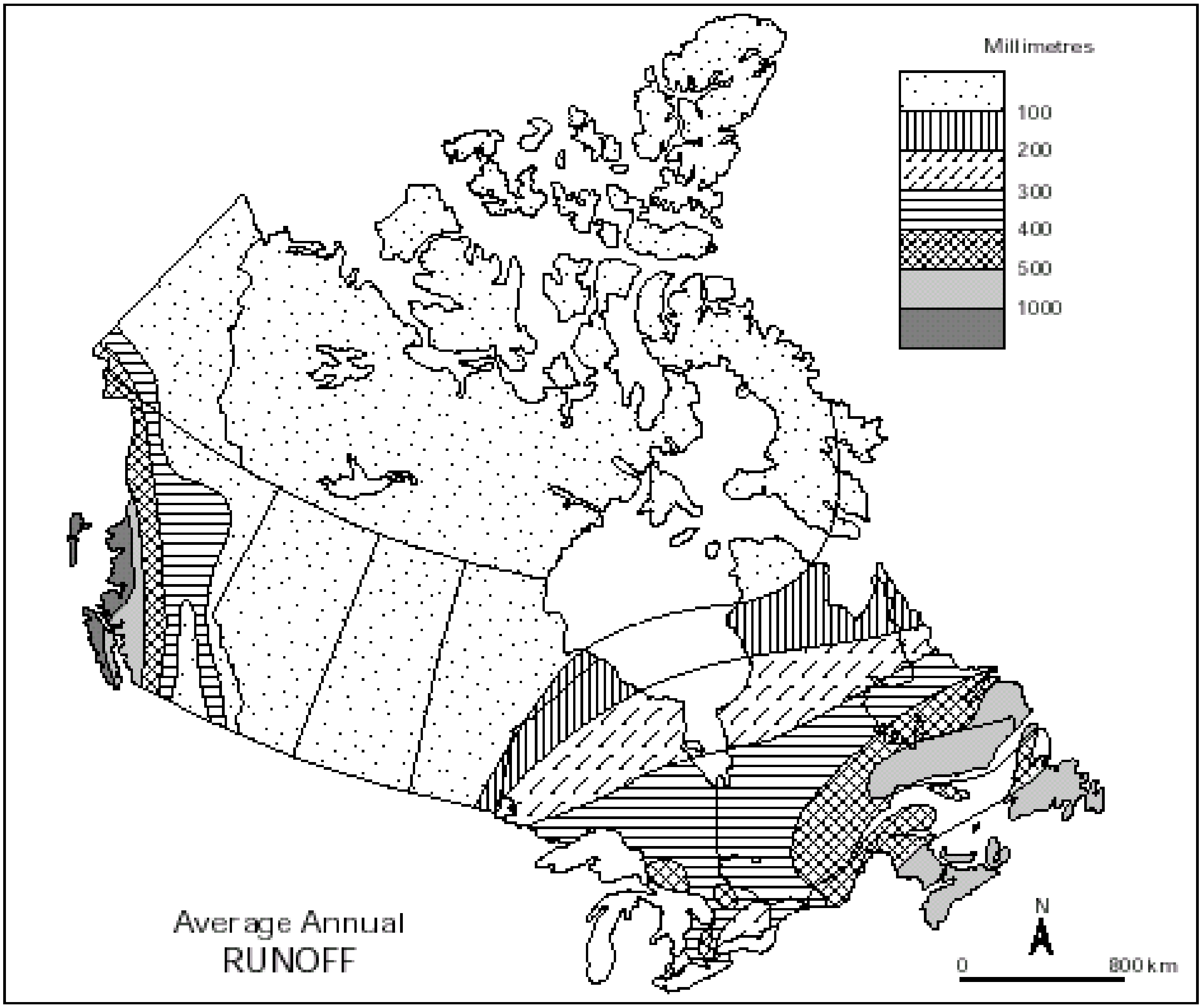
For sophisticated climate impact assessments of the hydrology of watersheds, more complicated evapotranspiration estimation methods are needed to answer questions related to vegetation changes and vegetation response to CO_2 enrichment and water resources impacts. Some evapotranspiration models have leaf area indices and stomatal resistance variables which can be modified to simulate new/different vegetation response under climate change (Smith and McBean, 1993). The level of sophistication that can be developed for climate impact assessment is hampered by the GCM scenario input. Many of the elements required are highly uncertain and the scale mismatch between GCM output and watersheds is a concern.

Evaporation and evapotranspiration play important roles in the hydrology of a basin but they are often poorly treated because of the lack of data and complexity of the parameter. Changes in evapotranspiration have significant impacts on hydrology: soil moisture, lake levels, runoff, groundwater. The specific effects of climate change on evaporation are not well known; what are the limiting factors in lake and over land evaporation? What is the role of soil moisture?

Surface Flows

For the purposes of this synthesis surface flows are limited to a discussion of runoff and streamflow (discharge). Runoff is the portion of precipitation that does not evaporate but drains through a variety of paths to reach the stream channel. Figure 1.7 shows the annual runoff for Canada. Runoff becomes stream flow once it enters a stream channel. Streamflow is defined as flow (or volume) in a channel while runoff is often represented as an average depth over a drainage basin area.

Figure 1.7: Annual average runoff for Canada



Variability and extreme events

Surface flows are variable spatially and seasonally. All flows in Canada show annual variation. For instance, Fisheries and Environment Canada (1978) found that for 60% of the stations gauged, the month with maximum monthly flow is June. Most annual peak flows in Canada are caused by snow (Fisheries and Environment Canada, 1978). That is, the snowpack accumulates over the winter and is released in the spring during the spring melt or freshet.

In Canada, the minimum long-term mean monthly flow may occur at one of two times. Southern Canadian rivers often have their low flow period in late summer following depletion of soil moisture reserves by evapotranspiration. In northern Canada, the low flow period is late winter when rivers are ice covered, and sometimes frozen solid (Fisheries and Environment Canada, 1978).

When these flows are depicted on hydrographs, the peaks on the hydrograph are influenced by the relative storage capabilities (Fisheries and Environment Canada, 1978). For instance, the Saskatchewan River has relatively little storage abilities and its hydrograph has a sharp peak and dip, while the St. Lawrence River has very smooth curve due to the large storage capacity of the Great Lakes. Essentially, the large storage tends to level out flows and reduces the predominance of the peak flow in the river.

Streamflow variability is also reflected in extreme events such as floods. Research has found that these extreme events may become more common under climate change scenarios (IPCC, 1996). These extreme flood events are often caused by climatic conditions (extreme precipitation, ice jams, and rapid spring snow melt) but they may also be significantly influenced by human activities. Flooding events have occurred throughout the country and have occurred frequently over time. Some of the major Canadian floods are listed in Table 1.7 with descriptions of some of the negative impacts.

Lawford (1990) suggested that potential changes to surface flows were the most significant climate change concern in the western part of Canada. For example, the consequences of low streamflows were brought home in the spring of 1988. There was very little snow in the southern prairies during the winter of 1987-1988, followed by a dry spring and early summer in 1988. The dry conditions limited spring runoff and dry soil conditions occurred in nearly all prairie river basins. Problems caused by the drier conditions included conflicts over water use along some of the smaller rivers, insufficient water quantity to dilute municipal wastes, irrigation users found there was no water available. These shortages were particularly acute in southern Saskatchewan. The hydrological drought of 1988 is representative of the conditions which could occur more frequently if climate change leads to drier conditions (Lawford, 1990).

Table 1.7: Great Canadian Floods

1798	Floods at Montreal and Trois Rivières, Quebec were described in contemporary reports as the "worst in living memory".
1826	The Red River in Manitoba rose 2 m higher than during the famous flood of 1950
1865	The St. Lawrence River rose 3 to 4 m at Sorel and Trois-Rivières, Quebec. 45 drowned.
1883	A wall of water along the Thames River drowned 18 in London, Ontario
1928	The Rideau, Chaudière, and Quyon rivers in Québec overflowed their banks. Several drowned.
1937	The Thames River at London, Ontario flooded leaving 4,000 homeless.
1948	Floods in the Fraser Valley in British Columbia left 9,000 homeless. This flood has been called the "worst in British Columbia history".
1950	The Red River in Manitoba rose 10 m above normal. 100,000 were evacuated.
1954	The Etobicoke Creek in Ontario flood during Hurricane Hazel. 80 died.
1973	The Saint John River in New Brunswick flooded causing $12 million damage.
1974	The Grand River flooded Cambridge, Ontario causing $7 million damage. Extensive flooding across the Prairies.
1979	The Red River in Manitoba crested higher than in 1950. The Yukon River flooded 80% of Dawson, Yukon Territory
1980	Boxing Day floods along the Squamish River in British Columbia caused $13 million in damages
1986	The rain-swollen North Saskatchewan River rose 7.6 m above normal levels and forced 900 Edmonton residents to flee their homes.
1996	Saguenay flooding causes almost a billion dollars in damage and national precipitation records were set.
1997	Red River floods in South Dakota, United States and Manitoba causes the displacement of thousands of residents and millions of dollars of damage.

(modified from Phillips, 1990)

River Discharge/Streamflow Trends

A number of studies have explored the detection of trends in hydrologic flow data; a good Canadian survey is presented in the Proceedings of the National Hydrology Research Institute (NHRI) Workshop on "Using hydrometric data to detect and monitor climatic change" (Kite and Harvey, 1992). Streamflow characteristics such as the magnitude of the mean and low flows may be changing with time. Low flows appear to be happening later in the year and high flows earlier in the year consistent with what might be happening due to an "enhanced greenhouse effect" warming. Forty-one hydrometric stations in Ontario with a minimum of 30-years of data ending in 1990 were analysed by Ashfield *et al.* (1991). Mean monthly flows increased for the period September to January in over 50% of the stations while approximately 25% of the stations show a downward trend in flow for April to September period. Increasing low flows were shown in 35% of the stations. Anderson *et al. (*1991) analysed low, average and maximum flow time series for 27 stations (unregulated flow) across Canada; the data indicated a decrease in summer low flow, an increase in winter average and low flows but little trend in maximum flows.

The timing of hydrologic events is important to ecosystems (wetland and perched lake renewal) and for water resource management (reservoir filling), for example. The timing of peak of spring snowmelt discharge is particularly important because it often contributes a considerable portion to total annual flow. It may be more sensitive to temperature than precipitation because it is tied into snow accumulation and melt. It may be a good indicator of climate change impacts on hydrology. Burn (1994) analysed the long-term record of 84 unregulated river basins ranging from northwestern Ontario to Alberta for changes in the timing of peak spring runoff. In the sample, the more northerly rivers exhibited a trend to earlier spring snowmelt runoff; the observed impacts on timing are more prevalent in the recent portion of data. Spring runoff has been occurring progressively earlier in more recent years and this may be a reflection of higher spring temperatures. A high degree of correspondence between spring peak runoff timing for the Bow River, Alberta and regional spring temperature departures is depicted in Figure 1.8 (Burn, 1994).

The trends in river discharge of the St. Lawrence River (at Cornwall) are illustrated in Figure 1.9. Since 1860, there were two main low flow periods: the 1930s and 1960s. The long-term mean is approximately 7,000 cubic metres/second. The recent period of discharge (1970s-1990s) is above this long-term mean.

Figure 1.8: Trends for Bow River, Alta. peak spring runoff and regional spring temperature departures (Burn, 1994)

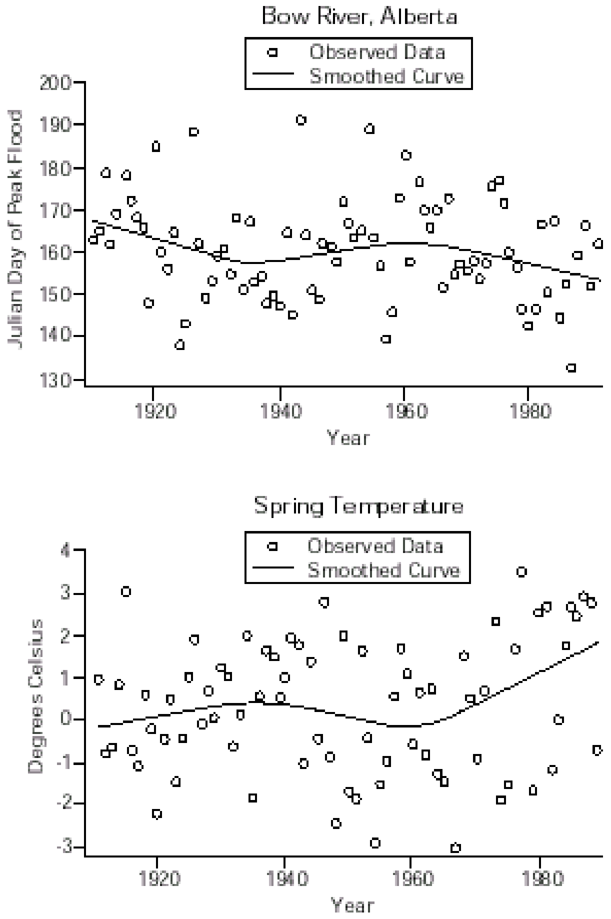


Figure 1.9: **Discharge Trends of the St. Lawrence River (at Cornwall) (1861-1994) and at Ville de Lasalle (1955-1994)** (Environment Canada, 1994b)

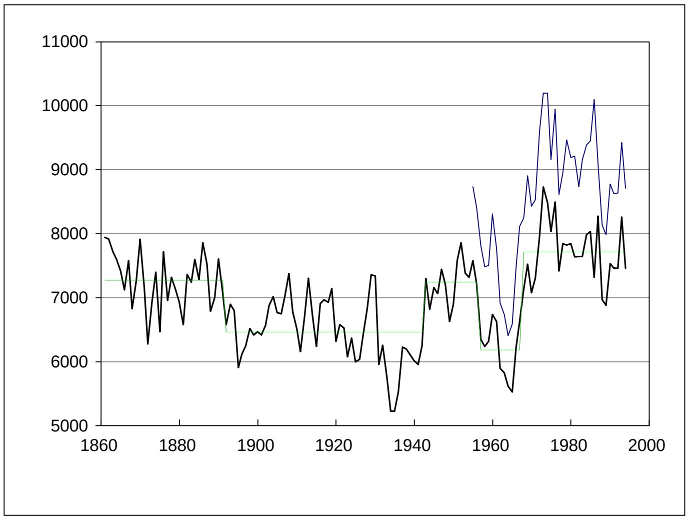
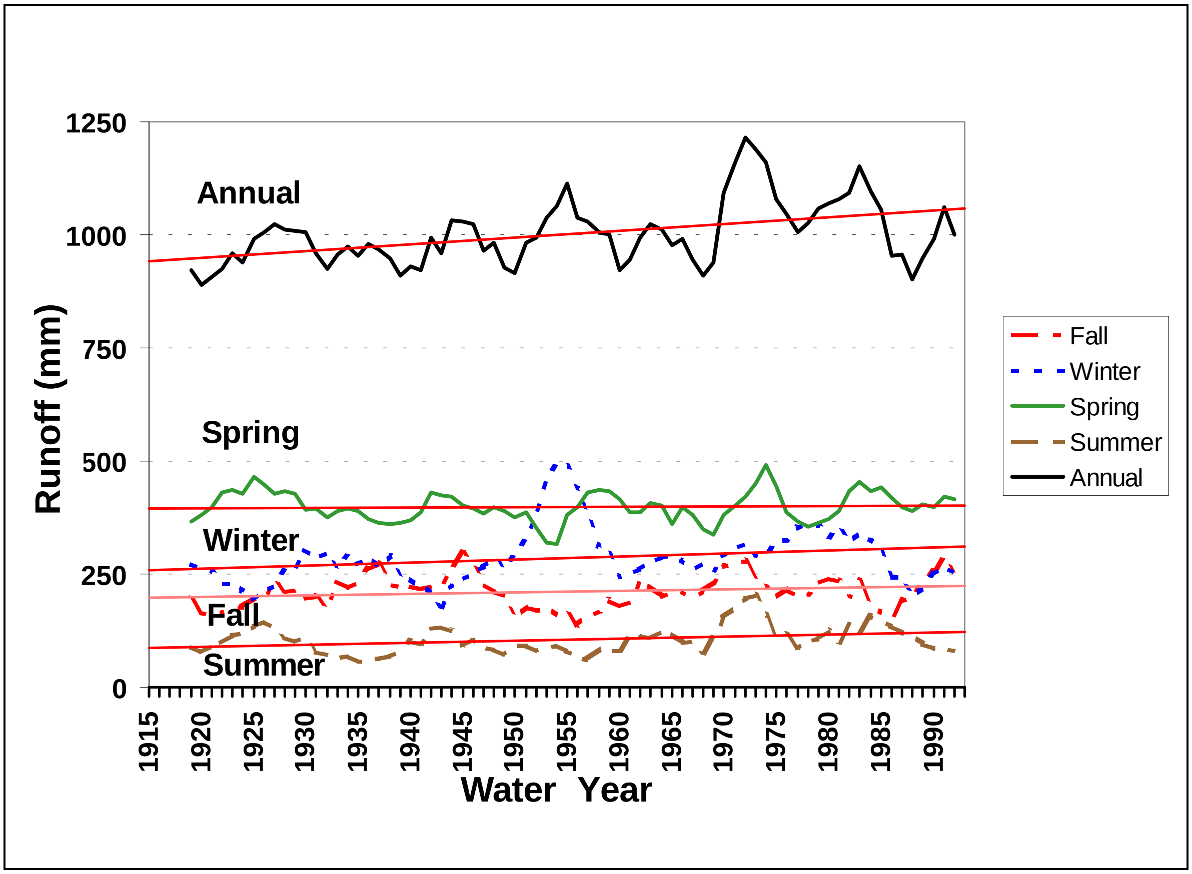


Figure 1.10: Seasonal and Annual Runoff (5-year Moving Averages) for the St. Mary's River, NS **(Clair *et al*., 1997, 63)**



Runoff Trends

Annual and seasonal runoff trends (5-year moving averages) for the St. Mary's River Basin in Nova Scotia are presented in Figure 1.10. There is a long period of uniform or slightly increasing runoff until 1970 when a dramatic rise in runoff occurred with increased variability (Clair *et al.*, 1997). When analyzing the last 25-year time period, there is trend of decreasing runoff in winter and a less dramatic decrease in summer. During this period, there has been a longer ice season in rivers (Clair *et al.*, 1997).

A trend analysis of 16 southern prairie basins (natural flow) indicate a moderate trend toward increased annual runoff from basins in the southern prairie grassland in contrast with a moderate decrease in the northern prairie grassland region (Wiens, 1991)

Climate Change Impact on Streamflow and Runoff

Climate change scenarios for hydrologic impact assessment have been developed from GCM output (equilibrium and transient runs), hypothetical changes in temperature and precipitation, and spatial transposition analogues (Mortsch and Quinn, 1996). Current climate inputs to hydrologic models have been adjusted or replaced by these scenarios to study the response of the hydrologic system as depicted by the models. Table 1.8 surveys the recent Canadian research on climate change hydrological impact assessment; it summarizes the basins assessed, methods used, scenarios applied, and some annual hydrologic impacts identified. Overall, the impact of climate change on runoff and streamflow is variable across Canada. Although the general trend is for climate change scenarios to suggest annual increases in temperature and precipitation, the runoff response is increases or decreases in flow. The response is dependent upon the region and scenario used.

One of the difficulties with climate impact assessment is the lag in incorporating the most recent advances from the GCM research community into impact studies. As a result, there are no Canadian impact assessments that used the most recent GCM runs with the effects of aerosol cooling. Table 1.8 indicates that there are also regional gaps in climate impact assessments; of particular note are the lack of hydrologic impact studies in watersheds of the Eastern Arctic and Atlantic Canada.

Climate change studies have used various hydrologic models and scenarios as methods to assess hydrologic impacts. There are many methodological challenges. Empirical relationships between temperature and precipitation and runoff, and/or the water balance approach have been the primary modeling methods; only a few studies have used deterministic models (Ng and Marsalek, 1992; Walker, 1996; Morin and Slivitzky, 1992; Slivitzky and Morin 1996). The primary climate change scenarios are hypothetical changes of temperature and precipitation or output from equilibrium GCM runs. Monthly scenario changes (differences and ratios) have been applied to current climate elements. In applying this method, changes are made to the mean of climate variables (e.g. temperature and precipitation) but the variability remains the same. At present, the spatial resolution of GCMs do not allow development of scenarios of the extreme precipitation events that are so critical for generating extreme floods and associated impacts.

Spatial transposition scenarios introduce a change in the mean and the variability but there are caveats in using these scenarios (Mortsch and Quinn, 1996). Potential changes in variability are more important to water resources management than a change in the mean (Katz and Brown, 1992). Spatial resolution of scenarios is also important. GCM resolution is too coarse for many small watershed assessments. There is a strong requirement in the hydrologic climate impact assessment community for "better" climate change scenarios for "prediction". Limited area models may meet some of the spatial requirements but the temporal scale issue will not be resolved for some time. However, the community must recognize that regional hydrologic sensitivity studies can play a valuable role in climate impact assessment research.

Climate change impacts on runoff and streamflow are significant. Climate change would have an effect on the magnitude of the mean, minimum, and extreme flows as well as their temporal distribution and duration. Also, there will be regional changes in water supply. Seasonal hydrologic changes include:

- potential increases in winter runoff due to more winter rainfall events because of warmer winter air temperatures;
- less precipitation stored in snowpack;
- decreases in the volume of the spring runoff due to reductions in winter snowcover;
- an earlier onset of the spring freshet because of earlier spring warming;
- summer and fall low flows decline further because of higher evapotranspiration and reductions in groundwater base flow contributions; and
- summer and fall low flow periods last longer (Leavesley, 1994).

The impact assessments also indicate that there may be an increased variability in flow. Firstly, decreases in mean annual flow suggest a decrease in streamflow persistence due to a decrease in baseflow and higher evapotranspiration; low flow periods increase in frequency and duration. However, more extreme rainfall events or rain on snow may cause more extreme runoff events and flooding (IPCC, 1996; Whetton *et al.*, 1993).

Numerous studies have been conducted concerning the impact of climate change upon streamflow and runoff. Some of the details of the Canadian impact assessments are summarized below. Using the results of three GCM models and the Thornthwaite water balance model to estimate stream flow at The Pas on the Saskatchewan River, Cohen *et al.* (1989) indicated that under the GISS model scenario, the flow would increase by approximately 15% while the under the GFDL scenario the flow would decrease by nearly 20%. With the OSU scenario, the flows remained stable. The uncertainty in the impact of the scenarios makes it difficult to make water resource planning decisions.

Ng and Marsalek (1992) studied the sensitivity of streamflow simulations to changes in climatic input data for a small catchment with significant snowfall and a high conversion of precipitation into streamflow (>80%). In the simulation experiments, hypothetical temperature and precipitation changes were incorporated into a simulation period of 29 months. The impacts on annual streamflow, seasonal/monthly streamflows and monthly streamflows, and monthly maximum peak flow were evaluated (Ng and Marsalek, 1992). Their key findings include:

- Temperature increases barely affected annual streamflow; they led to larger and earlier winter runoff when precipitation was stored in the snowpack, and increased winter/spring streamflow peaks.

- Effects of precipitation fluctuations were more direct. Annual and seasonal streamflow changes were directly proportional to precipitation changes and monthly peaks increased about twice as much as precipitation.

For British Columbia and the Yukon, climate data from 18 stations were modified by the CCC GCMII $2xCO_2$ scenario to assess the hydrologic response to warming. The water balance method indicates an increase in annual, winter and spring runoff. The summer low flow period would be lower in southern BC and slightly higher in northern British Columbia and the southern Yukon. The spring freshet flows increased and occurred up to one month earlier (Coulson *et al.*, 1997).

Nkemdirim and Purves (1994) estimated the potential impact of climatic change on streamflow in the Oldman River basin in Alberta using an analogue approach. Historical records of temperature and precipitation at three stations were searched for values which matched those modeled for the region of the basin by the GISS, GFDL, and OSU GCMs. An increase of 1^oC in mean annual temperature over a five-year period combined with normal precipitation reduced streamflow by 15% annually; a 1% increase in precipitation combined with current climate temperature conditions increased streamflow by 1%.

The CCC GCMII climate change scenario was applied to the Hydrologic Simulation Program FORTRAN (HSPF) for the Bay of Quinte Watershed. Air temperatures increased 1.6^oC to 9.6^oC in the scenario. The effect of the climate change scenario was to reduce overall runoff to the Bay of Quinte by 12%. Major shifts in runoff for the hydrologic year also occurred. Runoff shifted from a typical pattern of cold-frozen low flow winter with snow stored on the ground followed by a rapid snowmelt and spring freshet to a $2xCO_2$ pattern where snowfall was replaced by more rain, frequent runoff events and a minor spring freshet. Drought frequencies increase but the extreme high flow rates remained similar. Over the long-term, phosphorus concentrations in runoff increased about 8% due to reductions in flow rather than increases in phosphorus loadings to the Bay (Walker, 1996).

In an impact assessment of the Mackenzie River, Soulis *et al.*, 1994 and Kerr, 1997 report that in the CCC, GFDL and composite scenarios for the Basin, precipitation increased in all cases. This should have translated into higher runoff but in the two GCM scenarios, increased evapotranspiration lead to lower flows and lake levels. Spring break-up occurred earlier and the spring flows were higher.

Table 1.8: Canadian Climate Impact Assessments on Hydrology: A Review of Scenarios, Methods, and Impacts

Author	River Basin	Climate Scenario	Annual T&P Scenario Changes	Hydrologic impacts (annual)	Hydrologic Model
Western Canada					
Nkemdirim and Purves, 1994	Oldman River, Alberta	• 5-yr historical analogues (T & P) • GISS87 • GFDL87 • OSU88	• 5-yr historical analogues (T & P) • +4.6°C, +11% • +6.2°C, +2% • +2.8°C, +6%	discharge: • -19.5 to - 46.1%	empirical: runoff function of T & P (Langbein)
Zaltsberg, 1990	Wilson Creek, Manitoba	• hypothetical • GFDL80 • GISS84	• -2°C, +20% • +2°C, -20% • +2.8°C, +48%, • +4.5°C, +10%	runoff: • +79 to+90% • -49% to -61% • +83% • -5 to -11%	water balance; empirical: runoff function of T & P (Langbein)
Coulson, 1997	British Columbia (19 stations representing basins)	• CCC92		runoff: • -29 mm to +184 mm	Thornthwaite water balance
Cohen *et al.*, 1989; Cohen, 1991	Saskatchewan River	• GFDL80 • GISS84 • OSU88 • GFDL87 • GISS87	• +2.2°C, +18% • +4.4°C, +19% • +3.0°C, +8% • +6.7°C, +7.5% • +4.6°C, +19%	runoff (high & low irrigation): • -65%, -70% • +33%, +40% • +2%, -4% • -27%, -36% • +28%, +35%	Thornthwaite water balance
Central Canada					
Croley, 1990; 1992	Great Lakes - St. Lawrence Basin	• GISS84 • GFDL87 • OSU88	• +4.3 to +4.7°C; -7 to +18% • +5.7 to +7.2°C, -4 to -7% • 3.2 to +3.5°C , +5 to +8%	runoff: • -2 to -41% • 0% to +8% • -19 to -28%	Large Basin Runoff Model
Walker, 1996	Bay of Quinte Watershed, Ontario	• CCC92	• 1.6 to 9.6°C	runoff: • -12%	deterministic Hydrologic Simulation Program - FORTRAN (HSPF)
Sanderson and Smith, 1993; Smith and McBean, 1993	Grand River, Ontario	• GISS87 • GFDL87 • CCC92	• +4.7°C, +1.9% • +5.3°C, +0.4% • +5.7°C, -6.3%	runoff: • -11% • -21% • -22%	empirical Thornthwaite water balance; HELP model
Morin and Slivitzky, 1992; Slivitzky and Morin, 1996	Moisie River, Québec	• CCC92 • transient (UKTR, GFDL, ECHAM1-A)	• +4.2°C, +1.1% • see sect 2.3.4.2	runoff: • -5.0% • see sect 2.3.4.2	deterministic CEQUEAU
Atlantic Canada					
Ng and Marsalek, 1992	Waterford R., Newfoundland	• hypothetical	• +1, +2,+3,+4°C ±5,10,20%	• flow peak increased • change in timing	deterministic Hydrologic Simulation Program - FORTRAN (HSPF)
Northern Canada					
Singh, 1987;1988	• La Grande River • Caniapiscau River • Opinaca-Eastmain River, Québec	• GISS84 • GFDL80		runoff: • +15.6, +16.5% • +13.0, +15.7% • +20.2, +6.7%	Water balance
Soulis *et al.*, 1994	Mackenzie River.	• composite • GFDL(R30) • CCC92	• +3.5°C, +10% • +6.0°C, +3% • +3.5°C, +3%	runoff: • +7.1% • -7.1% • -3.7%	modified square grid approach

CCC92 - Boer et al., 1992; McFarlane et al., 1992
OSU88 - Schlesinger and Zhao, 1988
GFDL80 - Manabe and Stouffer, 1980
GISS84 - Hansen et al., 1983, 1984; see Cohen 1991
GISS87 - see Cohen, 1991

GFDL80 - Manabe and Stouffer, 1980

The St. Lawrence River: A Case Study of a Large River

A number of activities in the St. Lawrence River, from the outlet of Lake Ontario to Québec City, are highly sensitive to low water levels and significant impacts will result from decreases in flows and water levels. Recreational boating, which is very important to the local economy is particularly sensitive to low water levels; Bergeron (1995) has shown an increase in boating accidents during years of low water levels in 1988 and 1989. Hydroelectric power production at the Beauharnois power development at the outlet of Lake Saint-François is directly related to the flows of the St. Lawrence; its annual power production for the 1943-1991 period was 12.4 terawatt hours (TWh), representing about 7.2% of the total power production of the Hydro-Québec power grid.

The economic success of the Port of Montréal, which generates about $1.2 billion in commercial activity annually, is closely linked to the frequency of low water levels (Bergeron, 1995). A decrease of about 30 cm in the low levels during the 1988-1991 low period represents a decrease of about 15% in the average annual tonnage of 550,000 tons/year that is handled by the port.

Downstream from Montreal, Lake Saint-Pierre currently supports a large commercial freshwater fishing industry, with 1992 landings of 572 tonnes and a commercial value of $1.7 million which represented 60% of total freshwater catches in the St. Lawrence corridor (St. Lawrence Centre, 1996). High water levels in the spring help fish to swim upstream to their spawning grounds at the mouths of rivers and ensure sustained productivity.

Figure 1.11:
Quarter-monthly levels (IGLD 1985) at Montreal Harbor - Jetty No. 1 for the 1930s under present regulation conditions for Lake Ontario (plan 58D) and chart datum. (Courtesy Michel Slivitzky)

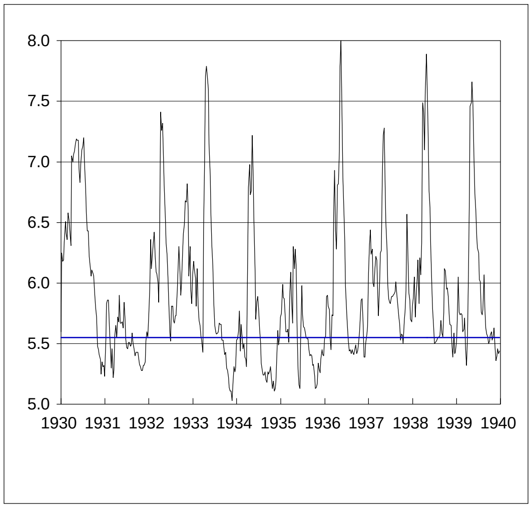


Figure 1.9 shows the historical flows of the St. Lawrence at Cornwall for the 1861-1994 period and at Ville de Lasalle, for 1955-1994. Since the mid 1970s, average outflows from the Great Lakes were among the highest in history, with sustained low water periods in the 1930s and the 1960s. An analysis of the historical low flows during the 1930s under present Lake Ontario regulation conditions, shows that during five years in the 1930s (Figure 1.11) the mean weekly level at the Port of Montreal would have been below chart datum for as long as 20 to 28 weeks.

Table 1.9:
St. Lawrence Flows at Montréal - Historical and $2xCO_2$ Conditions (Monthly flows in cubic meters per second)
(Levels Reference Study, 1993)

	1900-1990	$2xCO_2$	Difference
mean	8200	5100	-3100
maximum	12800	7600	-5200
minimum	5900	3300	-2600

Current levels and flow conditions would be totally transformed under $2xCO_2$ climate change scenarios. Table 1.9 shows the difference in monthly average and extreme flows between current long-term flow conditions and a $2xCO_2$ scenario (Levels Reference Study, 1993). The average mean flows and water levels could be lower than the historical minimums, while the maximum flows would be lower than the present mean. Under such a climate change scenario, there is a 38% reduction in power projected for Beauharnois equating to 4.7 Twh. An average annual reduction in river flow of about 3,100 m^3/s would potentially reduce the range of Montréal Harbor levels by about 1.25 m. This would have a catastrophic effect on overseas commercial navigation into the Port of Montréal. The impacts and adaptation measures could be dramatic, including unprecedented channel dredging, and structural dams and navigation locks below Montréal that could totally transform the river. Decreases in spring flows of about 5,000 m^3/s in Lake Saint-Pierre will reduce the high water levels by about 1 to 1.4 m and prove very damaging to the productivity of freshwater fisheries.

The Moisie River, Quebec: A Case Study

The Moisie river basin, on the North shore of the St. Lawrence River, is roughly oriented north to south with a length of 320 km and a width of 70 km and covers an area of 19,250 km^2. Its hydrology is representative of the whole North shore area which supplies nearly 41% of Hydro-Québec's total hydroelectric power production. Climatological information is available at Sept-Îles (at the southern end) and Wabush Lake stations (at the northern end). Normal annual temperatures are +1.1°C and -3.8°C respectively, while annual precipitation is 1125 mm and 895 mm. Average annual runoff of the Moisie River near Sept-Îles is about 720 mm.

Morin and Slivitzky (1992) used the output of the Canadian Climate Centre (CCC) General Circulation Model (GCM), coupled with the hydrologic deterministic model CEQUEAU (Morin and Couillard, 1990) to evaluate the possible impact of $2xCO_2$ on the hydrologic regime of the Moisie River. Slivitzky and Morin (1996) used the same procedure with the output from three climate change scenarios using transient climate change experiments performed with coupled ocean-atmosphere GCMs from: the United Kingdom Meteorological Office in the United Kingdom (UKTR); the Max Planck Institute in Germany (ECHAM1-A) and the Geophysical Fluid Dynamics Laboratory in the United States (GFDL89).

For calculating the impact on runoff, monthly changes in temperature and precipitation as output by the GCMs, were applied to observed daily values, for the 1966-1989 period, to simulate daily flows under changed climatic conditions. Table 1.10 presents the results from the hydrologic control run, the CCC GCMII and the three transient climate scenarios. Average temperature and precipitation differences as output by the climate scenarios are presented in columns three and four while column five presents the resulting annual average runoff as output by the hydrologic simulation model. For the CCC GCMII the outputs correspond to $2xCO_2$. For the transient models, Decade 2 corresponds to global temperature increases of about 1.16°C, while Decade 3 corresponds to a global warming of about 2° to 2.5°C in all three models.

These runoff differences, based on the hydrologic control run, are small and probably within the accuracy of the various interpolation and simulation procedures. Given the regional definition of the four climate change scenarios that were examined, the long-term annual averages of runoff might not be significantly affected on the Moisie river watershed. In similar regions on the North Shore of the St. Lawrence River the effects may be the same.

Morin and Slivitzky (1992) analyzed in detail the monthly hydrologic changes that might occur under a CCC 2xCO_2 scenario; the same pattern occurs under the three transient scenarios. Spring runoff arrives sooner because of warmer winter temperatures while increases are mainly caused by increases in snowmelt from increased winter precipitation. Summer and fall decreases in runoff are due to decreases in summer precipitation and increases in summer and fall temperature and evapotranspiration.

Table 1.10: Moisie River hydrologic impacts of various climate change scenarios

		Temperature Difference	Precipitation Difference.	Runoff	Runoff Difference.
Model	**Period**	**(°C)**	**(mm)**	**(mm)**	**(%)**
Base control run	**1966-89**	**----**	**----**	**715**	**----**
CCC	**2xCO_2**	**+4.2**	**+1.1%**	**679**	**-5.0**
ECHAM1-A	**Decade 2**	**+0.5**	**+20**	**754**	**+4.2**
ECHAM1-A	**Decade 3**	**+0.6**	**-2**	**704**	**-1.5**
UKTR	**Decade 2**	**+2.9**	**+62**	**756**	**+5.7**
UKTR	**Decade 3**	**+4.2**	**+80**	**760**	**+6.3**
GFDL89	**Decade 2**	**+1.5**	**-4**	**719**	**+0.6**
GFDL89	**Decade 3**	**+3.4**	**+110**	**796**	**+11.3**

Changes in Hydrologic Variability

Hydrologic variability is likely to increase in much of Canada under various climate change scenarios. Increases in rainfall intensity and variability will likely result in larger and/or more frequent and severe floods (IPCC, 1996).

Increases in hydrologic variability will alter physical characteristics, water quality, and biological communities of aquatic ecosystems. Such changes will necessitate changes in the way humans manage water. Physical changes due to increasing hydrologic variability include increased erosion of stream and river banks and increased sediment loading and sedimentation of channel bottoms (IPCC, 1996). These impacts are likely to be largest for streams and rivers in arid regions where riparian vegetation is sparse (IPCC, 1996, 349, Grimm *et al*., 1997) and in agricultural areas during winter when soils are more exposed (IPCC, 1996). In particular, variability will impact (i) water quality, (ii) the productivity and biodiversity in streams and rivers, and (iii) water management activities.

Water Quality

Increases in hydrologic variability will likely alter water quality in several ways. Increases in the severity of summer droughts will likely cause lower dissolved oxygen concentrations and higher concentrations of plant nutrients and contaminants (Schindler, 1996). Increases in flood size and frequency will likely cause increased loadings of sediments, nutrients, and contaminants from agricultural and urban areas (IPCC, 1996). In Canada, these water quality changes will probably be of greater magnitude in densely populated urban areas and agriculture-intensive regions.

Productivity and biodiversity

Increases in hydrologic variability may reduce the productivity and biodiversity in streams and rivers of Canada. Larger floods are likely to increase scouring of streambeds, sediment loading, and sedimentation. These factors tend to reduce the abundance of organisms and the habitat available for recolonization in streams and smaller rivers. More severe droughts result in water quality deterioration (low dissolved oxygen concentrations, higher temperatures and contaminant concentrations) and increase the probability of desiccation. Organisms become concentrated in refugia (e.g., deeper pools) during extremely low flows increasing the probability of elimination from predation or intense competition.

Water Management Changes

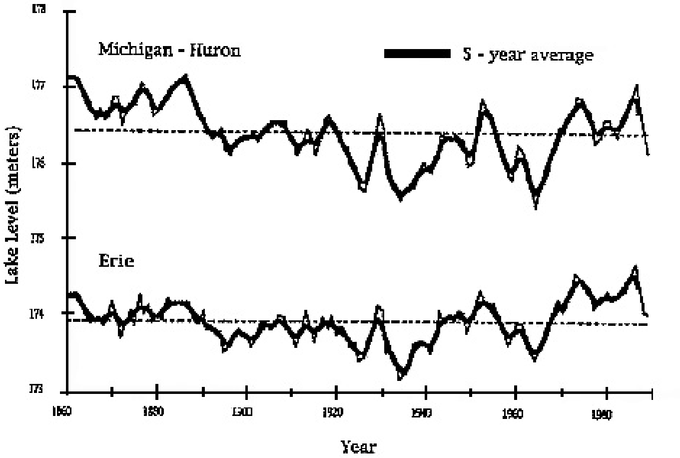
Greater hydrologic variability will have large impacts on water resources management in Canada. More frequent or larger floods would lead to increased expenditures for flood management and place additional pressure on public finances and on the insurance industry (IPCC, 1996). Increased severity and size of floods will lead to modification to flood control structures to accommodate larger probable maximum flow events.

Lakes

Great Lakes Water level Trends

Hydrological flows into and out of the lakes; net basin water supplies and lake levels are influenced by climate changes. There are three primary types of water level fluctuations: short-term variations due to storm surge and set-up, seasonal and annual. Historically, the annual water levels in the Great Lakes have fluctuated in a range of approximately 1.8 m from maximum to minimum levels. Fluctuations have included extremely low periods in the 1930s and 1960s and since the late 1960s the lakes have been in a high period culminating in record levels in 1986 (see Figure 1.12 for Lakes Michigan-Huron and Erie water level time series). A drought from 1987-1990 resulted in major declines in lake levels but Michigan, Huron, and Erie have remained above the long-term mean. Seasonal cycles (0.3-0.4 m) are superimposed on the annual levels; generally, there is a minimum in January or February and levels rise due to snowmelt and spring precipitation and reach a maximum in June (e.g., Erie and Ontario) or September (Superior). In the late summer and autumn the lakes begin their seasonal declines (Hartmann, 1990b; Magnuson *et al.*, 1997). Water level fluctuations have important economic and environmental implications.

Figure 1.12: Mean Annual Lake Levels
(Nuttle, 1993b, 5)



Climate Change and Great Lakes Levels

Table 1.11 summarizes the impacts on the Great Lakes of four GCM climate change scenarios linked to hydrologic models of the Great Lakes. All scenarios project a decrease in annual runoff for all the Great Lakes. Similarly, mean annual outflows and mean annual water levels decline under climate change scenarios.

In general, climate change scenarios project long-term lake levels to decline to or below historic low levels in the Great Lakes. For Lake St. Clair, the CCC GCMII scenario suggests surface area decreases of 15 percent and volume reductions of 37 percent. The mean Lake St. Clair water level may decline 1.6 m and displace the shoreline 1-6 km lakeward exposing the lake bottom (Lee *et al.*, 1996).

Wetlands, fish spawning, recreational boating, commercial navigation and municipal water supplies would be affected by low lake levels. Also of concern is the exposure of toxic sediments and their remediation (Rhodes and Wiley, 1993. Responses to adapt to these large changes in lake levels in developed areas would be costly; Changnon (1993) estimated the costs for dredging, changing slips and docks, relocating beach facilities, extending and modifying water intake and sewage outfalls for a 110 km section of the Lake Michigan shoreline including Chicago to range from $US 298 to $US 401 million for a 1.3 m decline and $US 605 to $US 827 million for a 2.5 m decline in water levels.

Table 1.11: GCM Impacts on the Great Lakes by Scenario

	GCM scenarios			
Lake/River	**CCC**	**GFDL**	**GISS**	**OSU**
Change in Annual Runoff (%)				
Superior	-12	-26	-2	-8
Michigan	-38	-27	-24	-14
Huron	-36	-19	-29	-9
Erie	-54	-22	-41	-19
Ontario	-34	-28	-33	-7
Mean annual outflow changes (%) from ase				
Superior	-13	-	-2	-19
Michigan-Huron	-33	-	-25	-20
Erie	-40	-	-32	-23
Ontario	-39	-	-	-
St. Lawrence at Montreal	-40	-	-	-
Mean annual water level changes (m) ase case				
Superior	-0.23	-	-0.46	-0.47
Michigan-Huron	-1.62	-2.48	-1.31	-0.99
Erie	-1.36	-1.91	-1.16	-0.87
Ontario	-1.30	-	-	-
St. Lawrence at Montreal	-1.30	-	-	-
Change in mean annual surface water rature (C)				
Superior	+5.1	+7.4	+5.6	+4.8
Michigan	+5.6	+5.5	+4.7	+3.4
Huron	+5.0	+6.0	+4.7	+3.6
Erie	+4.9	+5.0	+4.4	+3.0
Ontario	+5.4	+5.9	+4.9	+3.6

(Mortsch and Quinn, 1996, 904)

Small Lakes Climate Change Impacts

There are approximately 25,000 lakes in the Mackenzie River Delta which would be sensitive to changes in river ice growth, the discharge of the Mackenzie River, ice break-up and jamming, changes in sea level, and changes in flooding magnitude and frequency on water levels due to climate change (Marsh and Hey, 1989; Marsh and Schmidt, 1993). The Mackenzie Delta lakes are highly productive because of the frequent spring flooding of the delta by the Mackenzie River which adds nutrients and sediments and ensures that water levels in perched, higher elevation lakes or high-closure lakes (33% of lakes) are maintained (Marsh and Hey, 1989). At present they are flooded at a 2- to 10-year frequency by the spring runoff which is controlled by snowmelt runoff from southern portions of the basin and ice jams in the main delta channels. Climate change could alter the lake-water balance between floods and reduce the flow and water levels in the Mackenzie River and Delta. Marsh and Lesack (1997) assessed the impact of climate change on the hydrology of these delta lakes between floods and modeled the water levels for high, perched lakes. Lake levels declined more rapidly between episodes of flooding and a typical high-closure lake would disappear within 10 years. These delta perched lakes are particularly vulnerable since they show a slightly negative water balance if not flooded by the Mackenzie River during spring peak flow (Marsh and Lesak, 1997).

In the Prairie provinces, there are a large number of semi-permanent prairie sloughs fed by groundwater, precipitation and spring snowmelt that can dry out during serious droughts (Poiani and Johnson, 1991; 1993a,b). Eilers *et al.* (1988) found that in north central United States some drainage lakes and seepage lakes are responsive to precipitation; their lake levels declined substantially during the late 1980s drought. Also during the drought of the 1980s, water supply decreased significantly to Old Wives Lake and by 1988 it was completely dry (Wittrock and Wheaton, 1992). Lakes in Saskatchewan south of 53°N are small, shallow and saline (Wittrock and Wheaton, 1992). Climate variability alters lake levels and affects the salinity and composition of the flora and fauna (Hammer, 1990). These lakes are vulnerable to climate change. More information is needed to determine how precipitation and evapotranspiration changes will affect water supply, chemistry and the biology of saline lakes.

Permafrost prevents winter movement of groundwater; melting of permafrost and deepening of the active layer would allow drainage of water from northern lakes. Water losses would also be enhanced by increased evaporation.

Limited research has been conducted concerning the impact of climate change on small lakes.

Climate, Heat Exchange, Thermal Structure, and Lake Ice on Large Lakes

The following sections describe the importance and impact of climate and climate change on the heat exchanges, thermal structure and ice on large lakes.

Climate and Heat Exchanges of Large Lakes

Lake heat exchanges play an important role in understanding lake dynamics, lake hydrology, and ecosystem responses. The paucity of data contributes to the difficulty in evaluating lake heat exchanges in remote regions. Consequently, much of the detailed research on large lakes in Canada has focused on the “data rich” Great Lakes, which has extended application to other regions of Canada. This synopsis focuses on heat budget research on large lake systems using the Great Lakes as the example to discuss potential impacts of climate change.

Heat Storage and Surface Heat Flux

Schertzer (1997a) provides a comparison of the monthly mean surface heat flux of the Great Lakes. In general, positive changes in lake heat storage occur from February to September primarily through net radiative transfer as the turbulent components are relatively small. During autumn cooling, negative changes in the lake heat storage is associated with larger turbulent exchanges as the net radiative exchange is small. Maximum heat loss through the lakes surface occurs in the period December through January.

Climate Change Impacts Considerations on Heat Budgets of Large Lakes

Various GCM and climate transposition scenarios (see Schertzer and Croley, 1997a; 1997b) have been used to examine potential climate change impacts requiring computation of the lake heat budget components. Boyce *et al*. (1992) specifically incorporated the CCC GCMII scenario to assess the response of Lake Ontario to deep water cooling withdrawals and to global warming. Detailed International Field Year for the Great Lakes (IFYGL) meteorology and radiation fluxes (Davies and Schertzer, 1974) established the baseline climate. Comparison of climate change conditions to base climate responses (using IFYGL data) indicated significant changes to the lake thermal structure resulting from changes in the surface heat balance. Specifically, both longwave radiation fluxes to and from the lake increased by similar amounts meaning that net longwave radiation was slightly affected. From April through December, evaporative cooling of the lake was increased. In the winter months, January through March, the changes were extremely variable, both positive and negative. Sensible heat flux did not change greatly from May through November but the downward sensible heat flux increased markedly in the winter (January through April). Sensitivity tests indicated that Lake Ontario was much more sensitive to air temperature increases occurring in the winter months than another lake or another time period.

Climate and Thermal Structure of Large Lakes

Lake temperature is one of the fundamental limnological variables with significance for understanding physical, chemical and biological responses as well as defining habitat. Variability in lake temperature is largely due to the diversity of climate as well as lake morphometry. There are as many as 2 million freshwater lakes in Canada and broad-based thermal classification as amictic, monomictic or dimictic are applied as one descriptor. This synopsis focuses on the thermal structure of large lake systems using the Great Lakes to describe thermal stratification characteristics and variability. Potential changes in thermal structure indicated by applying climate change scenarios are also discussed.

Seasonal Thermal Characteristics

The large deep Great Lakes are subject to major seasonal changes in the net heat input and as a consequence go through an annual thermal cycle. Under current climatic conditions, the Great Lakes are dimictic (mix from top to bottom twice yearly in the spring and autumn), the timing being associated with fluctuation through the temperature of maximum density (4 ºC). In winter, the surface waters are all generally below the temperature of maximum density. In spring, nearshore water progressively warms to above 4^{o}C and the thermal bar forms and advances to the mid-lake (Rodgers, 1965). The disappearance of the thermal bar marks the onset of full thermal stratification with progressive deepening of the thermocline. At the end of summer, lakes have achieved maximum heat storage and with continued surface cooling in the autumn, thermal stratification breaks down. The autumn overturn marks the end of the summer stratification and deep mixing from autumn storms continues to cool the lake below the temperature of maximum density.

Temperature Modeling

One-dimensional temperature models have had wide application in the lower Great Lakes for long-term analysis of thermal structure. For example, Lam and Schertzer (1987) have simulated basinwide and lakewide daily vertical temperature profiles for Lake Erie (1967-83) and have established the long-term monthly mean depth and variability of the epilimnion-mesolimnion and mesolimnion-hypolimnion interfaces under current climatic conditions as well as the seasonal temperature variation with depth. Stratification characteristics of large lakes is provided in Croley *et al.* (1996) and Croley (1997b). Higher order 3-D models are usually required in order to simulate the spatial variation in vertical lake temperature, however, the data and computational requirements are more rigorous. Long-term simulations in combination with observations are essential for establishing a climatology of thermal structure for the large lake systems as well as dynamical responses of temperature and current structures in response to surface meteorological forcing. Little is known about potential changes in frequency of occurrence or variability in lake hydrodynamical responses under a changed climate nor how it would impact on ecosystem components.

Climate Change Impacts on Thermal Structure of Large Lakes

Large lakes are essentially integrators of climate conditions. Consequently, it can be argued that long-term thermal records of large deep lakes may be useful in helping to define expected variations under current climate “normals” and thus deviations outside such a range could be indicative of a response to changed regional climatic conditions. As such, a climatology of lake temperature (observations and simulations) is essential, not only for selected Great Lakes but also for selected large lakes across the latitudinal and longitudinal domain of the country. Projections of potential changes to the physical regime of selected lakes has been conducted by examining responses under warm conditions as analogues of climate change (Rodgers 1987; Schertzer and Sawchuk, 1990), by application of GCM scenarios (Boyce *et al.*, 1993) and by application of transposition scenarios to the Great Lakes region (Croley, 1995). Schertzer and Croley (1997a and 1997b) provide a summary of these studies. In general, these studies indicate that climate warming using CCC GCMII scenarios (and others) can have significant impact on basin and lake hydrology and thermal structure, especially in susceptible lakes and embayments. Climate warming has the potential to increase lake evaporation, reduce net basin supplies, and reduce lake levels and flows. Of particular concern for water quality and habitat are projections that warmer climates can result in reduced frequency of buoyancy-driven water column turnovers. In many scenarios, the lake surface water temperatures may not fall below 4^{o}C (temperature of maximum density). This could result in significant environmental impacts since spring and fall turnovers are important for nutrient distribution, oxygenation of lake water and so forth (Lam *et al.* 1987a and 1987b; Schertzer and Lam, 1991). Simulations using hypothetical lakes at different latitudes (Meyer *et al.*, 1994) reinforce some of the potential climate change impacts suggested from Great Lakes studies. The study suggested particular sensitivity to climate warming near transition regions at latitudes ranging from 30^{o} to 45^{o} N/S and 65^{o} to 80^{o} N/S. In warmer latitudes, periods of stratification may be enhanced. In colder high latitudes, the frequency of overturn is likely to increase and there is the potential for sub-polar lakes to change from cold monomictic to dimictic. Ice formation in sub-polar regions have the potential to be reduced or be totally suppressed.

Lake Ice

The dynamics of lake ice cover is greatly influenced by regional climate forcing. Investigators first began to quantify the relationship between climate variables and the length of the ice season in Europe over 50 years ago, to benefit navigation and transport, as potential indicators of climate trends and to assist the development of climate change hypotheses (Walsh, 1995; Skinner, 1992). Research has primarily focused on the relationship between regional air temperature and the freeze date, break-up date and ice cover duration. Although some process-based models have incorporated the dynamics of ice growth, the availability of snow and ice thickness data is often a limiting factor (Varvus *et al*., 1996; Gu and Stefan, 1990; Patterson and Hamblin, 1988).

Richards (1964) identified the ability to predict freeze date, break-up date and ice cover extent on the Great Lakes, using freezing degree-day (FDD) analysis. In a literature review, Barry and Maslanik (1993) found a 1ºC change in autumn or spring air temperature causes a four to six day change in mean freeze-up or break-up date. Break-up date is also influenced by snow and ice thickness, surface albedo and mechanical action (e.g. wind); it is a less effective climate indicator. The sensitivity of the ice cover cycle to air temperature fluctuations has been noted to increase with latitude (Walsh, 1995).

There is general agreement between Canadian air temperature and ice cover trends over the past century. Williams (1971) identified a trend toward earlier ice break-up and shorter ice duration for the Great Lakes from 1870-1940, but found no significant trend from 1940-1971. Hanson *et al*. (1992) detected a significant trend toward earlier break-up from 1965-1990 on the Great Lakes (except Lake Ontario, which experienced a less significant, trend). Skinner (1992) identified a similar trend in northwestern and central Canada. Schindler *et al*. (1996) found a 15-day decrease in the ice duration since 1970, due to earlier break-up, at the ELA in northwestern Ontario, agreeing with analysis of Wisconsin lakes (Anderson *et al*., 1996; Robertson *et al*., 1992). These recent trends have been attributed to higher spring air temperatures and below average snow cover (Schindler *et al*., 1996; Walsh, 1995; Skinner, 1992).

There has been limited modeling of the effect of future climatic warming in Canada on lake ice. Assel (1991) applied a FDD and ice cover model to Lake Erie and Lake Superior under 2xCO_2 warming scenarios (U.S. EPA, 1989). A lack of significant midlake ice formation and a reduction in the ice cover duration of 5-13 weeks on Lake Superior and 8-13 weeks on Lake Erie was predicted. Under the present climate, annual maximum ice extent for the combined area of the Great Lakes occurs near the end of February (Assel *et al*., 1983). It averages about 60%, and varies from about 30% in mild winters to over 90% in severe winters (Assel *et al*., 1996).

The limited ice research in Canada is often attributed to the lack of nationally consolidated data. The Atmospheric Environment Service maintains a database of 250 lakes across Canada, including date of first permanent ice, complete freeze over, first deterioration of ice and water body clear of ice (Skinner, 1992). Other organizations, including the Dorset Research Centre in south central Ontario, maintain ice records for other lakes (Dorset Research Centre, 1994; Skinner, 1992). It may be possible to employ individual lakes as regional climate indicators, but

Wynne *et al.* (1996) found the break-up dates of 62 lakes in the Laurentian Shield failed to behave similarly over time.

Walsh (1995) suggested monitoring by remote sensing of lake ice cover as a method to detect climate change on a national or global scale. This would require sufficient orbital coverage and fine resolution, to permit frequent sampling (ideally daily) and spectral separation for smaller lakes (Walsh, 1995; Barry and Maslanik, 1993).

Groundwater

Groundwater, like other water resources, may be subject to a range of impacts resulting from climate change and increased climate variability (Mimikou *et al.,* 1991; Kuchment, 1989). Thus, groundwater must be considered as a principal component of the assessment of the impact of climate change on the hydrologic cycle (Kovalevskii *et al*., 1989; van der Kamp and Maathuis, 1992; Thomsen, 1990). Relatively little is known about the specifics of climate change impacts and the extent to which they may translate to societal concerns. Groundwater resources are directly linked to climate change through hydrologic processes such as precipitation and evapotranspiration and through interaction with surface water. Groundwater resources are also affected by anthropogenic processes such as the consumption of groundwater by pumping. The importance of understanding of the impacts of climate change on groundwater resources is highlighted by the value of groundwater.

Groundwater is an important water resource in most regions of Canada; for example, statistics indicate that 26% of Canadians rely on groundwater as a water supply (Environment Canada, 1993). Reliance on groundwater varies from province to province, and is greatest in rural areas, where 90% of the population relies on groundwater for all, or part, of their water supply. In addition, groundwater is the single largest reservoir of freshwater. The global groundwater resource is thought to contain 500 times the quantity of water held in lakes, rivers, reservoirs, and wetlands (Freeze and Cherry, 1979). While vast in quantity, groundwater resources are not uniformly distributed at even local scales. Further, hydrogeologic conditions such as low hydraulic conductivity often limit recovery of the resource. Needless to say, it is important not to mine the resource.

However, there is limited knowledge of the groundwater resources in Canada (Hofmann, 1996; Bruce and Mitchell, 1995; Mitchell and Shrubsole, 1994). Researchers complain that groundwater is often *out of sight*, and thus *out of mind*. This same characteristic makes groundwater resources difficult to accurately measure.

Canada can be divided into six hydro-physiographic regions based on a similarity of geology, climate, and topography (Herr, 1978). For each region, different factors may define the impacts of climate change on groundwater flow systems. In northern regions, the impact of climate change on permafrost will be an important factor in determining the changes to groundwater flow systems (Michel and van Everdingen, 1994; Hinzman and Kane, 1992). In coastal regions, changes in sea-level may be a principal factor in determining shifts in salt water-fresh water interfaces (Cole *et al*., 1994; Cieslak and Duffy, 1994; Werkheiser and Ayers, 1993; Buddemeier and Oberdorfer 1990). How climate change affects the amount of snow accumulation in mountainous areas is also expected to be a key factor in determining the effects on the hydrological cycle (Mimikou *et al*., 1991). In the Prairies, the impacts of climate change on groundwater-lake interactions become important (Crowe, 1993).

Groundwater is an important water supply. The principal detrimental impact of climate change is likely to be associated with declining groundwater levels that may result if groundwater recharge is reduced as a product of reduced precipitation, alone, or in conjunction with increased evapotranspiration (Sharma, 1989; Vaccaro, 1992; Hokett *et al*., 1990; Alexander *et al*., 1987; Flint *et al*., 1993; Sandstrom, 1995). For economic reasons, wells are generally excavated to the minimum depth required to obtain an adequate supply of groundwater. Declining groundwater levels would cause some wells to become dry and unusable while others would become less productive due to the loss of available drawdown (Soveri and Ahlberg, 1989).

Declining groundwater levels may lead to decreased discharge to surface water bodies (Crowe, 1993; McAdams *et al*., 1993; Freeman *et al*., 1993). Groundwater discharge to surface water courses is manifest in the base flow of rivers (Cooper *et al*., 1995; Timofeyeva, 1994; Panagoulia and Dimou, 1995). Base flow is the minimum flow that occurs in rivers between runoff events; it frequently defines the capacity of rivers and lakes as water supplies and the assimilative capacity of rivers and lakes for point and non-point source contaminants.

Groundwater flow systems occur over a wide range of scales and have differing abilities to retain and transport water; the residence times of groundwater vary from days to tens of thousands of years (van der Kamp and Maathuis, 1992). This spectrum is likely to delay and disperse the impacts of climate change (Wilkinson and Cooper, 1993). For example, a reduction in groundwater recharge may not translate to an immediate and equivalent reduction in the base flow of rivers. Instead, base flow may decline more slowly than recharge, and this decline may persist for some time following any subsequent increase in recharge. Impacts of climate change on groundwater resources may not be immediately detectable and the effectiveness of adaptation strategies targeted toward maintaining groundwater resources may be difficult to monitor.

The impacts of climate change on groundwater quality are less intuitive than the related impacts on groundwater quantity. For the case of elevated atmospheric CO_2, precipitation may become enriched in CO_2 and this may have implications relative to groundwater geochemistry through varying mineral solubility. It is likely, however, that groundwater impacts may translate to broader water quality concerns through changes to the water temperature (Kukkonen *et al*., 1994), chemistry (Webster *et al*., 1990; Peck 1988) and assimilative capacity of rivers and lakes (Crowe, 1993). Decreasing base flow may result in increased temperature variations as the influence of the stable temperature of groundwater is reduced relative to seasonal and diurnal fluctuations. These temperature fluctuations may have a detrimental impact on aquatic organisms which are sensitive to temperature and dissolved oxygen content (Meisner *et al.*, 1988; Sinokrot *et al*., 1995). Reduced base flow will also decrease the dilution of natural and anthropogenic contaminants within surface water bodies with obvious water quality impacts (Jury and Gruber, 1989).

The climate change impacts listed in the previous paragraphs are direct impacts; they are roughly proportional to the extent of climate change. Groundwater resources may also be impacted by climate change indirectly and these impacts may be out of proportion to the actual extent of climate change. For example, the extended growing seasons and elevated temperatures that might result from climate warming may cause agricultural practices to shift toward crops that require irrigation in areas where irrigation is not presently required. Irrigation consumes large volumes of water and a shift toward irrigation may impact groundwater resources to a much greater extent than predicted solely on the basis of direct climate change impacts such as reduced recharge (Howitt and M'Marete, 1990). In addition, irrigation is primarily applied during summer months when groundwater levels and surface water flows are at or near their annual lows.

Considerable research will be required to understand the potential impacts of climate change on groundwater resources, how these impacts might translate to societal concerns, what adaptation strategies might be applied to these concerns, and how these strategies might be implemented. At least two approaches to determining climate change impacts might be developed. The first may be to identify the climatic, physiographic, hydrogeologic, and anthropogenic factors associated with deleterious impacts such as declining groundwater levels. These factors would logically be related through a conceptual model such as a comparison of the rates of groundwater recharge, consumption, and discharge. These relations might then be used on a national scale to define, in a qualitative sense, the distribution of areas with an elevated risk of adverse impacts. A second and complementary approach may be to conduct detailed studies in contrasting settings such as northern, coastal, and prairie regions. The latter results would better define the range and mechanics of climate change impacts and would complement the former set, which are spatially comprehensive, but lacking in quantitative detail.

Groundwater - Climate Change Case Study: The Grand River Basin

McLaren and Sudicky (1993) used a simple two-dimensional (2D) steady-state flow model over a subregion of the Grand River Basin in southern Ontario to examine possible climate change impacts on groundwater (using GISS, GFDL, and CCC scenarios). Specifically, they looked at possible impacts concerning groundwater extraction for domestic/municipal use. The modeling indicated that a reduction in the rate of recharge of 15% to 35% which would result in a maximum impact (drawdown) at existing pumping centres of 5 to 20 m, respectively (McLaren and Sudicky, 1993, 66). In the northerly sections of the study area, drawdowns range from 2 to 7 m. These northerly areas are dominated by rural domestic uses which could be seriously affected by drawdowns, particularly those uses reliant upon shallow dug wells. The study also found that a reduction in the rate of recharge of 15% to 35% resulted in a reduction in the rate of groundwater discharge of 17% to 39% (McLaren and Sudicky, 1993, 66). The percent change in discharge rate is not equal to the percent change in recharge rate because as the recharge decreases, pumping wells capture a slightly higher portion of total recharge (McLaren and Sudicky, 1993, 66).

A prototype of research focusing on the impacts of climate change on groundwater resources at a regional scale is presently underway within the Grand River watershed in southern Ontario. This is a collaborative initiative of the Water Issues Division, Ontario Region, Environment Canada; the National Water Research Institute, Environment Canada; and the Grand River Conservation Authority. The research approach that is being developed for the watershed is to interpret the groundwater resources of the region through the analysis of water well construction records, to use this understanding to construct a model of groundwater flow across the watershed, to link ground and surface water flow models, and finally to assess the impacts of various climate change scenarios on the integrated water resources model.

Water Quality

Climate change is expected to cause changes in water quality. They are generally considered to be negative. This discussion will be limited to the effects of: increased temperatures, decreased water quantity, a change in seasonality of runoff, and water quality of large lakes.

Increased Temperatures

Higher air temperatures can deteriorate water quality. For example, increases in water temperature in streams and rivers reduce oxygen solubilities and increase biological respiration rates and thus may result in lower dissolved oxygen concentrations, particularly in summer low flow periods in mid latitude areas (IPCC, 1996). Summer dissolved oxygen concentrations in the hypolimnion of lakes, particularly the more eutrophic lakes, may also decline and areas of anoxia increase due to increased respiration rates in a warmer climate (IPCC, 1996). However, reduction in the length of winter ice-cover may reduce the incidence of winter anoxia in more northerly lakes and rivers.

Decreased Water Quantity

Lawford (1990) suggested that the effects of climate change on water quality in western Canada is dependent upon the effects upon water quantity. The drought of 1988 illustrated possible problems which could be amplified by climate change. For instance, soil erosion was common and caused sedimentation problems in streams. If water levels in streams and lakes are reduced due to climate change, the ability to dilute pollutants is reduced. Increased temperatures may also affect the solubility, and mobility of contaminants.

Change in Seasonality of Runoff

Changes in the seasonality of runoff may also affect water quality. In the mid and high latitudes the shift in high runoff period from late spring-summer to winter-early spring might reduce water quality in late summer - especially under low flow scenarios. Schindler (1997) noted that extended droughts in boreal regions can result in the acidification of streams due to oxidation of organic sulfur pools in soils. However, the acidic episodes associated with spring snowmelt in streams and lakes might be reduced under a warmer climate with lower snow accumulation and lower discharges during the spring melt (IPCC, 1996; Moore *et al*. 1997). Overall, water quality problems (particularly low dissolved oxygen levels and high contaminant concentrations) associated with human impacts on water resources (e.g., wastewater effluents, cooling water discharges) will be exacerbated more by reductions in annual runoff than by other changes in hydrologic regimes (IPCC, 1996).

Climate and Water Quality of Large Lakes

In large lake systems, eutrophication and toxics have been dominant areas of water quality investigation. Research has indicated that climate can be a significant factor in affecting limnological processes responsible for the transport, distribution and pathways of pollutants, and consequently, water quality conditions.

When large amounts of organic matter produced by algae in the epilimnion settles to the hypolimnion layer decomposition can deplete oxygen reserves resulting in hypolimnion anoxia. Depletion of summertime oxygen reserves can impact on lake biota (phytoplankton/zooplankton/ benthos species) and the health of fisheries. Anoxia can cause odorous and unpalatable water unsuitable as municipal drinking water supply. In addition, decaying algae and *cladophora* growth can foul bathing beaches, plug water intakes and reduce shoreline property values. Anoxia can also result in the release of nutrients and metals from the sediments into the water column.

In Lake Erie, Lam *et al.* (1987a) describe a water quality model for prediction of nutrient and dissolved oxygen concentrations under current climate conditions. Model verification with 1967-1982 data successfully simulated temperature, nutrient (total phosphorus and soluble reactive phosphorus concentrations) and dissolved oxygen concentration for basin and lakewide conditions. The model results demonstrated that within the critical shallow central basin hypolimnion of Lake Erie, both the thermocline dynamics and nutrient loadings act to control the occurrence of hypolimnion anoxia. The thermocline position and temperature within the water column form the direct linkage to the surface meteorological (climate) conditions. Further, climate-basin hydrology has a controlling influence on nutrient loading. Probability distributions for the depth of the hypolimnion and observed oxygen concentrations in the central basin of Lake Erie clearly indicate that anoxia occurrence (i.e., water quality) is correlated with climate forced thermal characteristics of the lake. This implies that changed climatic conditions can impact on water quality conditions such as nutrient and dissolved oxygen concentrations and ecosystem components dependent on these factors.

For susceptible lakes such as the Lake Erie central basin, decreased net basin supplies, lower water levels, an altered thermal cycle (potentially without overturn) can significantly impact on water quality conditions. Preliminary climate-nutrient loading scenarios indicate significant reductions in nutrient loadings through the Detroit River and from basin catchments. Water quality responses to climate warming effects can be approached by examining climate-water quality responses under anomalously warm conditions as an analogue of responses and simulations based on GCM scenarios (Schertzer and Lam, 1997).

Schertzer and Sawchuk (1990) investigated the response of Lake Erie central basin under a warm year 1982/1983 to assess the physical and hypolimnetic anoxia response as an analogue of climate warming conditions. The investigation indicated that the year was characterized by large reductions in surface heat losses in winter and above-average surface heat flux gains in summer. On an annual basis, the lake buffered large surface heat gains in summer through losses in other months. Observations indicated higher surface water temperatures, significant reductions in duration and extent of ice cover and an earlier disappearance of the 4°C isotherm signaling an earlier start to thermal stratification. In response to greater surface heating and low wind conditions, the thermocline formed higher in the water column and stratification lasted longer than in other years. The prolonged stratification period (despite a thicker hypolimnion) contributed to slight hypolimnetic anoxia in the central basin of Lake Erie. Considering that simulations under climate warming indicate that lake temperatures may not consistently experience complete "overturn" (i.e., Boyce *et al.*, 1993; Schertzer and Croley, 1997a) it is hypothesized that the water quality (nutrient and dissolved oxygen distributions) may be adversely affected. Increased temperature, changed nutrient and oxygen conditions are expected to impact on ecosystem components such as fisheries habitat and health.

Wetlands

Wetlands are defined as "lands saturated by surface or near surface waters for periods long enough to promote the development of hydrophytic vegetation (e.g., weeds, bulrushes, sedges) and gleyed (poorly drained) or peaty soils" (Environment Canada, 1994a, 28). Wetlands are categorized as either bogs, fens, salt and freshwater marshes, swamps and shallow water. Fourteen percent of the land surface in Canada is covered by wetlands which occur in diverse locations across Canada ranging from salt-water marshes in Hudson Bay and the British Columbia and Atlantic coasts; bogs and fens in boreal and subarctic Canada; shoreline marshes and swamps within the Great Lakes and St. Lawrence River Basin to sloughs or potholes in the Prairies (National Wetland Working Group, 1988; Zoltai, 1988). Twenty-five percent of the world's wetlands are found in Canada (Environment Canada, 1994a).

Wetland functions are important to the natural environment as well as to human society. Some include: primary productivity; enhancement of water quality through nutrient, sediment, and toxic chemical transformation and sequestration; buffering of wave erosion and flooding; contribution to baseflow; habitat for wildlife in particular rare or endangered species as well as fish, waterfowl, shorebirds, amphibians and mammals; commercial activities; and recreational and educational opportunities. A decline in wetlands in the Great Lakes Basin would have numerous implications including a negative impact on fisheries because half of the Great Lake fish species use wetlands for spawning and nursery habitat; and waterfowl use them as staging areas. Prairie pothole wetlands are extremely important for waterfowl breeding.

Wetlands are dynamic systems, which are considered transitional between terrestrial and aquatic ecosystems. The location, areal extent, productivity and diversity of wetlands are vulnerable to hydrologic cycle changes and predicted effects due to climatic change are of concern to wetland researchers. The following hydrological issues are of concern: changes in water balance components: precipitation changes, declines in surface runoff, lowered snowfall, decreased frozen season, reduced groundwater storage and increased evapotranspiration. Great Lakes Basin water levels are expected to drop significantly; these wetland impacts and others are likely to be severe (Croley, 1990; 1993; Lee *et al*., 1996; Mortsch, 1990).

Temperature increases associated with climate change may alter long-standing biogeographical barriers that affect ecosystem functioning, diversity, and location (Vitousek, 1994). Major changes in the ecosystems of Canada have been projected for $2xCO_2$ scenarios including the reduction of tundra, subarctic and boreal ecozones and the northward expansion of temperate grassland ecozones (Rizzo, 1990; Rizzo and Wiken, 1992). These changes can lead to die-offs and reorganization of the composition and structure of wetland vegetation communities based on temperature tolerances. The range of some species (e.g. exotic) may also expand and compete with indigenous species.

A high water table or frequent inundation are required to maintain wetland ecosystems. Naturally, the water supply to a wetland (through precipitation, surface runoff, and groundwater inflow) must exceed losses due to evapotranspiration and runoff. Climate change is expected to alter regional hydrologic processes by modifying the quantity and quality of water and thus disrupting this balance. Although periodic water level fluctuations and cycles of wet and dry years are necessary to maintain wetland diversity, the rate of change, the frequency of extreme events in these cycles as well as a decline in water storage associated with climate change could disrupt the functioning of wetland ecosystems and impair their multifunctional values (Mortsch, 1990; Martinello and Wall, 1993; Poiani and Johnson, 1993a,b). Wetland productivity is depressed by prolonged flooding or drying out while periodic water level changes increase vegetation diversity and productivity (van der Valk and Davis, 1978).

The position of the water table in wetlands controls the size of the aerobic and anaerobic layers in a peatland; the degree of anaerobicity affects the exchange of carbon gases (methane, carbon dioxide) with the atmosphere and export of dissolved organic carbon (DOC) (Rouse *et al*., 1997). Soil CO_2 efflux increases linearly with a reduction in water table while methane flux decreases exponentially (Moore and Knowles, 1989). A decline in water table can change a peatland from a net sink of CO_2 to a source (Roulet *et al*., 1992).

The various types of wetlands will react and adapt differently to climate change and variability. Marshes, for example, adapt more readily to lower levels than swamps. Although the landward edges of marshes would dry their herbaceous vegetation could colonize suitable exposed sites quickly. Trees, the dominant vegetation of swamps, would not be able to regenerate or colonize quickly. Enclosed and barrier shoreline wetlands and inland wetlands would be vulnerable to drying out. Open shoreline wetlands are not constrained from migration but colonization is limited by suitable substrate and seed banks. The flood and erosion protection functions of these wetlands as well as habitat would be diminished.

Bogs are particularly vulnerable to climate change given their reliance on precipitation. That is, precipitation is the major water supply into bogs, since they are isolated from the local groundwater regime by peat accumulation. A decline in precipitation (and resultant drawdown in water level) will alter vegetation organization. In addition, it will also expose the peat and sediments to aerobic conditions increasing oxidation and changing physical properties of (and hydrologic behaviour) and the flux of nutrients, gases and sediments from a wetland (Woo, 1992). Similarly, many ephemeral Prairie sloughs are fed only by the spring snowmelt and precipitation. During drought they dry out, and persist throughout a season with high precipitation. Semi-permanent sloughs are fed by groundwater in addition to precipitation and spring snowmelt and only dry out in serious drought when the groundwater storage is depleted.

Wetlands are disappearing at a rapid rate due to land use change; their quality is affected by pollution. For example, in a Manitoba study from 1930-1970, wetlands were reduced by more than 60% and subsequently, were further reduced by another 56% (Lawford, 1990). Similar reductions have been reported in southern Saskatchewan and in Alberta's parkland (Lawford, 1990). Climate change is yet another stressor. Given the diversity of wetlands across Canada, it is unlikely that climate change will affect wetlands uniformly. Climate change is not expected to be a smooth or linear process. The chief concern is that the rate of climate change will not exceed the adaptive capacity of wetland ecosystems.

The Frozen Regime

This section discusses river ice, permafrost and lastly glaciers. Freshwater lake ice has been explored under the lakes section.

River Ice

Earlier break-ups, of up to 15 days, are reported for the Saint John River, New Brunswick (Williams, 1970) and the Red River, Manitoba (Rannie, 1983). In northern and eastern New Brunswick and Prince Edward Island, there appears to be a mild signal showing less ice in the river; there is no change in southern New Brunswick and central Nova Scotia; while there is a significant trend to more days with ice in Cape Breton as well as most of Newfoundland (Clair *et al.*,1997).

Climate change will modify river ice cover in various parts of Canada differently. Temperate regions with intermittent river ice cover such as British Columbia and southwestern Ontario may have ice cover disappear completely or become more intermittent. In the far north, the warming of the cold winter temperatures may not cause winter break-up but the ice-free season may increase. Ice thickness may also decrease (Clair *et al.,* 1997). Intermediate regions may have winter break-up with associated flooding.

Permafrost

Permafrost is defined by Brown and Kupsch (1974) as "...the thermal condition in soil or rock having temperatures below 0^{o}C persist over at least two consecutive winters and the intervening summer." It is a thermal condition and ice may or may not be present.

In $2xCO_2$ GCM scenarios, discontinuous and continuous permafrost boundaries move poleward about 500 km (Woo *et al*., 1992) and the area of permafrost is reduced to less than 80% of its present coverage. Some portions of the globe, such as Siberia, have already witnessed retreat rates of 60-80 kilometres/1°C (Prowse, 1996). It has been suggested that areas with an annual mean temperature of -6 °C or less could have permafrost disappear completely (Prowse, 1996). Kwong and Gan (1994) conducted surveys of permafrost along the Mackenzie Highway south of Great Slave Lake. They found that the southern limit of the sporadic discontinuous permafrost zone has migrated northward by about 120 km. To determine if this migration was caused by warming, a detailed trend analysis (non-parametric Kendall's test) of monthly air temperature records for nine weather stations was conducted. The results show a regional warming trend for the period 1949-1989. Future warming caused by climate change would cause the permafrost to migrate further northward.

Permafrost confines water flow to the active layer and restricts interaction of the surface with the groundwater. An extended thaw season and melting of permafrost, ground ice, etc. will cause numerous impacts including:

- terrain slumping and changes in surface features and drainage patterns;
- thermokarst erosion;
- increased sediment load to rivers and lakes;
- an enhanced development and thickening of the active layer which will reduce overall surface ponding and flow due to greater storage in the active layer, longer period of infiltration and greater contribution to the groundwater flow network;
- opening of subsurface flow connections which were previously impeded allowing more drainage of peatlands and wetlands;
- peatland and wetland drying; they may become sources of atmospheric carbon;
- disappearance of patchy Arctic wetlands presently supported by surface flow;
- lateral or groundwater drainage of water bodies that have permafrost hydrologic divides; and
- flooding of thawed lakes

(Prowse, 1996; IPCC, 1996; Rouse *et al.*, 1997; Woo *et al.*, 1992; Mackay, 1992).

Glaciers

Glacial meltwater is a significant source of water for streams and rivers in mountainous regions; highest flows occur in early or midsummer (depending on latitude). The impact of climate change on glaciers will depend on their geographic location and their elevation. Southern British Columbia glaciers are generally at low elevations; warmer temperatures would lead to more of the annual precipitation falling as rain and would increase summer melt. Higher elevation glaciers would not be as vulnerable. Yukon and northwestern British Columbia glaciers would receive increased precipitation which will offset the higher temperature impacts; the glaciers are likely to continue to advance (Brugman *et al.*, 1997). Demuth (1994, 1995) also has shown that changes in precipitation/evaporation patterns may result in a retreat of glaciers along the eastern slopes of the Continental Divide.

Increased temperatures would lead to glacier melt. If snowfall amounts remain stable, the glaciers will melt and their equilibrium levels will retreat to higher elevations (Lawford, 1990). Initially, this melting would cause increased runoff, however, after a number of years, this increase would be replaced by decreased amounts of water coming from the diminished glaciers (IPCC, 1996; Brugman *et al.*, 1997). Once the glacier has largely melted there will be no glacial water input in the late summer and fall reducing flow significantly. But, if snowfall amounts increase, glacier mass balances may not change significantly and the total water yield from glaciers may increase (Lawford, 1990). Brugman *et al.* (1997) defined three characteristic areas of glacier impact due to 2xCO_2 warming for British Columbia and the Yukon; they are:

- a southern demise zone where most glaciers are thin and retreating;
- a transitional zone where glaciers with large, high accumulation areas advance and others retreat; and
- a northern growth zone where most glaciers advance.

Runoff from these glaciers is important to the maintenance of flow and habitat in the headwaters of several major prairie rivers. Contributions from glacial melt are particularly important in the transition from summer peak flows to base flow in these systems.

Predictions of trends in glacier mass balances are rather complex. During the 1980s, in glaciers around Garibaldi Provincial Park the mass balances of two decreased rapidly but, a third, experienced no net decline. It is unknown whether this is the result of micro-meteorological conditions in the park, the shape of the glaciers or difficulties with the survey methods (Lawford, 1990).

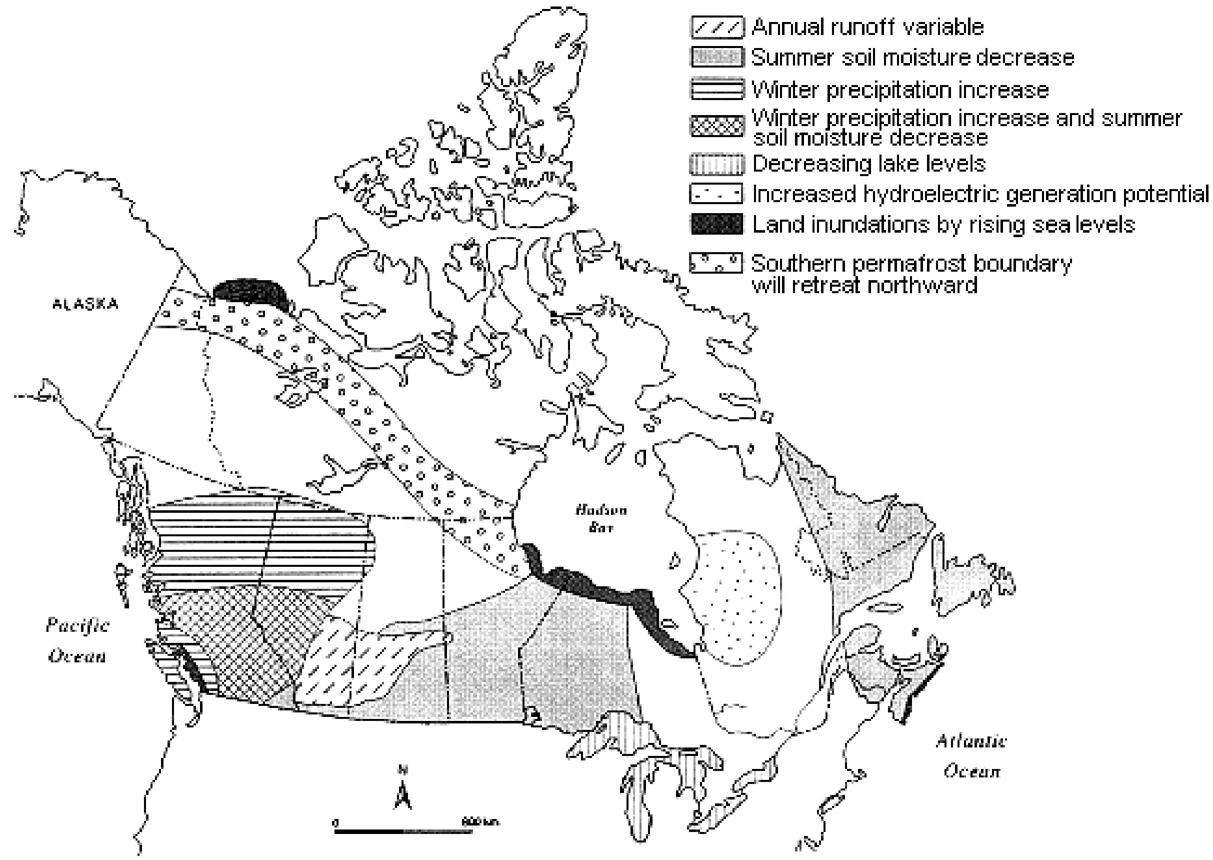
River and reservoir systems that are snow-fed or rely on glacier melt for spring and summer flow during the critical periods of high agricultural and municipal demand and low precipitation may have critical supply-demand mismatches. The Prairies region of Canada is particularly vulnerable (Cohen *et al*., 1989).

Summary

The impacts of climate change discussed in the previous sections are summarized in Table 1.12. The hydrologic impacts were assessed in Canadian climate impact assessments using various climate change scenarios and modeling methods.

Figure 1.13 generalizes some of the possible hydrological impacts implied by recent GCM climate change scenarios for regions of Canada. This includes winter precipitation increases on Vancouver Island, and southern coastal British Columbia, winter precipitation increases and summer soil moisture decreases for southeast British Columbia and southwest Alberta, summer soil moisture decreases for southeast Saskatchewan, southern Manitoba, northwest Ontario, and most of the Maritimes. The map also shows the movement of the southern permafrost boundary northward.

Figure 1.13: Summary of hydrological impacts in Canada
(Lawford, 1992, 12).



Summary of Hydrological Impacts in Canada

Table 1.12: Summary of hydrologic impacts from Canadian studies using various climate change scenarios*

Component	Impact	Area Studied	References
Evaporation/ Evapotranspiration	• increases	• Great Lakes; Mackenzie River Basin, Saskatchewan River	Croley, 1990, 1992; **Cohen,** ; 1987b; Soulis *et al.*, 1994; Cohen, Welsh and Louie, 1989
Runoff/Streamflow			
• mean	• decreases • increases	• Great Lakes; Saskatchewan River; Mackenzie River; Moisie River, Québec; Grand River, Ontario • Northern Québec; Saskatchewan River; Mackenzie River	Croley, 1990, 1992; Cohen, Welsh and Louie, 1989; Cohen, 1986, 1987; Soulis *et al.*, 1994; Singh, 1987; Ng and Marsalek, 1992; Morin and Slivitzky, 1992; Smith, 1991; McBean and Smith, 1993; Haas and Marta, 1988; Kerr, 1996; Walker, 1996
• minimum	• increased duration and frequency	• Grand River, Ontario; Bay of Quinte Watershed	
• spring peak	• earlier; maximum not as high	• Waterford River, Newfoundland; Great Lakes; Mackenzie River; Bay of Quinte Watershed	
• maximum	• remains the same or lower (minimal change)	• Bay of Quinte Watershed	
Lake level			
• minimum	• increased duration and frequency; attain all-time lows	• Great Lakes; Great Slave and Great Bear Lakes	Hartmann, 1990a and 1990b;; Croley, 1990, 1992 ; Kerr and Loewen, 1995; Kerr, 1996
• maximum	• decreases		
• annual cycle	• earlier seasonal maximum; amplitude decreases		
Soil moisture	• decreases; summer deficit	• Grand River, Ontario ; Great Lakes, Saskatchewan; Southern Ontario	Sanderson and Smith, 1990; Woo, 1992; Cohen, Welsh and Louie, 1989; Brklacich, 1990
Ground water			
• recharge	• decreases	• Grand River, Ontario	McLaren and Sudicky, 1993
• levels	• decrease	• Grand River, Ontario	
Snowcover	• decreases • more intermittent	• Bay of Quinte Watershed	Walker, 1996
Ice			
• lake ice	• ice cover reduced or eliminated • ice cover season reduced	• Great Lakes; Mackenzie River; numerous northern lakes	Assel, 1991; Andres, 1994; Skinner, 1993; Sanderson, 1987
Saltwater intrusion	• sea level rise affects coastal rivers	• St. Lawrence River and Saint John River	Slivitzky, 1993; Martec, 1987

* Methods of climate scenario development include General Circulation Models, historical analogues, hypothetical conditions, climate transposition; various types of models (empirical, water budget) were used to assess hydrological impacts.

WATER RESOURCES: CLIMATE CHANGE AND VARIABILITY

In "Hydrology: Climate Change and Variability", first order impacts on the hydrological cycle were analyzed. This section: "Water Resources: Climate Change and Variability" examines the second order impacts in terms of the "water resource". In 1933, Zimmerman proposed that the components of the environment can only be considered a "resource" if the component was needed/desired by humans (Mitchell, 1989a). In this instance, "water" is viewed as a resource through humans' various uses. In essence, this viewpoint is anthropocentric, but highlights impacts of climate change on humans' use of water.

This section limits its discussion to the following water resources issues:

- agricultural and rural water use,
- fisheries,
- recreation and tourism,
- human health,
- hydroelectric power,
- navigation,
- municipal water supply,
- reservoirs, and
- industrial and commercial enterprises.

Agriculture and Rural Water Use

Water Resources and Agriculture: An Important Link

Changes in water availability is one of the most significant concerns for agriculture. Water is already scarce in much of the plains areas of Canada, and according to Rosenberg and Katz (1991), it will become more scarce and expensive for future generations as water quality is degraded, underground supplies diminish, and competition for surface water increases. Furthermore, if inter-year variability in precipitation changes such that the probability of extreme events (e.g.,, droughts) increases, irrigation in some regions may become necessary, while in other regions, flood damages would be of greater concern.

Implications of water resources induced changes in agriculture may range from very macro issues (e.g., food security), to very micro level issues (e.g., management decisions on farms such as irrigation). In Canada, having an exportable surplus of most cereals, is affected by climate variability. However, as described for the United States by Adams *et al*. (1995), reductions in crop yields can have economic consequences for some regions, and may result in an inter-regional shift in production patterns.

Climate Change Impact on Agricultural Water

Impacts of climate change on agriculture vary in nature and magnitude. Each region of Canada will face a different challenge. Throughout most of the regions of Canada, climate change is expected to bring with it both improved opportunities and increased limitations (Smit, 1989b). Agricultural water use consists of three major types:

- water use for irrigation;
- water needs of livestock; and
- water needs for other farm operations.

In terms of agriculture, the following water-related factors are directly affected by climate change:

- amount of precipitation;
- timing of precipitation;
- extreme events;
- changes in soil moisture; and
- changes in temperature affecting evapotranspiration.

Research by Bootsma *et al*. (1984) in the Annapolis valley in eastern Canada, suggest a rise in temperature (with no precipitation changes) may reduce crop yields, but estimated yields increase if precipitation levels increase. Stewart and Muma (1990) used a $2xCO_2$ scenario (based partially on three GCMs) to suggest that potential for corn, soybeans, and winter wheat would increase significantly in the eastern region because the *precipitation: potential evaporation* ratio would be lowered to more optimum conditions (Bootsma, 1997). In eastern Canada, changes in the timing and intensity of precipitation could change reservoir storage and soil moisture levels. Both of these would affect agriculture directly as well as indirectly (Houtman, 1994).

Bootsma (1997) noted that few studies have looked specifically at CO_2-caused climate change impacts on agriculture in eastern Canada. But studies have examined agriculture's sensitivity to temperature and precipitation changes. Bootsma suggested that changes to wetter or drier conditions could have both positive and negative impacts in Atlantic Canada. For instance increased moisture supply would lessen drought-caused yield reductions, increase the occurrence of diseases, reduce available time for field work, and led to increased soil erosion. On the other hand, decreased soil moisture would have an opposite effect (Bootsma, 1997).

In Québec, increases in precipitation and soil moisture would reduce the need for supplementary irrigation. However, stockwater needs may increase partly due to the increased needs of animals, and partly due to changes in livestock numbers. Singh and Stewart (1991) found that Québec yields for some corps such as corn, soybeans, potatoes, and sorghum would increase, but yields for cereal and oilseed crops (e.g., wheat, barley, oats, sunflowers and rapeseed) would decline under a GISS climate change scenario.

In Ontario, Brklacich (1990) has suggested the need for irrigation in the southwest part of the province for grain corn, soybeans, and wheat. However, estimated yields may not be any higher than the present levels, since the estimated temperatures are beyond the optimal range, and the crops may suffer from heat stress. This will undoubtedly lead to lower farm level profitability.

In western Canada, the agricultural activities are more dependent on climate, although according to Goos (1989), crops in general, and cereal crops specifically, are much more dependent on climate than livestock. It is anticipated that crop production on the Canadian Prairies will become more vulnerable to droughts, as slight increases in precipitation are outweighed by substantial rises in potential evapotranspiration (Jackson, 1992). For the Prairies as a whole, studies have estimated an increase in the land base due to the northward expansion of production, which would be suitable for forage production. Unless additional suitable markets are found, these forages may have to be disposed off through livestock, which may increase stockwater use.

Information on the effect of climate change on the agriculture in the northern Canada is scanty. Goos and Wall (1994) state that should climate change occur as expected, the presence of ice and permafrost will be reduced throughout the north, which may have implications for the regional economic activity. Brklacich *et al.* (1997) suggested that agriculture in the Mackenzie Basin could benefit from climate change. That is, agriculture in the region could benefit due to the longer growing season, however, expanded agriculture would be required in order to make a commercial operation viable.

Irrigation Practices

Agricultural production in arid and semi-arid regions of Canada (such as interior of British Columbia, Southern Alberta and Saskatchewan) is very much dependent on water availability. Here, deficits in soil moisture are typically minimized through the use of supplementary irrigation. Moreover, dependence on irrigation in the various regions of Canada differs, with eastern Canada having minimal irrigation, and western Canada (particularly Alberta and British Columbia) showing greater use and dependence, as shown in Table 1.13. In western Canada, 82% of total industrial water withdrawals are related to irrigation (Lawford, 1990).

A warmer climate will affect irrigation by increasing evapotranspiration, and thus decreasing the water supply, which could trigger important social and economic effects (Peterson and Keller, 1990). Dudek (1989) has suggested that farming in arid and semi-arid regions dependent upon irrigation are particularly vulnerable to climate change. For Alberta, Byrne *et al*. (1989) estimate water shortages in the Oldman sub-basin. In parts of Manitoba, since soil moisture will increase, climate change may not necessitate additional irrigation.

For more detailed information concerning the impact of climate change and variability on agriculture, please refer to Chapter 4.

Table 1.13: Cropped Area and Irrigation in Canada, by Province

Province	Cropped Area in 1986 (000 ha)	Irrigated Area in 1988 (000 ha)	Ratio of Irrigated to Total Area
Newfoundland	40	0.05	0.0013
Prince Edward Island	300	0.25	0.0008
Nova Scotia	400	0.80	0.0020
New Brunswick	400	1.50	0.0375
Québec	3 600	40.00	0.0111
Ontario	5 600	42.00	0.0075
Manitoba	7 700	21.00	0.0027
Saskatchewan	26 600	105.00	0.0039
Alberta	20 700	565.00	0.0273
British Columbia	2 400	118.00	0.0492
CANADA	67 800	893.60	0.0132

Source: Figures on area obtained from Shady (1989). Last column estimated by authors

Rural Water Use and Climate Adaptation in Ontario: A Case Study

While the municipal, manufacturing and, especially, power generation sectors are the largest withdrawers of water in Ontario, agricultural users are estimated to account for 32% of total water consumption (Vandierendonck, 1996). Almost 2.4 million domestic users (22% of Ontario's population) not on municipal water services are estimated to contribute another 3% of consumption. Further, an unknown number of manufacturing, mining, municipal and other users compete with agricultural and rural domestic users for water supplies. Despite Ontario's apparent water wealth, Gabriel and Kreutzwiser (1993) found that scarcely a year goes by without water shortages for some uses in some parts of the province. Withdrawals, particularly of groundwater, are increasingly a source of conflict among rural and other users (See Hofmann, 1994; Hofmann, 1996; Leadlay, 1996). Climate variability periodically intensifies competition and conflict among users by decreasing supply, while often increasing demand. Anticipated climate warming will only exacerbate this situation (Wall and Sanderson, 1990; Koshida *et al*., 1993).

Little is known about rural water use in Ontario and many other parts of Canada. Rural water uses are rarely metered or monitored, and information on the impacts of, and responses to, dry spells is often anecdotal. In a survey of rural property owners in selected southern Ontario townships (Kreutzwiser, 1996), 35% of respondents reported experiencing a water quantity problem during the 1988 drought or subsequently. Drilling new wells, irrigating crops, deepening existing wells, and trucking in water for domestic use were the most frequently mentioned responses aimed at increasing water supplies. Reducing outdoor water use and installing domestic water-saving devices were the most frequently mentioned responses directed to reducing water use during shortages. These responses represent only a few among many possible adaptations to climate variability and change.

Fisheries

For inland freshwater fisheries, two important water-related factors are directly affected by climate change, they are:

- water quantity (e.g., lake levels, stream discharge/flow)
- water quality (e.g., water temperature) (McBean *et al*., 1992)

For the most part, climate change scenarios (as discussed in the hydrology section) suggest changes in these factors which would negatively impact fisheries.

Fishing is generally categorized as commercial, sport, or indigenous. Although these three types of fishing activities occur simultaneously, the various activities dominate in different regions. For instance, in the Atlantic and Pacific coasts commercial fisheries dominates, but in the Great Lakes sport fishing is most important. The landed value of commercial fishing in the Great Lakes in 1985 (Can and United States) was about $US 41 million whereas sport anglers are estimated to have spent about $US 2 billion in the same year (Jackson, 1990, 53). Indeed, hydrological changes caused by climate change can have significant economic and environmental effects on fisheries.

Water Quantity

Researchers have projected decreased river flows and lower lake levels throughout much of Canada due to climate change (*Hydrology: Climate Change and Variability*) which will have implications for fisheries. For example, the size of fish populations follows changes in streamflow since it is a measure of physical habitat space. The same is true of lake levels; a reduction in lake levels reduces the amount of habitat available. Overall, these various types of water quantity measures reflect available habitat space. There will also be increased competition for habitat among fish species and within fish species.

“Instream flow” has become an area of research focus where the negative impacts from human activity (such as hydroelectric projects) have been related to fish habitat. “Numerous statistical models show that standing crop or abundance of stream fishes is positively related to streamflow. For example, inter-annual variability in the number of Atlantic salmon parr in a Québec river from 1971-1977 has been related to seasonal streamflow” (Regier and Meisner, 1990, 12). In a study of trout in a Montana creek, a 62% decline in flow reduced the total number of trout by 90% (Regier and Meisner, 1990).

For migrating species, such as various salmonids, changes in stream discharge could also have negative effects on the population (McBean *et al*., 1992). In addition, spawning routes that are difficult to travel at present may become impossible to traverse (e.g., dried up streams). Not only are populations of a species susceptible to changes in water quantity, but the survival of the entire species may be affected. Some species may no longer be able to survive in areas where water declines have been substantial because the habitat has become unsuitable. On the other hand, other species may move in if the habitat is suitable for their needs.

Table 1.14 illustrates the importance of climate upon various lifecycle phases of fish found in British Columbia.

**Table 1.14:
Interactions of British Columbia Fisheries with Changes in Local Climate (Life history events affected by climate)**

Fishery	**Spawning Life**	**Early Sea Life**	**Adult**	**Migration**
Salmon (all species)	◆	◆	◆	◆
Herring	◆	◆	♦	♦
Halibut, Cod, Sole, Rockfish, etc.	♦	♦	⬩	⬩
Tuna	⬩	⬩	⬩	◆
Mackerel	⬩	⬩	⬩	◆
Pilchards	⬩	⬩	⬩	◆
Anchovy	♦	⬩	⬩	◆
Crabs	◆	◆	⬩	⬩
Shrimps	◆	◆	⬩	⬩
Prawns	◆	◆	⬩	⬩
Oysters and Clams	◆	◆	⬩	⬩
◆ ♦ ⬩	Legend large or most affected moderately affected small or least affected (adapted from McBean *et al.*, 1992, 12)			

Water Quality

Fisheries will be affected if water quality declines due to climate change. The *Hydrology: Climate Change and Variability* section described possible changes in water quality due to climate change and variability:

- temperature;
- oxygen (inverse relationship between dissolved oxygen and water temperature);
- flow and assimilative capabilities; and
- nutrients.

Water quality changes alter fish habitat. Impacts are positive and negative, and include:

- higher/lower production rates;
- the decline/increase of a population;
- the elimination of a population; and

- the introduction of a more tolerant exotics (McBean *et al.*, 1992; Regier and Meisner, 1990; Magnuson *et al.*, 1990).

The effect of climate change will depend on the suitability of the altered habitat for each particular species. Climate change/variability may cause habitat to become more suitable for some species and less suitable for other species. The ability to tolerate environmental changes varies among fish depending upon their tolerance levels. For instance, some species can not tolerate lowered dissolved oxygen conditions and warmer temperatures (e.g., trout) and would be affected negatively by climate change. For greater detail on water quality and fish, please refer to the Fisheries Chapter of the CCS.

Water temperature is a major factor in the distribution of fish species (Jackson, 1990). Fish are heterothermic ectotherms whose body temperatures are within a few tenths of a degree of the water temperatures in their habitat (Magnuson *et al.*, 1990). Habitat temperature directly influences their physiology and behaviour (Magnuson *et al.*, 1990). Changes in temperature can expand or decrease the size of available thermal habitat. Temperature, as a result, defines the northern and southern limits of fish species and the distribution of fish within a lake or river.

A change in mean annual temperature of 1°C may cause the retreat or extension of species for hundreds of kilometres or the complete loss of genetically unique stocks (Jackson, 1990). Water temperature also causes changes in the circulation patterns and turnover of water bodies, which has considerable implications on fish habitat. The fish in the Gulf of St. Lawrence may be particularly sensitive because many species in the Gulf are currently at the northern or southern limits of their distribution (Jackson, 1990). McBean *et al.* (1992) suggested that climate warming could cause the successful migration of non-salmonid warm-water species from southern portions of the Columbia River system. Climate change is not expected to eliminate existing species in British Columbia, but it could cause southern latitudinal margins to move northward and shift elevational limits upward (McBean *et al.*, 1992). Similarly, due to temperature related shifts, the invasion and expansion of several species in the Great Lakes including several minnow and sunfish species may occur (Minns and Moore, 1992).

Studies have been conducted to determine the climate change/variability impact upon fish habitat in lakes, particularly in the Great Lakes. Magnuson *et al.* (1990) estimated potential changes in the size of thermal habitat of representative cold-, cool-, and warm-water fish for southern Lake Michigan and the central basin of Lake Erie. Their research indicates that “the sizes of the habitat favorable for cold-, cool- and warm-water fish would increase in Lake Michigan whereas the habitats favourable only for cool- and warm-water fish would increase in Lake Erie” (Magnuson *et al.*, 1990, 25). Impact studies have also been undertaken for fish species in rivers. Meisner (1990) calibrated a hydrometeorological model of stream temperature for two southern Ontario streams (the Rouge and Humber Rivers) in the summer to estimate potential reductions due to climatic warming of thermal habitat for brook trout. Summer thermal habitat for brook trout in the streams declined by 42 and 30 per cent. Table 1.15 summarizes some of the key impacts of climate change on fisheries in the Great Lakes.

Temperature also controls the rate of embryonic and larval development of fish, but other factors complicate the overall effect on fish populations. In terms of Pacific salmon and other fish that migrate in systems at temperatures close to a physiological optimum, small temperature increases could cause suboptimal conditions and severe prespawning mortality (McBean *et al*., 1992). The net effects of increased temperatures and decreased oxygen levels could be a decline in suitable summer habitat and increased frequency of "summer kill" (McBean *et al*., 1992).

Table 1.15: Fisheries Impacts in the Great Lakes

Species	Impacts
• smallmouth bass • largemouth bass • bigmouth buffalo	• northward extension of range
• lake trout • lake whitefish	• northward contraction of range
• brook trout	• contraction of range to stream headwaters • reduced populations due to competition with other trout for remaining habitat
• whitefish • yellow perch (south) • walleye (south)	• decreased populations due to increased egg and larval mortality or inhibited reproduction
• alewife • yellow perch (north) • walleye (north)	• increased populations due to increased reproduction and reduced mortality
• lake whitefish • northern pike • walleye	• decreased sustainable yield

(Meisner *et al*., 1987; Hartmann, 1990b)

Other Effects

Fishing operations may also be affected in other ways besides impacts on fish species. For example, Hartmann (1990a) suggested that lowered lake levels may cause dock/harbour access difficulties. This access is important for sport and commercial fishing. In addition, fish stocking programs (for commercial and sport purposes) may become less successful if the species used can not survive in the habitat provided (Hartmann, 1990b). A change in species stocked may be required. Jackson (1990) found that there may be an increase in aquaculture production under climate change. In 1987, aquaculture represented three per cent of the landed value of Canadian fisheries. This figure is expected to rise to 25% by the year 2000 partially due to climate change, but also due to the problems in fisheries stocks (Jackson, 1990).

For more detailed information concerning the impact of climate change and variability on fisheries, please refer to Chapter 5.

Recreation and Tourism

This discussion will be limited to recreation and tourism interests directly related to water including outdoor water-based recreation, and winter recreation. Much recreation occurs in, on, or along water. Climate change-induced changes on hydrology, such as increased precipitation, lower water levels, and reduced water quality, can have impacts on recreation and tourism opportunities and experience. For instance, it affects amenity and aesthetic value, recreation opportunities (e.g., flows too low), and overall enjoyment and recreational experience.

Outdoor Water-Based Recreation

Outdoor water-based recreation and other summer outdoor recreational interests may benefit from an extended summer season and increased temperatures. In terms of camping, Rogers (1994) suggested an increase in economic benefits of $US 14 million due to the extension of summer season. However, the impact of increasing precipitation, including extreme events has not been well documented. The following summarizes some recreational/tourism concerns of low water and high water levels. Much of the suggested impacts of climate change are derived from the studies conducted of extremely high/low levels that have occurred recently.

Low Water Levels

- Due to degraded habitat, or loss of wetlands, recreation activities that depend upon ecosystem production, such as fishing and birding may suffer (Hartmann, 1990b; Rissling, 1996).
- Lowered lake levels could expose more beaches; uses could adapt by moving along with the shoreline (Hartmann, 1990b; Wall, 1990). However, public access to beaches may become an issue. In addition, exposed mud flats and other impacts that lower aesthetic value may occur.
- Lowered lake levels may cause marinas to be "high and dry" and cause stranded boating facilities, leading to the long-term loss of marina and harbour access. Lowered levels may cause insufficient water depth in some bays, channels and marinas, congestion in deeper areas, dry rot of some ladders and docks, and damage to boats due to grounding (Rissling, 1996). This would affect sport fishing and recreational boating (Hartmann, 1990b; Wall, 1990; Rissling, 1996).
- Riverine canoeing opportunities could be reduced as river flows become too low during all but peak runoff periods (Hartmann, 1990b, 64).
- Due to lowered levels, shoreline and bluff erosion may be reduced and the exposure of beaches may lead to the development of protective dunes (Rissling, 1996).

High Water Levels

- High water levels, may cause various impacts in the recreation/tourism industry. Although GCM scenarios largely project decreased water levels for much of Canada, some areas may face increased water levels, particularly during extreme events (flooding). In an Ontario Provincial Park study, high water levels in the late 1980s caused the following damage (similar impacts could be experienced due to climate change): reduction in beach areas, loss of shoreline trails, camping limitations, erosion of beaches and dunes, deposition on beaches, damages to facilities (hydro-poles), flooding of docks, and reduction of operating budget due to clean up costs (Rissling, 1996). High water levels can cause negative effects on recreational boaters such as access problems to docks and launch ramps, insufficient clearance under bridges, damage to docks, flooding of dry land facilities, and flooding of marinas (Rissling, 1996).

- For shoreline property owners, including cottagers, high water levels may cause increased shoreline and bluff erosion, damage to homes (e.g., flooding) costing thousands of dollars (Rissling, 1996).

Winter Recreation

Winter recreation (e.g., skiing, ice fishing, snowmobiling) may be negatively affected by the warmer winter temperatures which would reduce lake ice cover duration and thickness; precipitation as snow; and reliability of snow cover.

Some research has been conducted concerning the impact of climate change upon downhill skiing. Given the change in precipitation form (e.g., more precipitation may fall as rain instead of snow), suggested by climate change scenarios, the downhill ski industry in southern Ontario could be decimated. Wall (1990) suggested an annual loss of $36.5 million (1985 dollars) in skier expenditures in the South Georgian Bay region and a $12.5 million (1985 dollars) reduction the Collingwood ski area. Areas in northern Ontario will not be as severely affected, since the economic value of the downhill ski industry is less important in northern Ontario than southern Ontario.

For more detailed information concerning the impact of climate change and variability on recreation and tourism, please refer to Chapter 12.

Hydroelectric power

Although there are numerous forms of energy that can be affected by climate change and variability, this discussion focuses upon the form of energy most reliant on water resources: hydroelectric power. Hydroelectric power stations are found throughout Canada. Climate is a major factor affecting hydroelectric power production. In 1986, the National Energy Board (NEB) estimated that hydroelectricity formed 12% of Canada’s energy source (Jackson, 1990). Climate change will have two major implications for hydroelectric power. First, effects on the production of hydroelectric power and second, influences upon the consumption of hydroelectric power. This discussion will focus upon the production of hydroelectric power.

Much of the climate change and hydroelectric power research completed has focused upon the Great Lakes. The Great Lakes are extensively used for hydroelectric power production. Significant inter-annual variations in precipitation (consequently streamflow, lake levels, etc.) and/or significant reductions in precipitation (and consequently streamflow, lake levels, etc.) would reduce the productivity of a generation site. The reliable flow in the Great Lakes makes the siting of hydroelectric power facilities in the Lakes desirable. However, the flows in the connecting channels of the Great Lakes are not constant; since 1962 average annual Niagara River flows have varied from 161,800 cubic feet per second (cfs) to 253,300 cfs. Net annual generation at the [U.S.] Niagara Power project and the St. Lawrence-FDR Project varied from 9,550 to 18,000 GWH (gigawatt hours) and from 5,430 to 7,790 GWH, respectively (Jackson, 1990).

Although not as severe as climate change projections, record low levels and flows in the 1960s caused production losses of between 19-26% on the Niagara and St. Lawrence Rivers (Hartmann, 1990a). Losses in hydroelectric power generation are important since this form of energy production is relatively inexpensive and nonpolluting when compared to the primary alternatives, fossil fuel or nuclear power facilities (Hartmann, 1990a). Lower lake levels caused by climate change combined with increased consumptive use of water could result in a loss of 4165 GWH of power generation for the Canadian hydroelectric generating stations on the Great Lakes (Sanderson, 1987; Jackson, 1990; Wall, 1990). Ontario Hydro would have to find $111 million (1984 dollars) to replace this lost production with nuclear and fossil fuel generation (Sanderson, 1987; Wall, 1990).

The full impact of climate change and variability on hydroelectric power production, relies also upon changes in energy demand. It has been estimated that increased temperatures would cause lower energy demands in winter, but a slight energy increase in the summer (e.g., air conditioning) resulting in an average annual savings between $61-92 million (1984 dollars) (Sanderson, 1987; Wall, 1990).

Sanderson (1987, 4) found that shorter ice season in the Great Lakes would impact hydroelectric power production:

> *"At present an iceboom is placed near the head of the Niagara River to reduce the probability of ice blockages that reduce flow to the hydro power plant intakes. The expected reduction in Lake Erie ice cover under this $2xCO_2$ climate scenario would reduce the adverse effects of ice and shorten the duration of ice impacts on hydro production. In the St. Lawrence River, the operational practice is to form a stable ice cover. With warmer temperatures there will be fewer years during which ice cover forms, but there may also be an increase in the frequency of years during which ice is present but a stable cover can not be formed. For this reason $2xCO_2$ climate may necessitate changes in operating practices at the St. Lawrence stations".*

Singh (1987, 1988) assessed the impact of climate change scenarios on the hydrology on the La Grande, Caniapiscau and Opinaca-Eastmain Rivers that are part of the James Bay Project. Scenarios indicated an increase in runoff in these basins which would enhance hydro production. Jackson (1990) noted that although important in Canada, a surprisingly limited amount of research (with the exception of the Great Lakes) had been conducted concerning hydroelectric power and climate change.

For more detailed information concerning the impact of climate change and variability on hydroelectric power, please refer to Chapter 7.

Human Health

Humans use water for a variety of "health" uses, including drinking, cooking, bathing/cleansing, and recreational purposes. Climate change and variability influence water quantity and quality in with significant implications upon human health. Degradation, particularly of the quality of the water, could cause serious human health issues.

Hydrologically related effects include:

- exposure of contaminants through lower water levels and dredging activities;
- lowered assimilative capacity for treatment plants;
- closure of beaches (e.g., bacterial pollution after storms or due to low flows); and
- increased frequency of municipal water contamination (i.e., leading to sickness, etc.).

Climate change is expected to result in increased occurrences of extreme events. Extreme events are of particular concern for human health issues. Such events can cause direct harm to humans (e.g., drowning in floods). Other possible harm include:

- After heavy rainstorms excessive amounts of stormwater can exceed the capacity of treatment plants and sewage water may be released. In older systems storm-sewers and sewage sewers are often combined in combined sewers. Sewage can be combined with storm runoff when the capacity of the combined sewers is exceeded and this "mixture" is then released into water channels in order to cope with the system overflow. Floods may cause similar problems. This lack of treatment may cause the outbreak of various diseases.

- Heavy storms create breeding sites for insects or favorable conditions for rodents that carry diseases. Destruction or contamination of shelters and contamination of water supplies leaves human populations potentially more exposed to infectious vectors increasing the potential for epidemics (e.g., diarrheal diseases). For example, unusually large amounts of precipitation led to the outbreak of toxoplasmosis in British Columbia in 1995. The excessive rainfall lead to higher runoff which contaminated a reservoir with oocysts from domestic and wild cats (Centers for Disease Control, writ. comm., 1995).

- The disease malaria is spread by mosquitoes. The breeding sites of mosquitoes are water dependent and are influenced by water tables, river speed, water-level fluctuations and tidal movements which could be impacted by climate change. Under the CCCGCMII scenario, two types of malaria could occur in Southern Ontario given the warm temperatures required for the malaria-carrying mosquitoes (Duncan, 1996).

- Cryptosporidiosis causes severe diarrhea in children and can be fatal to immunocompromised individuals; it is one of the most prevalent water borne diseases in Canada. The disease is associated with dairy farms, domestic stock and water associated contamination. Natural events (e.g., floods, storms, heavy rainfall, snowmelt and swollen rivers) wash material of fecal origin, primarily from agricultural non-point sources into potable water. A Cryptosporidiosis outbreak occurred in the

Regional Municipality of Waterloo in 1991, and is believed to have contributed to one death. Under climate change the frequency of cryptosporidiosis may increase.

Hydrological variability can also cause problems for human health. Bacteria, viruses, or parasites (which cycle through cold-blooded insect vectors to complete their development) are sensitive to climate variability. In addition, diseases carried by small rodents, whose populations strongly depend on their immediate environment respond to climate and hydrological changes. For instance, the pulmonary hantavirus epidemic in the southwest United States may be attributed to increases in rodent populations caused by six years of drought, followed by extremely heavy spring rains in 1993. A 10-fold increase in the population of deer mice (which carry hantavirus) resulted.

For more detailed information concerning the impact of climate change and variability on Human Health, please refer to Chapter 11.

Navigation

Sanderson (1987) noted that water transport is the most efficient means of moving bulk cargo and that the Great Lakes-St. Lawrence Seaway is the busiest waterway in the world. Of all forms of transport, water transport is the most susceptible to changes in economic conditions because of its heavy dependence on resource-based commodities. For example, in the late 1980s and early 1990s, shipping has been negatively affected by the economic recession and a severe drought that drastically decreased the 1988 wheat harvest (Statistics Canada, 1994, 100). There are two key climate change/variability issues concerning navigation. First, the projected decline in water levels in many freshwater systems throughout Canada. And second, the projected shorter ice cover season and subsequently longer shipping season.

Decline in Water Levels

Shipping relies heavily upon adequate water levels. The section on *Hydrology: Climate Change and Variability* outlines the projected changes under various climate change scenarios. Under a 2xCO_2 scenario in the Great Lakes, mean flows in connecting channels may be reduced by 20-40% (including losses due to increased consumptive uses of water) (Jackson, 1990). The low water levels typical of the 1930s and 1960s could become the norm (Jackson, 1990). If lower water conditions occurred, numerous negative impacts would result as summarized in the following:

- Given the lower water levels, cargo loads would have to be lightened, thus more trips would be required to transport the same amount of cargo (Hartmann, 1990a and 1990b; Wall 1990; Sanderson, 1987; Marchand *et al*., 1988).
- There may be a need for costly dredging of channels (Hartmann, 1990a and 1990b; Wall, 1990; Sanderson, 1987; Marchand *et al.*, 1988). If channels are not dredged, costs could rise by up to one third due to lowered cargo loads (Wall, 1990; Sanderson, 1987). Some severely contaminated areas such as the Areas of Concern identified by

the International Joint Commission, may be restricted from dredging due to governmental environmental legislation (Hartmann, 1990a and 1990b).

- Increased traffic may result causing backups at current "bottlenecks" (such as locks) in the system (Hartmann, 1990a and 1990b).
- Overall, increased costs will be incurred by navigation operators (Marchand *et al*., 1988; Sanderson, 1987; Hartmann, 1990a and 1990b; Jackson, 1990; Wall, 1990). Sanderson (1987) and Marchand *et al*. (1988) estimated Great Lakes shipping costs would increase by 30%. Cohen (1986) suggested that annual navigation economic loses would be approximately $27.8 million (United States dollars) in the Great Lakes.

However, the costs of lowered water levels would be offset by the benefits of a longer shipping season as discussed below.

Longer Shipping Season

Currently, numerous shipping channels in Canada are closed for parts of the winter season due to the ice cover. Ice extends over much of the Great Lakes and St. Lawrence River during the winter months. Similarly, ice limits shipping in the Canadian Arctic Archipelago and Mackenzie River to a very short summer ice-free season. These limitations are illustrated by the six-week commercial shipping season for the Port of Churchill (Jackson, 1990). However, projections under various climate change scenarios suggest a longer shipping season in most parts of Canada due to increased temperatures and longer ice-free periods (Table 1.16).

Table 1.16: Summary of Navigational Impacts In Canada

Area	Climatic Change	Navigation Impacts
Marine Arctic	Reduction in ice cover	• longer shipping seasons in Labrador, Hudson Bay, etc.; more use of Port of Churchill for grain, arctic resupply, etc. • more shipping in high arctic; possible greater need for search and rescue, navigation aids. etc.
Marine-Mackenzie	Less ice cover, higher water levels	• longer season, increased draft and payloads
Marine-Great Lakes	Lower Lake Levels	• reduction in available draft and efficiency of lake fleet leading to higher shipping costs • possibly could be mitigated by structures to control lake levels
	Less Ice Cover	• makes 11 month or year round navigation more feasible

(modified from IBI Group, 1990, 4)

Under a $2xCO_2$ climate change scenario, the following average maximum ice covers declined (current average maximum ice cover in brackets): Lake Superior 0% (72%), Lake Michigan 0% (38%), Lake Huron 0% (65%), Lake Erie 50% (90%), and Lake Ontario 0% (33%) (Sanderson, 1987). These statistics show that ice cover will be drastically reduced. It is estimated that this longer ice-free season will increase the shipping season in the Great Lakes-St. Lawrence by one to three months (Sanderson, 1987; Wall, 1990).

Jackson (1990) stated that with an ice-free Gulf of St. Lawrence and Atlantic Coast, annual operation costs (e.g., icebreaking) of $18.5 million would be eliminated. However, he noted that increased marine activity would also increase costs for buoy tending and search/rescue.

Jackson (1990) also warned that other factors beyond a longer shipping season impact the viability of navigation. For instance, Churchill, Manitoba would appear to benefit from a longer shipping season; however, the amount of grain recently shipped through the port has been at a 60 year low. Market forces, especially the competition from Thunder Bay determine the viability of the Port. However, recently Churchill has become popular as a cruise destination and this popularity is expected to increase due to the impacts of climate change (Jackson, 1990). There is a need for more research not only concerning navigation, but the integration of navigation with other sectors.

Municipal Water Supply and Demand

Under current climate, the human demands for water are increasing due to population growth and economic development, and demands will further increase under a warmer climate requiring more intensive water resources management (IPCC, 1996). Lawford (1990) suggested that if the current trends of increasing demand in western Canada continue, water demand would approach availability at certain times in the year. However, improved management of water infrastructure, pricing policies, and demand-side management of supply have the potential to mitigate some of the impacts of increasing water demand (Mitchell and Shrubsole, 1994; Frederick and Gleick, 1989).

Climate Change and Municipal Water

A study in the Grand River by Robinson and Creese (1993) found climate change would cause important changes to the municipal water systems of Cambridge, Kitchener and Waterloo. They concluded that:

> *"The water supply subsystem will be more affected on the supply side than the demand side. Annual maximum day water use will increase marginally in comparison with the BOC [basis of comparison] climate scenario. The effect is small enough that the uncertainty in the forecasting of future populations is enough to obscure it. The Mannheim artificial recharge scheme will be significantly impacted by a reduction in stream flow in the Grand River. With the BOC climate scenario, it will be 2024 before a new source of water is needed. With the GISS and GFDL scenarios this point will be reached five to six years earlier, and with the CCC scenario, eleven years later in the year 2013. The Mannheim scheme will also be affected by changes in water quality in the Grand River brought about by changing climate..."* (Robinson and Creese, 1993, 185).

Municipal Water Demands

In Cohen's (1987a) study, $2xCO_2$ scenarios using GISS and GFDL GCMs were used to project municipal water use in the Great Lakes area. Using regression models based on monthly potential evapotranspiration for May to September, summer water use is projected to increase by 5.6% in the GISS scenario and 5.2% in the GFDL scenario. If winter water use remains unaffected by climatic change, annual water use is projected to increase by 2.6% (GISS scenario) and 2.4% (GFDL scenario). Cohen (1987a) cautioned that the projections do not include extreme events, such as summer dry spells.

Municipal Lawn Watering Demands

Lamothe and Périard (1989) conducted a study of the use of municipal water for residential lawn watering in Québec. This watering has been a concern since the 1970s given the large amounts consumed and the costs involved. One hour of lawn watering is estimated to use the same quantity of water as a family of five in one day (Lamothe and Périard, 1989). Watering lawns in the Québec City Region is estimated to cost $2.5 million (1979 dollars) annually. Climate change has become an additional concern. Lamothe and Périard (1989) suggested that climate warming will increase water demand for lawn maintenance by 20-30%. In order accommodate this increased demand, costly new infrastructure would be required. Lamothe and Périard (1989) maintain that regardless of climate change, it would be prudent to implement water conservation actions now. Examples of water conservation techniques include the implementation of water meters, effective water pricing schemes, lawn watering restrictions, and the use of drought tolerant grass varieties.

Climate Variability and Water Use

A study by Akuoko-Asibey *et al*. (1993) was conducted in Calgary concerning the impact of climate variability on water use. It was revealed that:

- weekly water consumption per capita remains fairly steady when mean maximum weekly temperatures are below 15°C;
- weekly water consumption per capita tends to increase with increasing temperatures especially when daily temperatures are above 15°C; and
- weekly water consumption per capita decreases with precipitation and that water use per capita does not fall below 400 million litres (ML), irrespective of natural rainfall in the City of Calgary (Akuoko-Asibey *et al*., 1993).

Long Term Planning: Municipal Water and Climate Change

Few municipalities incorporate the notion of climatic change in their long term planning. The Regional Municipality of Waterloo in its Long Term Water Strategy Grand River Supply Option report (by Paragon Engineering, 1994) recognized the need to take into account natural variations, variations caused by human activities, and climate change. To assess the possible impact of climate change on the Grand River supply option, Paragon Engineering conducted a series of reservoir yield simulations with all the river discharge inputs lowered. The assessment involved reduction of 5, 10, and 20% in all river discharges throughout the system (Paragon Engineering, 1994). The results are summarized below:

> *"As expected, as the percentage reduction in discharge increases, the reliability of achieving specified discharges decreases, and the minimum discharges in the river go down. Examination of the detailed simulation outputs indicates that the majority of the augmentation failures occur in the October to December period, as the reservoirs go into shortage more frequently. The reliability in meeting augmentation targets under conditions of reduced inflows could be improved by reducing the October target to the November to December level. ... However, the results indicate that there is still a relatively high reliability of achieving augmentation targets, even with a 20% reduction in flows. For example, with a 5% reduction in all river discharges, augmentation failures at Doon would occur on average for a period of one month in 3 years of the 39 years in the period of record. When a 20% reduction in discharges is considered, there would be 9 years when failures in meeting the augmentation targets would occur for a one month period. It must be recognized that these are average values, and it could well be that some years could have one or more months of shortage, while others may have only one or two weeks of shortage.*
>
> *When compared to the existing conditions, for which there is 100% reliability of achieving the Doon augmentation discharge and thereby abstracting 16 million imperial gallons per day (MIGD) it is clear that under condition of climate change, periods of shortage will occur. If abstractions beyond 16 MIGD are considered as previously described, during early spring and winter it would be possible to either rest or recharge the aquifers, to allow them to be stressed during periods of Grand River supply shortages. Nevertheless, the risk of shortage does increase under the climate change scenario. The number and duration of shortages would increase, mainly in the late summer and fall, and the severity of low flow conditions would increase" (Paragon Engineering, 1994, 30).*

Reservoirs

Burn and Simonovic (1996) assessed the impact of climate change on the Shellmouth Reservoir located in the western portion of Manitoba. Climate change will likely result in lower reliability for recreation and water supply demand and higher reliability for flood control for the Shellmouth Reservoir. The outcome is consistent with the work by Klemes (Burn and Simonovic, 1996). The Burn and Simonovic study found that reduced water availability will likely increase the occurrence of water shortages and thus reduced water demand reliability. Similarly, lowered reservoir storage capacity due to lower flow conditions is anticipated to lead to more violations of recreation requirements (Burn and Simonovic, 1996). Reduced flows may result in fewer flooding events and therefore greater flood control reliability. The researchers suggested that "there are apparently potential benefits that can be realized from reducing the current high priority placed on flood control and increasing the priority assigned to water supply and recreational purposes since flooding conditions are expected to occur less frequently under changed climatic conditions" (Burn and Simonovic, 1996, 476). Needless to say, this conclusion is not consistent with those researchers who believe that extreme events such as flooding will become more common under various 2xCO_2 scenarios.

Industrial/Commercial Enterprises

Industrial Enterprises

Industrial enterprises use water resources for (i) production processes and effluent discharge, and (ii) transportation. Examples of such enterprises include grain shipment, food processing, pulp and paper processing, petroleum refining, organic chemicals, metal mining and refining, iron and steel production, metal casting, metal plating and plastics fabrication (Hartmann, 1990b). Thus, lowered water levels (particularly in the Great Lakes) and lower stream flow would likely have negative impacts upon industrial enterprises.

Commercial Enterprises

Many commercial enterprises are successful due to their shoreline location or proximity to a water body, e.g., marinas, hotels, resorts, and restaurants. This relationship is particularly true for the Great Lakes. If lake levels decline as suggested in various climate change scenarios, these businesses will experience problems similar to those of the 1960s (Hartmann, 1990b). This includes such problems as reduced scenic views, inaccessible docking facilities, and unusable water intakes or waste disposal outlets (Hartmann, 1990b). Fortunately, some of these enterprises can adapt by moving with the shoreline. Unfortunately there are many enterprises (e.g., infrastructure) that can not adapt so easily. Other commercial business which may suffer from climate changes, include those reliant upon skiing, snowmobiling, ice fishing, and river boating (e.g., flows may be too low).

Conflict and Competition Over Water

There is the potential for competition and conflict over water if the significant declines in streamflow, ground water levels and lakes levels suggested by climate change scenarios are realized. There could be competition between water uses (e.g., consumptive and non-consumptive), upstream and downstream users, rural and urban areas, arid and non-arid regions as well as interjurisdictional water concerns. Often allocation of water to critical, immediate needs such as municipal water supply and irrigation can "overshadow" other uses such as instream biological uses (fish habitat, aquatic ecosystems), recreation, and navigation. This section highlights some of the water quantity issues in the Great Lakes-St. Lawrence Basin, the Saskatchewan River, the transboundary waters of the Prairies, the Mackenzie River Basin and rural ground water. Limited, variable water supplies also exacerbate water quality problems and there are potential issues over access to "high" quality water.

Lakes Superior and Ontario regulation plans have been designed based on historical sequences of water supplies and were found to lack robustness during simulations with more extreme conditions. For example, with the low net basin supply sequences, the minimum outflows called for by the regulation plans were greater than the water supplies to the Great Lakes. Lake levels fell below the lakes' lower regulation limits (Lee *et al*., 1994). The existing regulation plans were not designed for the low net basin supplies and connecting channel flows expected with climate change scenarios (Hartmann, 1990b). To maintain lake levels connecting channel flows would have to be reduced while maintaining connecting channel flows would reduce lake levels. Upstream, lake interest such as recreational boating, ecological resources (wetlands, fisheries), shoreline cottagers, marinas and would have to be balanced with downstream, riverine interest such as power production, port facilities, the St. Lawrence Seaway, and ecological resources (wetlands, fisheries). The Boundary Waters Treaty (1909) mandates a hierarchy of Great Lakes interests that must be protected or enhanced; they include: domestic and sanitary water uses, navigation, power and irrigation (Hartmann, 1990b). These priorities may have to be modified to consider other commercial, industrial, riparian, recreation and ecological interests as well. Most institutional arrangements for water resources management in the Great Lakes have focused on managing for an overabundance of supply. Climate change scenarios suggest that with declines in lake levels of 20 cm to 2 m and annual runoff decreases of up to 50%, the paradigm may have to switch to managing under conditions of water scarcity (Mortsch and Quinn, 1996).

The 1988 drought affected the Mississippi River shipping industry; barges were stranded due to low flow in the river. As a solution, Illinois and other down-river states proposed an increase in the diversion of water out of Lake Michigan at Chicago down the Illinois River to raise the level in the Mississippi Waterway. The flow of 3,200 cfs would be increased to 10,000 cfs for 100 days. Since the United States Supreme Court had set the diversion amount, the president would have to declare an emergency for the diversion to occur (Changnon, 1989). The other Great Lakes states and Canada objected and the U.S. Army Corps of Engineers refused to allow the diversion. Diversion of water out of the Great Lakes is an extremely sensitive interjurisdictional issue. In the United States, legal precedent in the 1980s on water controversies in Wyoming, Idaho, Oregon, and Colorado has made interbasin transfer legally possible. The signing of the Great Lakes Charter in 1985 was a response to proposals to divert water out of the Great Lakes to the Great Plains. However, some believe that the precedent for drought-created out-of-basin transfer to the Mississippi had been set in 1952-56 (Botts, 1981, Changnon, 1994). Climate change will lead to requests for enhanced diversions from the Great Lakes to serve water needs in and outside the basin for municipalities, navigation, hydrogenerating and agriculture. For example, urban water demands from large cities like News York and Philadelphia may increase diversion interest (Changnon, 1994)

The Saskatchewan River is an important reliable, high-quality alpine water resource for the semi-arid Great Plains region which is shared by the Prairie Provinces. There have been formal arrangements on water in place since 1948 but in 1969 the federal and provincial governments signed the Master Agreement on Apportionment. Its "..major provision commits Alberta to allowing one-half of the natural water flow arising in or flowing through Alberta to pass into Saskatchewan. Saskatchewan has a similar commitment to Manitoba..." (Pearse *et al.*, 1985 in Wittrock and Wheaton, 1992). The droughts of the 1980s put the Agreement to the test; individual jurisdictions had to make difficult choices to meet interjurisdictional commitments (Bjonback, 1991). Irrigated agriculture and reservoir evaporation are primary consumers of surface water in the Canadian Prairies (Bauder, 1991). Climate change scenarios where runoff decreases and consumptive use of water increases have the potential to lead to disagreements over water apportionment. In the South Saskatchewan Basin, alpine runoff supports some 500,000 hectares of irrigation in southern Alberta (there is approximately 650,000 hectares in all of the Canadian Great Plains). The strategic upstream location of a large user in addition to climate change scenarios which suggest decreases in soil moisture and reduced Rockies and Plains runoff would significantly reduce flows entering the province of Saskatchewan; this has major implications for Alberta's responsibilities to meet water requirements to Saskatchewan under the Master Agreement on Apportionment (Bjonback, 1991, 168-169). There could be growing conflict over upstream and downstream use (irrigation, hydroelectric generation, recreation, municipal and industrial use, waste assimilation, instream ecological requirements) and provinces could use more of their share. The Master Agreement of Apportionment "...is fragile since any of the parties could unilaterally pass legislation that would exempt it..." (Pearse *et al.*, 1985 in Wittrock and Wheaton, 1992). The role of such an institution in future economic development and environmental management is critical since many major rivers of the Prairies cross interjurisdictional boundaries.

Surface water is shared between the Prairie Provinces and the States of Montana and North Dakota (e.g., Souris-Red Rivers, St. Mary-Milk Rivers). Surface water in Alberta, Saskatchewan and Manitoba currently provide sufficient water to meet present and some future growth in demand but water in the international tributaries is beginning to be used to the extent of the full apportionment (Bauder, 1991). The 1980s were a difficult decade for this region. In nine out of ten years, the flow in the Milk River was below normal and six of ten years flows were below normal for the other Missouri tributaries. Significant problems were encountered in meeting irrigation and international flow apportionment requirements (Bjonback, 1991, 168). The 1980's experience could become the norm under the low water supply conditions of some climate change scenarios.

The hydrology and water resource base of the Prairie Provinces in the Great Plains is strongly influenced by the climate of the Rocky Mountains; a large portion of the water supply and its availability is controlled by snow and ice melt. The drier, United States of Montana, Wyoming, North and South Dakota and parts of Nebraska are more reliant on groundwater (Bjonback, 1991). In watersheds where there is more reliance on groundwater, the watersheds are not as well defined and the interrelationship between the land surface characteristics and the water resource are relatively unknown and not well documented or monitored; the effects of climatic change and variability will be more difficult to define and respond to (Bjonback, 1991). In many jurisdictions, surface water is legally apportioned but ground water is not. The Ogallala Aquifer is being heavily used for irrigation in the agricultural and cattle industry. Water supplies may be seriously depleted by 2020; to maintain the industries, new sources will have to be found elsewhere. Climate change scenarios exacerbate the situation. The Great Lakes have been considered as a source of water (Ashworthy, 1987; Botts, 1981).

In the Northwest Territories (NWT) of the Mackenzie River Basin, water and the river are a major component of the regional lifestyle. Climate change scenarios suggest significant changes in water levels and flows (Kerr, 1997). The NWT is downstream from British Columbia, Saskatchewan, Alberta and the Yukon and upstream changes in these jurisdictions will affect the region. It is very concerned that without protection through agreements with upstream jurisdictions, diversions of water would reduce flows and negatively affect the region (Mortsch, 1997). The Mackenzie River Basin Transboundary Waters Master Agreement will be a new mechanism to respond to the interjurisdictional water management of the river.

In southern Ontario, drought is a reoccurring problem. Some parts of the Province are affected almost every year. During dry spells, competition and conflict between rural users of groundwater and surface water emerge. Groundwater supplies are particularly vulnerable (Kreutzwiser, 1996). There has been conflict over rural water supplies for use in urban areas in Ontario (Hofmann, 1996; Leadlay, 1996). Climate change is expected to exacerbate recharge, drawdown and groundwater supply problems. Rural domestic water supplies are vulnerable (McLaren and Sudicky, 1993). Climate change may heighten current conflicts; the issue reinforces the need for proper water resource management, allocation and conflict resolution.

Concluding Comments

Table 1.17 summarizes some of the key gaps in knowledge concerning climate change and water-dependent sectors. For a more detailed analysis of gaps in the following sectors (i.e., not necessarily water specific), please refer to the appropriate sector.

Timmerman and Grima (1988) suggested that even though climate change may significantly influence social and economic structures, most research efforts have focused on biophysical aspects. They believed studies should be set within a framework of social understanding and economic analysis and that easily interpretable information should be provided to decision-makers (public and private) which would allow them to make the most efficient economic responses.

Changnon (1987) concluded that since climate impacts research is still in its infancy, definitive answers are not readily available. Decision-makers and policy makers need analyses of risks, opportunities and vulnerabilities in order to plan for climate change effectively.

CLIMATE CHANGE AND VARIABILITY: ADAPTATION

The previous sections have outlined the impacts of climate change and variability on the hydrological system and uses of water. This section focuses upon what should be done in terms of “adapting” to these impacts.

In the Great Lakes-St. Lawrence Basin Project, “adaptation” to climate change and variability implied the following:

- a process of change (behaviour, action, attitude, policy, decision-making); which
- leads to action(s) (passive, reactive, or anticipatory); having
- desired outcome(s) and an anticipated duration.

Table 1.17: Summary of Gaps/ Limits in Research

Area	Gaps
Agriculture	• Studies have focused upon the potential impacts, under the assumption that producers do not adjust. As a result, results tend to be more conservative and overestimate the negative impacts (Mendelsohn *et al*., 1994, 1996) • More research is needed on water conservation methods, including reducing the use of irrigation, and enhancing on-farm retention (Lawford, 1990) • Agriculture policy making and planning is not conducted with climate change in mind (Stewart *et al*., 1988)
Fisheries	• Studies have focused upon the Great Lakes and British Columbia fisheries; little is known about the Northern, inland and small lake fisheries. • Studies have involved more expert judgment than empirical evidence. • Lack of monitoring for current conditions, let alone for future conditions.
Recreation and Tourism	• Limited studies related specifically to water recreation, and mostly based on expert judgment than empirical evidence. • A major focus of research has been on downhill skiing in Ontario
Hydroelectric Power	• Only studied in Great Lakes and Québec (Jackson, 1990); Singh, 1987; Sanderson, 1987). • Few studies concerning hydro completed(e.g., no studies in British Columbia).
Human Health	• Limited research has been conducted concerning human health, and even less as it relates to water resources • Studies have involved more expert judgment than empirical evidence.
Navigation	• The limited research in this area has focused upon the Great Lakes, with some work in the North and Maritimes • Studies have involved more expert judgment than empirical evidence (except studies of Great Lakes).
Municipal Water	• Few studies have been completed concerning municipal water (Prairies) • There is a need for research on adaptation responses • Appears to be little municipal interest in planning for climate change (e.g., only one example found).
Reservoirs	• Few studies completed.
Industrial/ Commercial Enterprises	• No research completed

Adapting to possible impacts of climate change is important given the significance of the impacts. Impacts including increased precipitation, lower lake levels, lower streamflow, decreased water quality, decreased lake ice cover, and increased incidence of extreme events.

Simple, easy to implement adaptation strategies can be classified as “no regrets” measures. “No regrets” options have been gaining favour because they address known environmental problems in addition to climate change. They continue to be valuable from a benefit/cost perspective irrespective of the magnitude of climate change. Much of the discussion in this section will focus on “no regrets” options and very general adaptation strategies. However, for significant impacts such as a potential decline in streamflow of 50%, very specific, dramatic strategies will be required. More research is required on adaptation.

The Importance of Adaptation

Burton (1995, 7) suggested six reasons why we must adapt to climate variability and change now:

1. Climate change cannot be totally avoided. We are already committed to some change.
2. Anticipatory and precautionary adaptation is more effective and less costly than forced, last minute emergency adaptation.
3. Climate change may be more rapid and more pronounced than current estimates suggest. There is a possibility of nasty surprises.
4. There are immediate benefits to be gained from better adaptation to climate variability and extreme atmospheric events.
5. There are immediate benefits to be gained by the removal of maladaptive policies and practices.
6. Climate change brings opportunities as well as threats. There are future benefits to be gained from climate change.

The Economics of Adaptation

It is particularly important to implement adaptation strategies related to water and climate change because of the fundamental importance of water. But, there are also large economic benefits to adaptation.

In economic terms, water's contribution to the Canadian economy has been estimated to be between $7.5-$23 billion/year (Environment Canada, 1992). In comparison to other countries, Canada has an abundance of water. For instance, Canada has approximately nine percent of the world's annual freshwater runoff, and only one percent of the world's population (Bruce and Mitchell, 1995). Just as water is not distributed equally throughout the world, water is not distributed equally throughout Canada. This unequal distribution has lead to the use of irrigation systems in southern Alberta, the construction of water supply pipelines from London to Lake Huron and from Regina to the Qu'Appelle River (Bruce and Mitchell, 1995). This misperception of water abundance has often led to the misuse and abuse of water in Canada (Environment Canada, 1992).

Canada spends billions of dollars adapting to the current climate. As outlined in Table 1.18, it is expected that climate change will cause the costs of adaptation in water resources to rise. These adaptations include construction and expansion of dams, drainage ditches, and other flood or drought control mechanisms.

Table 1.18: Estimated Costs of Adaptation in Water Resources Management in Canada's Current Climate and Trends under Climate Change

Sector/Activity	Total Cost ($M)	Percent Attributable to Climate Adaptation	Costs of Climate Adaptation ($M)	Possible Trend Under Climate Change
Tile Drains, Drainage Ditches, Storm Sewers	852.6	75	639.5	increase
Water Storage Tanks	27.4	10	2.7	increase
Dams, Reservoirs	173.3	70	121.3	increase
Flood Control	4.7	80	3.7	increase
Total	1,058.0		767.2	

(Herbert and Burton, 1995; Mortsch, 1995)

This synthesis uses the following scheme to classify adaptation possibilities:

- share the loss;
- bear the loss;
- research;
- education (behavioural); and
- modify the events, prevent the effects, avoid the impacts (structural and non-structural).

Following a discussion of the above adaptation categories, a listing of more specific adaptation possibilities (e.g., to adapt to floods, drought, changes in streamflow, groundwater, lake levels, soil moisture, water quality, and snow/ice) and possible evaluation criteria are provided.

Share the Loss

Adapting by "sharing the loss", involves society at large or a larger group of citizens absorbing the costs for impacts. Adaptation measures include:

- government subsidies and grants (e.g., improved irrigation systems, expanded water supply systems, subsidies for fisheries);
- insurance (e.g., flood insurance, crop insurance, etc.); disaster relief (e.g., government provided, or collected through donations by other groups); and
- sharing water supplies (e.g., municipalities sharing water supplies).

The measure receiving the most attention is insurance. Please refer to Chapter 10 for more information and detail.

Researchers have voiced concerned over issues of maladaptation. For instance, government subsidies could be (and are currently provided) for tiling fields for drainage purposes. It has been suggested that such tiling efforts may increase under climate change (e.g., more intense storms, flooding). However, such drainage also reduces wetlands, which are currently under threat and may be more threatened under climate change.

Bear the Loss

If the adaptation method chosen is "bear the loss", each citizen is basically on their own to cope with impacts. For instance, in some floodplain areas, insurance is not offered. When living in such an area, citizens must be willing to accept the consequences (e.g., bear the loss). However, such citizens may be assisted by improved flood forecasting and flood warning or other improvements, which may assist in reducing damage, but they are still responsible for all damage costs.

It is important that citizens are aware of the potential losses and make informed choices in locating in vulnerable areas. Such information could be attached to a deed of a property.

Research

Gaps in Canadian Water

There are gaps in the current knowledge of Canadian water. These gaps not only hinder water management in absence of climate change, but also complicate attempts to adapt to projected climate change impacts and scenarios. There are numerous adaptation strategies that improve the current management of water, as well as under climate change conditions. That is, if water was better managed today, it would be advantageous for conditions under climate change. Some of these strategies are referred to as "no regrets" strategies because they are beneficial under current conditions and also assist in the adaptation to climate change. They address current environmental concerns as well as future ones under climate change.

Data, information, knowledge, and improved understanding of the sources, quantity, dependability and quality of water are imperative for effective water management and there is a need for improved research (Figure 1.13 (Hofmann and Davidson, 1997; Mitchell and Shrubsole, 1994). Given the size of Canada and the amount of water within its borders, this is indeed a formidable task (Government of Canada, 1992, 2).

Figure 1.14: Differing levels of Research

Data → Information → Knowledge → Understanding

A perceived problem in information gathering which needs to be addressed is the "data rich, information poor syndrome". In this "syndrome" the emphasis is on data collection with lesser attention provided for the equally important analysis of the data (Mitchell and Shrubsole, 1994).

Moreover, in many instances, data are gathered for specific projects with limited scope and geographic area reducing its usefulness to other projects. In addition, there is often overlap in the data collection activities.

Indeed there are many areas where there is inadequate information concerning water in Canada: groundwater; northern regions hydrology, cold regions, small lakes, rural water, and water quality.

Groundwater in particular, has been seriously neglected in Canada (Bruce and Mitchell, 1995; Hofmann, 1996). There is limited understanding of the behaviour of groundwater and concerns over numerous forms of pollution (Bruce and Mitchell, 1995; Hofmann, 1996). For instance, over 35% of rural wells in Ontario are polluted with bacteria or nitrates and Environment Canada predicts that 5-10% of the 150,000-200,000 underground storage tanks are leaking (Bruce and Mitchell, 1995). This current lack of knowledge about groundwater in Canada, complicates the research concerning climate change and variability.

Wasny (1986) found that there is a significant gap particularly concerning urban-water issues and other more socio-economic issues because much of the research focus has been on physical processes of the hydrological cycle. Approximately 80% of total water research funding in 1983 was directed to water cycle and quality issues, whereas about four per cent was directed to all economic, social, legal and institutional research (Wasny, 1986). It is not surprising that there are numerous gaps in the climate change literature concerning economic, social, legal and institutional research, particularly as it pertains to adaptation.

There has been an increasing trend towards specialization, both in topic and geographic area, in water research (Wasny, 1986). Although specialization is needed, there is increasing need to synthesize the different fragments and formulate a "bigger picture". Moreover there is a need to recognize that research is a means, not an end of generating beneficial change to Canada water management (Wasny, 1986).

The *Hydrology: Climate Change and Variability* and *Water Resources: Climate Change and Variability* sections outlined gaps in the current knowledge where research is needed. These areas include (and are similar to the gaps of knowledge in water resources, regardless of climate change):

- precipitation;
- evapotranspiration;
- runoff;
- lake ice;
- permafrost;
- water quality;
- northern regions;
- small lakes;
- rural water supplies; and
- groundwater.

Education/Behaviour

The Framework Convention of Climate Change recognized the need for public education, participation and access to information in response to climate variability and change (CCPB, 1994). The Canadian Climate Program Board (CCPB) (1994) recognizes that advances have been made in public education, but admits that many citizens are misinformed about climate change research and have misperceptions about the climate change issue. For example, many believe that climate change is a result of industrial pollution and that they can not personally take actions to help. It is important that citizens receive relevant and accurate information.

Moreover, it is essential that citizens be involved in the development of adaptation strategies (CCPB, 1994). However, the citizen level is but one level where education and involvement in adaptation strategies is needed. Since adaptation will affect all levels of society, e.g., individual, organizational and political levels, communication about the human significance of climate change is needed at all levels (Smith and Lenhart, 1996).

The following outlines some of the key groups which should be targeted for communication activities:

- individual citizens;
- impacted sectors (e.g., agriculture, forestry, water, navigation);
- politicians;
- industry;
- impacted/vulnerable regions;
- other researchers/scientists; and
- decision-makers/policy-makers.

The Process

The misperceptions (as noted above) held by the public concerning climate variability and change are found in many other environmental issues. Processes used for decision-making and for information dissemination affect the perceptions of the public. It is important that the process used (e.g., public participation programs) are effective in ensuring the decimation of information. This decimation of information is two-way. Decision-makers and researchers can learn from the public, and the public can learn from the decision-makers and researchers.

For example, until recently, citizens did not feel they could effectively assist in the waste management problem until the introduction of the Blue Box program with intense public education and involvement programs. Similarly, water conservation programs, although arguably not as successful, emphasize the need for citizen assistance. The misperceptions and misunderstandings of the public are largely due to how decisions are made and the lack of public involvement or communication with the public. Increasingly there is a recognition that the traditional top-down, centralized, expert-driven, and technical process has its limitations for environmental decisions (Armour, 1992; Child and Armour, 1995; Hofmann, 1996; Mitchell and Shrubsole, 1994). Instead, these researchers believe that bottom-up, decentralized approaches with high levels of public involvement are more effective.

Not only should the public be better informed about climate change and adaptation (e.g., through public participation programs), decisions made to adapt to climate change (e.g., new water conservation programs, new infrastructure) also require public consultation. In terms of decision-making, Wondolleck (1985) explained that environmental managers must realize that their most important contribution to an issue is not in the final decision, but rather the process used (e.g., who was involved, extend of involvement, information used, alternatives used, analysis used, etc.). There are often two factors at the heart of many decisions: the legitimacy of the decision-making process and the public's acceptance of the decision (Armour, 1992). Armour (1992, 32) explains that "... people will not willingly consider the merits of a decision if they feel they have been treated unfairly in the process of reaching it". Rather than persuading the public, Armour concluded that structuring the process in order to achieve publicly acceptable decisions is more effective.

Public Participation

Given this emphasis on process, it is not surprising that there is a general consensus in the literature that public participation is an essential component of environmental decision-making (Mitchell, 1989a; Law and Hartig, 1993; Child and Armour, 1995; CORE, 1995). There are many benefits to public participation, including:

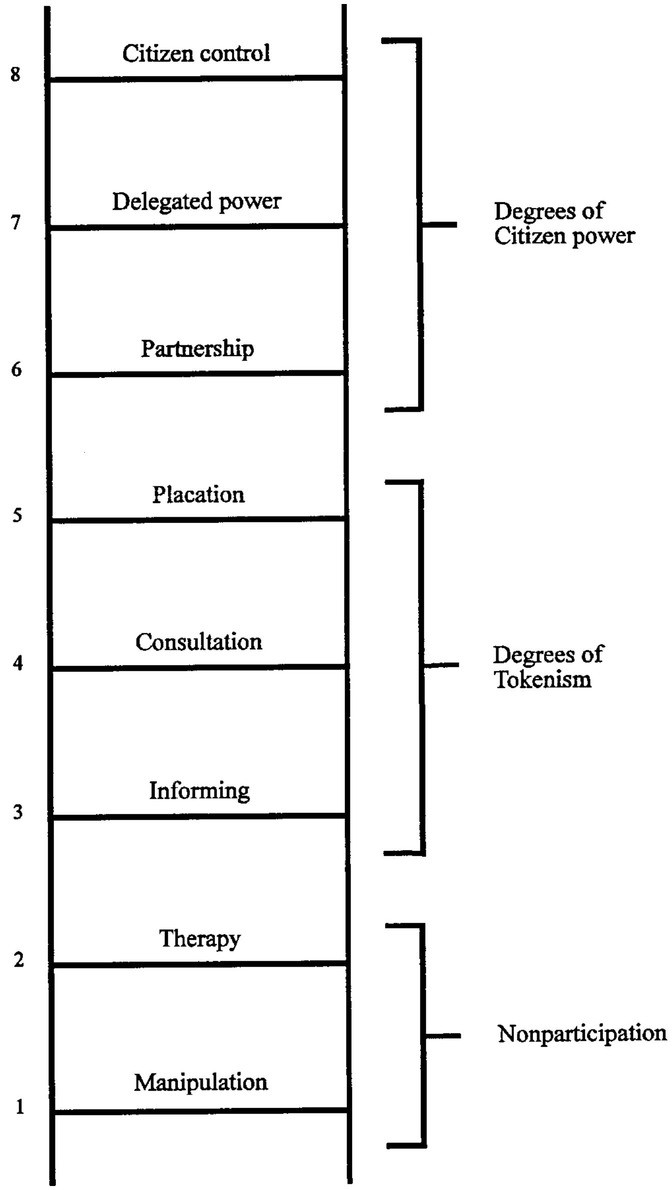
- improved communication (leads to increased awareness and understanding by citizens and "buy-into" various initiatives;
- reduced conflict;
- incorporation of local knowledge; and
- increased trust.

In terms of climate variability and change, this emphasis on process and public involvement is important for a number of reasons. For instance, public education programs will be more successful if the public is involved in their design and implementation. Moreover, important adaptation decisions (e.g., construction of dams, land use restrictions) may receive more public support if there is heightened public understanding and public involvement in the adaptation decision-making process.

Given the importance of effective public participation, managers are exploring new forms of public participation and partnerships, often delegating power to citizens. There have been many advances in public participation. For some time, attendance at public meetings was the extent of a public participation effort. Recently innovative approaches such as round tables, partnerships, and creative workshops have been utilized (Hofmann, 1996).

The approach used for public programs depends upon the goals and extent of participation desired. Arnstein (1969) created an eight rung Ladder of Citizen Participation (Figure 1.15).

Figure 1.15: **Arnstein's Ladder of Citizen Participation**
(Modified from Arnstein, 1969)



The underlying philosophy of her Ladder was that with increasing power, citizen participation became increasingly meaningful and less token. The first two rungs (1) manipulation and (2) therapy were considered non-participatory forms since their real objective was not participation but rather to cure, convince or educate the public. The next three rungs: (3) informing, (4) consultation and (5) placation, progressed to a level of 'token' participation where participants can hear and be heard ... but there is no guarantee that their views will be heeded to by decision-makers. Citizen power is gained in rung (6) partnership in that citizens can "negotiate and engage in tradeoffs with powerholders" (Arnstein, 1969, 217). At the top two rungs, (7) delegated power, and (8) citizen control, citizens gain the majority of the decision-making power. Although the top two rungs may not be a desired outcome for climate change public involvement programs, at present, public participation in this field has barely entered the bottom two rungs. If climate change scenarios become reality, for some major decisions, the public will undoubtedly demand increased participation and power in decisions to cope with the change.

Again, the "public" and citizens involved in these processes vary. There are a number of different “publics”, including citizens, impacted sectors, politicians, and decision-makers. All these different "publics" require different communication approaches. In some cases, one individual may find themselves classified into several publics.

Behaviour

Adaptation to climate variability and change as a “behavioural process”, however, is not well understood or appreciated (Smit, 1993). What kinds of adaptation actions, for example, are likely to be most acceptable to potential adapters, and why? What personal and societal factors influence adaptation, particularly more enduring change in water user behaviour? Will more accurate and more effectively communicated information about the likelihood and implications of climate extremes enhance adaptation, or are water users more likely to be influenced by the most recent extreme experienced? Kreutzwiser's (1996) survey of rural water users, for instance, suggests that potential adapters may find supply enhancement actions more acceptable than actions aimed at reducing water demand. Perceived frequency of dry spells was one of several factors associated with perceived effectiveness of supply enhancement and demand management actions. Notably, respondents' assessment of the likelihood of future dry spells was influenced by their most recent experience with wet or dry spells

Education and behavioural changes in the public go hand in hand. Without effective education programs (e.g., through public involvement programs) behaviourial changes will not take place. One important behavioural change is the wasteful use of water by consumers. Adaptations through behaviour changes include simple water conservation measures such as turning off the water while brushing teeth, or lathering up in the shower, etc.

Modify the events, prevent the effects, avoid impacts

Adaptation strategies that modify the events, prevent the effects, and avoid impacts have been divided into two categories for the purposes of this discussion:

1. Non-structural approaches
2. Structural approaches

Non-Structural Approaches

Recently non-structural approaches to water management problems have been gaining increased attention. Non-structural approaches include examining the management of water, including:

(i) legal,
(ii) institutional, and

(iii) economic approaches (McDonald and Kay, 1988). This discussion is organized according to these three approaches.

The increasing focus on non-structural approaches is due to the loss of credibility, negative environmental impacts, and failure of technocentric or structural approaches and the realization that policy generation and implementation tremendously affect water resources.

Legal Issues

An important legal issue facing water managers is the legal title of water. Throughout Canada there are conflicts over the right to use water or the "legal title" to water. Each province in Canada has its own legislation governing such issues and thus the conflicts differ from province to province. Basically, legal title to water in Canada is based on variations of riparian law and/or prior appropriation law. Riparian law basically states that landowners have title to surface water channels running through their property with certain "reasonable use" limitations (e.g., cannot consume all the water) (Lucas, 1990). Prior Appropriation law basically grants water permits or title to water based on a first come first served basis (Lucas, 1990).

Smit (1993) suggested that various changes should be made to the current legal system governing water rights in Canada in order to adapt to climate change. For instance, the removal of riparian water rights with prior appropriation was suggested. The reallocation of water rights including allowing the selling of water rights or the banking of water was also recommended. Another suggestion was to change the basis for a water right from withdrawal quantity for a specified use to consumptive quantity for that use (Smit, 1993).

Institutional Arrangements

Institutional arrangements involve the structures and policies used to manage water. This includes, for example, the agency structure set up to govern water internationally, nationally, provincially, and locally. These institutional arrangement have been plagued with numerous problems including:

- lack of inter-agency co-operation (Mulamoottil *et al.*, 1996);
- overlapping and competing jurisdictions, e.g., edge and boundary problems (Gilchrist, 1983; Mitchell and Shrubsole, 1994);
- lack of integration (Kreutzwiser, 1991; Mitchell and Shrubsole, 1994); and
- decline in funding (Mulamoottil *et al.*, 1996; Mitchell and Shrubsole, 1994)

If climate change projections are realized, the institutional problems will hinder adaptation to negative impacts.

The "Big Picture"

There is a consensus in water management literature of the need to look at the "Big Picture" (Mitchell, 1984). That is, there is a need to look at the inter-relationships of water with other components of the environment. Within this “Big Picture” is the issue of climate change.

Other components of the environment (e.g., industrial land uses) can have negative impacts on water. However, since different components of the environment are managed by different government agencies with fragmented and overlapping responsibilities, it is difficult to resolve problems unless an integrated approach is used (Mitchell, 1991). There are numerous terms to describe such as approach including integrated water management, ecosystem approach, and comprehensive planning, to name a few. Downs *et al*. (1991) discovered 36 terms which are used to basically define the same principle: the need to manage in big picture perspective, instead of managing water in isolation. The unit of management most favoured for this "integrative approach" is the watershed or river basin due their inherently integrative nature (Kreutzwiser, 1991). Nevertheless, all these approaches share principles of examining the "big picture" and integrating the various parts of this picture. Although there is support for this concept, implementation has been relatively unsuccessful.

Watershed and Subwatershed Planning

Watershed and subwatershed planning are important adaptation measures for climate change and variability. With such planning current management can be improved and preparations for the future, including climate change, can be planned for. This type of planning ensures a more anticipatory approach to climate change as opposed to reactive. The benefits of watershed and subwatershed planning will be felt irrespective of the magnitude of climate change.

Watersheds are considered logical planning units, however, watersheds are often fragmented by political boundaries. This fragmentation results in inconsistent application of plans and a lack of common management direction (Hardy *et al.*, 1994). Integrated Subwatershed Planning is considered one method of overcoming these and other deficiencies.

In the past, the difference between watersheds and subwatersheds plans was related to stream order. Presently, the difference is based on detail. Watershed plans outline broad future visions for the watershed and general strategies to achieve them (Hardy *et al.*, 1994). Subwatershed plans provide more site specific direction and greater detail on local environmental issues and possibilities for human development (Hardy *et al*., 1994).

However, both types of plans are important documents for guiding land use development proposals, particularly in the rural-urban fringe. Subwatershed Plans are considered important planning tools that coordinate human growth with the natural environment, and will result in benefits for planning, development and maintenance activities (Paragon Engineering, 1992). In the past, the main tool for dealing with urban runoff were stormwater management plans and the recognition of other environmental considerations was limited. Subwatershed planning provides a broader planing tool than the storm water management plans which are used on a site by site basis with not consideration to larger scales and integration (Paragon Engineering, 1992). Beyond issues of urban runoff, subwatershed plans can include provisions for maintaining riparian corridors, areas of environmental significance, and stream naturalization projects which are also important in the context of adapting to climate change.

Implementation of the "Precautionary Principle"

In 1990, the Second World Climate Conference in Geneva stated the following:

> *"Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing cost-effective measures to prevent such environmental degradation" (Myers, 1993, 74).*

This viewpoint is known as the precautionary principle. The endorsement of this principle (e.g., by government agencies and the private sector in Canada) will assist in adopting various adaptation strategies, including "no regrets" strategies.

Anticipatory and adaptive approaches

Typically water management was dominated by a rational, comprehensive, and technical approach. This approach is characterized by rigid goals and processes in a very expert driven environment with limited public input (Berman, 1990). However, this approach has been losing favour and anticipatory and adaptive approaches have been gaining favour (Riebsame, 1988). This new approach recognizes that uncertainty, surprise, complexity, and change are a major component of the planning and management process; and that flexibility is needed (Berman, 1990; Mitchell and Shrubsole, 1994). It also recognizes the limits of technology and the need for a consultation process (including the acceptance of local knowledge as legitimate information) (Mitchell and Shrubsole, 1994). Where the regional impacts of climate change are highly uncertain, flexible and adaptive approaches to deal with these potential impacts are needed to ensure that the system remains robust and resilient enough to cope with climate change (Smith and Lenhart, 1996). The CCPB (1990) suggests that the current water resource system would be made less vulnerable to climate change by becoming more robust, flexible, and resilient.

Zoning and Building Permit Process

By amending land use zoning and building permit standards, various adaptations to climate change can occur (Smit, 1993; Kreutzwiser, 1991). For instance, building codes could discourage the construction of basements which would avoid problems associated with basement floodings. Similarly, land use zoning could prohibit the construction of dwellings in flood-prone areas or protect open spaces. Other planning or zoning-related techniques include conservation easements, purchase of development rights, transference of development rights or the acquisition of land by governments (Wright, 1994).

Incorporate current climate variability and future change into long term planning

Planners and managers should incorporate climate change in the long term planning of water (e.g., water strategies for municipal water supply) (Smith and Lenhart, 1996; Titus, 1990). Just as population will change water use, so will climate variability and change. With the incorporation of climate variability and change in long term planning, future generations will be able to cope with changes more readily (Smith and Lenhart, 1996). Leaving more water in-stream to support the fisheries and other ecological uses and as a buffer for uncertainty in supply would be a viable strategy due to the uncertainty of future supplies due to climate change (Bjonback, 1991).

Inventory existing adaptation strategies

Currently society adapts to climate-related changes to water resources. An inventory and analysis of these adaptation measures should be conducted to determine possible strategies for coping with climate variability and change (Smith and Lenhart, 1996, 195).

Tie disaster relief to hazard-reduction programs

Funds for disaster relief (e.g., for impacts of climate change) could be tied to the implementation of long-term hazard reduction policies. Such requirements may be a valuable investment, particularly if hurricanes and storms increase as a result of climatic change (Smith and Lenhart, 1996, 195).

Contingency planning

Develop contingency plans for the short-term to adapt to water extremes (e.g., shortages or excess). The cost of developing contingency plans is relatively small compared with the potential benefits (Smith and Lenhart, 1996). This strategy is considered a "no regrets" approach since it would be beneficial under current climate variability, regardless of climate change.

Use of future hydrologic and climatic data

Currently, when planning and designing new water projects, designers use historic hydrologic and climatic data. The use of this data assumes a consistency, however, with projected changes due to climatic change, this consistency is no longer realistic (Williams, 1989). Designers of new infrastructure should consider using future hydrologic and climatic projections to ensure the infrastructure is suited for the future.

Economic Issues

Perhaps the most important economic issue facing the water sector are the enormous costs (to municipalities) to replace or expand aging water supply and treatment infrastructure. Currently, one third of Canada's wastewater is not yet treated (Environment Canada, 1992). If climate change scenarios of lower streamflows occur, large amounts of untreated water may become a greater concern (e.g., lower streamflows). In addition, climate change may require that more advanced treatment (e.g., tertiary, etc.) are required in existing treatment facilities. Two key reasons have been suggested to explain the financial difficulties facing municipal water supply:

- the investment into infrastructure was below the required amount (Fortin and Mitchell, 1990). In Ontario, in the 1980s, investment was about half of what it should have been (Fortin and Mitchell, 1990).
- water consumers do not pay the full cost of services, thus there is little incentive to conserve (Fortin and Mitchell, 1990; Millerd, 1984; Tate, 1984).

Various changes have been recommended to respond to the infrastructure renewal and expansion issue, including demand management, water conservation, and amending the current undervaluing of water. These changes will help the current situation, but would also be beneficial to respond to climate change impacts.

Demand Management

Traditionally, water has been supplied in Canada using the "supply management approach". That is, water was manipulated, using structural methods, in order to meet the demands of Canadian water users (Tate, 1990). This approach leads to a structural focus, a belief that water is limitless, causes water to be undervalued, and promotes a water system that is wasteful instead of economically efficient (Tate, 1984). Given the current financial problems facing water supply agencies, increasing demands, polluted water, and diminishing sources this supply management approach has lost favour (Mitchell and Shrubsole, 1994). In addition, a demand management approach would exacerbate some of the suggested impacts of climate change (e.g., reduced water quantities).

Demand management involves modifying consumers demand (including total demand, peak demands) for water. This can be accomplished through a variety of methods, but the most promising approach appears to be the appropriate setting of water prices (Fortin and Mitchell, 1990; Rivers and Tate, 1990; Tate, 1990). Numerous studies show that increased water prices will lead to declined water consumption (Harris, 1991; Fortin and Mitchell, 1990; Rivers and Tate, 1990; Tate, 1990). While the "supply management approach" involves managers accommodating infrastructure to suit consumer needs, demand management attempts to reduce consumer needs through pricing and water conservation. As shown in Table 19, In comparison to other countries, Canadians pay very little for their water.

Tate and Lacelle (1992) found five main types of rate schedules in Canada: (1) flat rate, (2) constant unit rate, (3) declining block rate, (4) increasing block rate, and (5) complex rate. They found that the flat rate (which also includes a minimum bill with small additional charges based on water use) was the most popular rate in Canada. They concluded that most of the rate schedules had financial incentives to conserve water, avoid waste or minimize the costs of providing water.

Typically, it is believed that a method whereby the consumer pays by volume is most beneficial (Fortin and Mitchell, 1990; Tate and Lacelle, 1992). This water pricing process would also involve metering the amount of water consumed.

Table 1.19: Comparison of Average International Water Prices, 1986

Country	Cost (cents/1000 L)
Canada	25
United States	53
France	75
United Kingdom	50
Sweden	50
Australia	165
Germany	99
Italy	17

(Tate, 1990)

The Value of Water

Linked with the concept of demand management is the notion that water is currently undervalued and under-priced. Currently, water bills incorporate a cost only for the provision of supplying water... there is no charge for water itself. It has been suggested that water is a resource like any other and should be treated in such a way (Gray, 1983). That is, water should be considered a resource with economic characteristics (Gray, 1984). Research has indicated that there would be many benefits for charging for the water resource itself (Hofmann, 1994, Mitchell, 1984). This current undervaluing or non-value of water leads to its consideration as a free good, which results in exploitation, waste and abuse. Mitchell (1984) noted that placing a value on water is fraught with problems, including ethical and political issues.

In terms of climate change, the recognition of the value of water would assist in the adaptation of possible negative impacts. That is, water would not be abused to the same extent, which would assist in adapting to lowered water quantities.

Water Conservation

As discussed previously, water conservation involves both structural and non-structural approaches. If the scenarios projections of decreased water quantity occur, water conservation may become an important adaptation. The following provides some example of non-structural approaches to water conservation:

- water use restrictions;
- rate structures, pricing policies, incentives through rebates and tax credits, other sanctions (fines);
- public education, information transfer and training;
- regulatory (legislation, codes, standards and by-laws) (Environment Canada, 1992);

- lawn watering bans (Smit, 1993); and
- banning use of ornamental fountains and similar water users (Smit, 1993).

Structural Approaches

The following strategies are approaches that may assist to adapting to water under climate change.

Reduce pollution

The polluting of water has the same effect as reducing water supplies. Reducing the pollution going into water supplies increases the supplies available for consumption by humans and other organisms. Also, it has been suggested that climate change could lower runoff and water levels, this would increase concentrations of pollution in water. Therefore, it is important to reduce pollution to ensure water quality is not further deteriorated. Reduced pollution is beneficial whether or not climate changes (Smith and Lenhart, 1996, 197).

Municipal Water Supply Infrastructure

If climate changes brings about increased water consumption as projected, the need for increased municipal water supply will occur. Since new infrastructure is costly and water is scarce in some areas, improvements to municipal infrastructure may be required. One such improvement is the reduction of water wasted due to leaks. Currently, approximately 10-30% of water in a municipal supply system is lost due to leaking pipes (Environment Canada, 1992). Generally, if unaccounted water in a municipal supply system exceeds 10-15%, a leak detection and repair program is considered cost effective (Environment Canada, 1992). That is, for every $1.00 spent for leak detection repair programs, $3.00 can be saved (Environment Canada, 1992).

Marginal changes in construction of infrastructure

When planning the construction of new water resource infrastructures or the expansion of existing infrastructure, marginal changes should be considered to accommodate climate change and variability. For example, marginal increases in the size and capacity or ability to cope with variability of dams, canals, and pipelines could be considered. Such marginal changes may be less costly than adding capacity in the future (due to climate change) (Smit, 1993; Smith and Lenhart, 1996).

Interbasin transfers

Smith and Lenhart (1996) suggest that inter-basin transfers may result in more efficient water use under current and changed climate and that transfers are often easier to implement than fully operating markets for water allocation. Interbasin transfers may also be a short-term strategy for coping with droughts or other water shortages (Smith and Lenhart, 1996). However, Smit (1993) noted that there are many costs with interbasin transfers including economic, environmental, political, and social.

Numerous interbasin transfers exist (e.g., Columbia River system). In the Great Lakes, the Great Lakes Charter limits diversions and in some instances prohibits diversion. However, attention is often directed at proposed mega-project transfers. Perhaps the most infamous proposed transfer scheme was the North American Water and Power Alliance (NAWAPA) (McDonald and Kay, 1988). The scheme proposed to transfer 136-308 (cubic kilometres) km^3 of water mostly from the Columbia, Kootenay, Fraser, Yukon, Laird, Peace and Skeena rivers in Canada and the Copper, Susitna and Tanana rivers in Alaska (McDonald and Kay, 1988). Almost 20% of total runoff would be transferred from these rivers to the southern water-deficient areas in central Canada, southwestern United States and northern Mexico (McDonald and Kay, 1988). The scheme proposed the construction of 240 reservoirs, 112 irrigation systems and 17 navigable channels (McDonald and Kay, 1988). The scheme had caused nervous reactions in Canada since Canada would be the primary donor of water and the United States the primary recipient of water.

Floodproofing

Projections for increased frequency of flooding have been made under various climate change scenarios. Structures can be elevated in order to reduce flooding effects. The following are some examples:

- land height can be built up by placing landfill and holding it with a retaining structure (if the area is not excessively large) (Smit, 1993);
- marina and harbour infrastructure can be raised (e.g., fender systems, docks, walkways) (Smit, 1993);
- threatened buildings can be raised (Smit, 1993); and
- Dikes and other flood proofing measures can be constructed.

Components like tanks, containers, incinerators and structures used in hazardous waste treatment can be floodproofed. The following examples involve hazardous water treatment structures and components:

- grading (create slope between 2-5% for runoff) (Smit, 1993);
- fencing (around facilities to stop the flotation of containers and lessen structural damage from flood debris) (Smit, 1993);
- "upgrade the structural integrity of containers" (Smit, 1993); and
- "elevate containers and/ or facilities above flood level” (earth fill - provided it does not erode, and column piers/walls)(Smit 1993).

New dam sites, reservoirs, and dikes

Another climate change adaptation strategy involves developing new infrastructure such as dam sites, reservoirs, and dikes. These structures would assist in maintaining water levels and coping with floods and droughts. Smith and Lenhart (1996) suggested that on potential dam sites, for example, development should be forbidden, or developed only under conditions that would allow the conversion to a dam if necessary.

Water Conservation: Structural

Water conservation strategies include both structural and non-structural approaches. Some of the structural approaches are listed below:

- water saving devices (e.g., low flow toilets, and shower heads);
- drought resistant landscaping (e.g., rocks and other plants or objects which do not require watering);
- water metering;
- improvements to irrigation systems (e.g., leak reduction, watering only when required (e.g., not according to timers);
- water recycling systems;
- wastewater reuse;
- flow control devices;
- distribution system pressure reduction;
- efficient sprinkling/irrigation technology;
- leak detection and repair; and
- elimination of combined sanitary/storm sewers to reduce loadings on sewage treatment plants (Environment Canada, 1992; Lenhart and Smith, 1996).

Natural Channel Design

Rivers, streams and other natural channels are components of the hydrological cycle whose size, position, and capacity are determined by factors such as geology, climate, and vegetation (Tate, 1994). Humans have altered these natural channels for a variety of reasons including flood control, and convenience (e.g., channels can be a "nuisance" for roads, construction of building etc.).

However, recently it has been discovered that maintaining channels close to their natural state has many benefits including long-term sustainability, biodiversity, and water quality benefits. In the 1993 Mississippi flood, it was found that control structures and land use changes in the upper Mississippi and Missouri basins exacerbated the floods (Tate, 1994). Natural channels are designed to accommodate flooding naturally. Given this, there has been a trend towards returning channels to a more natural state (e.g., allow meanders to develop, etc.).

Some of the characteristics of a healthy, functional, and naturalized channel are:

- efficient transport and storage of a variety of flows and sediment loads;

- relatively small width-to-depth ratios;
- well vegetated; dynamic but stable banks;
- a substrate much coarser grained than banks, with low amounts of finely grained materials in the interstitial spaces of riffle substrates;
- a meander pattern and geometry that are appropriate for the stream class;
- a stream slope less than valley slope;
- a hydrograph that shows response to sudden amounts of precipitation (MNR, 1994).

Natural channels would have an increased ability to absorb the fluctuations in volume that are projected under climate change scenarios, and assist in keeping water temperatures down (e.g., shading).

Specific Adaptations

The previous discussion has focused upon very general and broad water adaptations, and has provided very few specific adaptations. Table 1.20 summaries some specific adaptations for several components of the hydrological cycle or possible hydrologic events. For increased detail on specific adaptations of impacted sectors (e.g., agriculture, forestry, fisheries, etc.), refer to the relevant chapters of the CCS.

Evaluation of Options

There are numerous options available for decision-makers in order to adapt to climate change and variability. All these options must be evaluated. The following criteria form a basis for evaluating adaptation options:

- flexibility,
- timeliness,
- technical feasibility,
- equity,
- political realism,
- urgency,
- compatibility, and
- cost (Goklany, 1992; Mortsch, 1996; Titus, 1990).

Adaptation options can also be classified as “anticipatory adaptation” or “reactive adaptation”. Although anticipatory adaptation is generally more favoured, unforeseen impacts would generally lead to reactive adaptation.

Table 1.20: Specific Adaptations for Changes to the Hydrologic System

Impacts On	Change Use (Location, Use)	Reduce Loss (Prevent, Modify Effects)	Accept Loss (Share, Bear Loss)
Flood	- restrict development on flood plains - change operating rules to increase flood storage	- construct/upgrade flood storage reservoirs, dikes, river channelization - improved tiles, ditches, storm sewers - review dam safety - flood proofing	- improved flood forecasting and flood warning -formulate evacuation plans - flood insurance, disaster relief - plan for disaster relief and emergency preparedness
Drought	- reduce water requirements - abandon/expand agricultural lands	- increase water stored in reservoirs - change farming practices to increase soil moisture - expand irrigation - expanded municipal water storage tanks	- contingency plans for allocating water during shortages - share water supplies regionally
Streamflow	- reduce/increase use as reliable flow/yield changes - reduce/increase hydro-power generation - increase regional efficiency of water supply systems through coordination - reduce leaks - adopt water pricing and market instruments to reallocate available supplies	- increase reliable flow/yield by adding reservoir storage - exploit new sources of water (e.g., groundwater, interbasin transfer)	- share water sources through interconnections and coordinated management - accept lower reliability to increase effective supply
Groundwater	- reduce/increase use as sustainable yield changes - increase number/depth of wells to exploit recharge over larger area	- exploit new sources of water (surface water)	- institute management of groundwater withdrawals
Lake Levels	- restrict lakeshore development -decrease/increase recreation and shipping as levels change	- dredge harbours, raise seawalls and bulkheads - control structures - interbasin transfers to maintain levels	- flood insurance, disaster relief
Soil Moisture	- abandon/expand agricultural land - expand forest by planting -change crops/tillage systems - manage wetland habitat to reduce loss/ degradation by other causes	- expand irrigation - artificial wetlands	- subsidize agriculture - crop insurance, farm income supports
Water Quality	- expand/restrict use of affected water bodies - expand/restrict fisheries - redirect fishery to exploit species that benefit from change - change land use practices to control erosion - control point and non-point discharge of wastes	- increase/decrease level of water treatment - stock lakes and rivers from hatcheries - augment streamflow during low-flow events - install aeration and/or other mixing devices	- subsidize fisheries
Snow and Ice	- decrease/increase recreational use and shipping as ice cover allows -expand/restrict hydro-generation as ice allows	-increase/decrease investment in ice breaking to maintain shipping channels -modify water intake structures to prevent ice build-up	

(Mortsch, 1995; Nuttle, 1993b)

Summary

In terms of water resources, Canadians are currently spending billions of dollars adapting to the current climate. For instance, lawn watering bans are common in many communities, and dams, dikes, and other costly structures are used to maintain/reduce water flows. However, attention must be given to adapt to potential changes caused by climate change and the fluctuations of on-going climate variability.

There are numerous strategies for adapting to climate change including the following: share the loss, bear the loss, research, education, modify the events, prevent the effects and avoid the impacts. Under each of these categories there are a variety of options available.

However, the most promising options are those considered “no regrets” strategies. These strategies involve changes or policies that would be of assistance for adapting to climate change, as well as the current climate and its variability. Examples include water conservation (e.g., water pricing, water-use reductions), and more integrated water resource management practices.

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CHAPTER TWO

IMPACTS OF CLIMATE CHANGE AND VARIABILITY ON UNMANAGED ECOSYSTEMS, BIODIVERSITY, AND WILDLIFE

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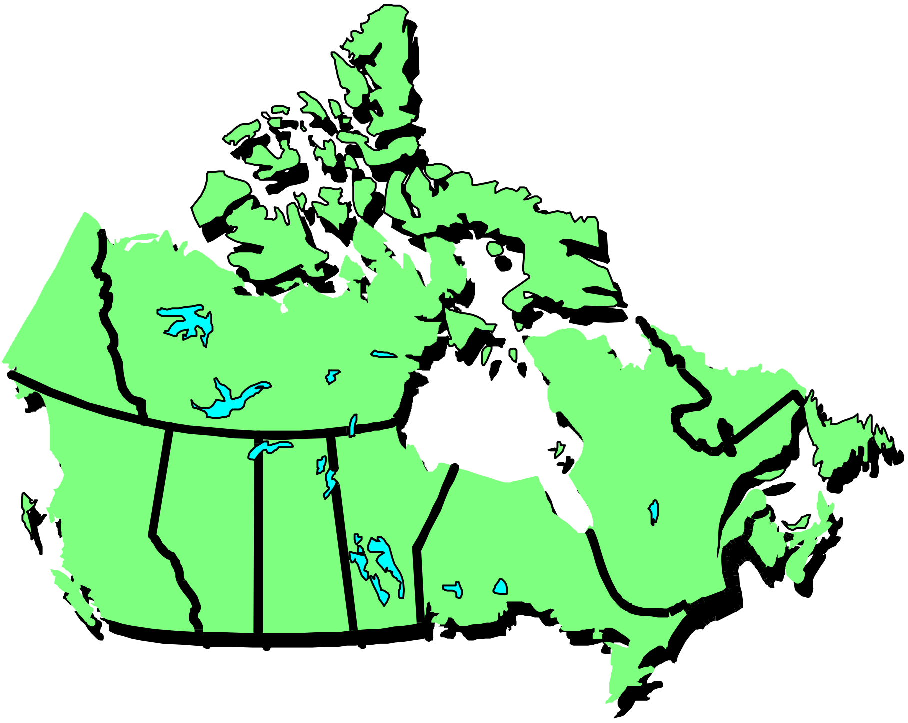

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EXECUTIVE SUMMARY AND RECOMMENDATIONS FOR FURTHER RESEARCH

Earth's climate is changing, and the scientific consensus is that there is a discernible human influence behind the present changes.

Over the past century, Canada's average annual air temperature has increased about 1.1°C. However, there are regional variations. Temperatures in parts of the west rose 1.5°C or more, comparatively little change occurred in Atlantic Canada, and declines were recorded in the eastern Arctic. Studies also suggest that changes in the frequency and/or intensity of extreme climate and weather-related events have occurred over the past century. Such events, happening at vulnerable times of the year, may cause more ecological change at the local to regional level than predicted changes resulting from long-term climatic trends.

Small variations in climate, such as a one or two degree change in mean annual temperature, can have significant repercussions for the characteristics and functions of unmanaged ecosystems.

- Freshwater habitat for salmonids and other key aquatic wildlife will be lost in parts of Canada. From 1970-1990 at the Experimental Lakes Area near Kenora, northwestern Ontario, air temperature rose approximately 1.6°C and precipitation decreased. The ice-free season on lakes increased about two weeks, lakes became warmer, and thermoclines deepened. The cessation of lake trout recruitment in one lake may be linked to a reduction in cold water at the bottom of the lake. Projections of the suitable habitat available to brook trout after a global warming scenario reveal that their breeding range in Canada will be severely restricted as groundwater warms up

- Re-acidification of lakes in sulphur-enriched basins of the Precambrian Shield has occurred with a drier climate. At Swan Lake near Sudbury, Ontario, lake water pH recovered from 4 in 1977 to 5.8 by 1985 because of lower emissions from local smelters. The years 1986 and 1987 were extremely dry, causing the lake surface area to shrink and oxidation of reduced sulphur compounds in the exposed shore zone and elsewhere in the drainage basin to occur. The following year, 1988, was extremely wet, and the newly formed sulphuric acid was flushed into the lake, dropping its pH to 4.5.

- A warmer, drier climate will increase substantially the number of wildfires and area burned, with consequences for wildlife. Warm, dry episodes characterized the 1980s in large parts of Canada. While the mean annual area burned across Canada had been about one million hectares in the 1970s, it grew to 5.0 and 5.5 million hectares in 1981 and 1982, respectively. Where forest habitat is already partly fragmented with patches linked by corridors, fire can sever those links, causing even greater fragmentation and consequent disruption of migration pathways.

- Changes in snow cover and soil moisture will cause significant changes to arctic tundra vegetation. At a site near Churchill, Manitoba, where snow accumulation was augmented by installing snow fences, rapid changes in plant community composition were observed over a

14-year period. All species which favoured snow-free and very dry conditions disappeared while species more tolerant of wetter conditions became established.

- With an increase in air temperature, plant growth should increase. Satellite data have provided evidence of an overall increase in terrestrial photosynthetic activity from 1981 to 1991. In Canada, the largest increases occurred in a wide band extending from the Yukon and British Columbia southeastward to the Great Lakes, then northeastward to Labrador.

- Invasion of southerly species into Canada can be expected as a consequence of climate change, posing a threat to biodiversity. A study of the entire distribution of Edith's checkerspot butterfly concluded that the species is moving its range northwards into British Columbia as southerly populations disappear and new ones arise on the northern border of its range.

- Lower seawater temperatures since the mid-1980s are considered the cause of some of the recent decline in size-at-age of Atlantic cod on the northeastern Scotian Shelf and off Newfoundland. Differences in bottom water temperature can explain 90% of the variance in growth rate of different stocks of Atlantic cod in the North Atlantic.

- Some breeding colonies of seabirds are at risk because of rising sea level. Over 405,000 breeding pairs of seabird of 8 species, including nearly 400,000 pairs of common murre and Canada's second-largest colony of northern gannets, would be lost from Funk Island off Newfoundland alone. For common murres this represents almost 70% of the population of northeastern North America.

- The polar bear could become extinct through starvation if the Arctic Ocean becomes seasonally ice-free for a long enough period. The disappearance of ice-bound algae would disrupt the algae–zooplankton and crustacean–fish–seal–polar bear food chain; and perhaps more importantly, no ice habitat would mean no chance for the bears to hunt seals.

There are many known dependencies of ecosystems, biodiversity and wildlife upon climate that make them vulnerable to climate variability and change. For example:

- The link between climate and regional vegetation zonation is well established. The northern limit of tree growth is determined largely by energy constraints such as low air temperature.

- Annual precipitation commonly accounts for 90% of the variance in primary production in grasslands while temperature is the most important variable controlling decomposition.

- The winter range of most species of songbird in North America is determined mostly by habitat distribution; but once that is taken into account, the northern boundary of the winter range of many species coincides with January isotherms reflecting daily energy requirements of about 2.4 times Basal Metabolic Rate.

- The timing of animal migration is well known to correlate closely with weather conditions. The departure of snow geese from winter quarters, for example, is triggered by temperatures above 18°C.

The current suitability of most ecosystems in Canada as wildlife habitat is determined as much by human management of those habitats (especially through agriculture, forestry, and fisheries) as it is through natural characteristics of those systems. Thus changes in human-related land and water use may have as much influence on the quantity and quality of wildlife habitat as changes induced directly by climate change.

There are several recommendations for further research:

- Long-term, multi-disciplinary monitoring and research on fundamental ecological conditions and trends, like that at the Experimental Lakes Area in northwestern Ontario, is rare in Canada, and even worldwide. As a result, understanding of many critical ecological processes and ecosystem-level behaviour is limited. Such monitoring and research must continue where it exists and be expanded into ecosystem types where it is lacking.

- For the oceans, an improved understanding of changes in basic physical parameters such as water temperature, salinity, and ocean currents is needed. More complete information on species life histories is also required, to allow better predictions of the impacts of climate change and variability on fish and other marine organisms.

- Plant–herbivore and other trophic-level interactions require more study. Insects are known to respond to plant nutrient concentrations and the levels of chemical defenses. Most studies have revealed changes in carbon:nitrogen ratios under increased carbon dioxide. Hence changes in insect behaviour should be expected.

- Research has to consider not only the direct ecophysiological effects of changes in climatic variables, but also any modifications to those effects caused by soil feedbacks and biological interactions between different organisms. Many studies dealing with the impacts of climate change on ecosystems are limited by their failure to consider some of these important interconnections.

- The lack of data on the pattern of diversity found in wild, healthy populations, particularly in those species that are not commercially exploited, is a serious constraint. We need to know what our biodiversity is before we can assess the impacts that climate change may have on it.

- Although much information on effects of *weather* — especially extreme events — finds its way into the literature, there has been no attempt to integrate these disparate sources into an evaluation of the overall effects of *climate* on wildlife as a first step towards designing a research strategy. If climate is an important driver of many populations, then clearly wildlife biologists need a better understanding of its effects, if only to improve current population models.

BACKGROUND AND OBJECTIVES OF THE CHAPTER

This chapter was prepared as a contribution to the national sectoral report of the Canada Country Study: Climate Impacts and Adaptation. Overlaps in content can be expected with several other chapters in this volume (including Agriculture, Fisheries, Forestry, Water Resources, and Wetlands), with some chapters in the Cross-cutting Issues volume (e.g., Changing Landscapes), and with various chapters or sections in each of the Regional Report volumes.

This chapter has three basic objectives:

1. The primary objective is to evaluate, through a survey of the literature, the impacts of climate variability and change on unmanaged ecosystems, biodiversity, and wildlife in Canada. The scope of this topic proved to be too large to allow a thorough review of the literature in the time allotted. Thus, a case study approach was adopted. The three sections of the chapter focus on ecosystems, biodiversity, and wildlife, and are presented in that order to allow for a progression toward increasingly specific aspects.

2. A second objective of the chapter is to briefly outline potential adaptive responses of humans to changes in ecosystems, biodiversity, and wildlife caused by climate variability and change.

3. The third objective is to identify important gaps in knowledge and needs for further research. These proved to be numerous, and often fundamental in importance. The next phase of the Canada Country Study will set about addressing some of these gaps.

IMPACTS ON UNMANAGED ECOSYSTEMS

Introduction

Earth's climate is changing. Over the past century, the average annual air temperature has risen about 0.3 to 0.6°C globally (IPCC, 1996a), and about 1.1°C for Canada (Environment Canada, 1995). Changes in other key climatic elements such as precipitation have also been observed (Environment Canada, 1995). It is important to recognize that recent climate change has not been uniform across Canada. For example, while temperatures in parts of western mainland Canada have risen 1.5°C or more over the past century, comparatively little change has been observed in Atlantic Canada; and declines have actually been recorded in parts of the eastern Arctic over the past 50 years (Environment Canada, 1995). Perhaps even more importantly from a biotic standpoint, changes in the frequency and/or intensity of extreme events are suspected to have occurred over the past century (Katz and Brown, 1992). Analyses of the chronological records found in such proxy data sources as tree rings, glacial ice cores, and lake and ocean bottom sediments have provided ample evidence of past climatic change, and accompanying ecological change. Approximately 1,000 years ago, the Northern Hemisphere was about 0.5 to 1°C warmer than the subsequent "Little Ice Age" which lasted from roughly 1400 to the late 1800s. That seemingly small increase in mean temperature in medieval times was sufficient to allow the Vikings to conduct agriculture in southern Greenland. About 4,000 to 8,000 years ago, the global mean temperature was as much as 1°C warmer than today. During the Wisconsin glaciation of the last ice age when mean global air temperature was only about 5°C colder than now, much of Canada lay under glacial ice which at its thickest point may have been over three kilometres deep (Bird, 1967).

This first section of the chapter reviews the scientific literature on the implications of climate variability and change for Canada's "unmanaged" ecosystems (i.e., those ecosystems that remain relatively "natural" as opposed to cultivated or developed). The interconnectedness of climate and ecosystems is illustrated by the major role that air temperature and precipitation play in explaining the general location and extent of terrestrial biomes (Box, 1981; Holdridge, 1947; Woodward, 1987). Relationships between climate and biota have been used to develop scenarios of potential ecological change based on climate change. For example, changes in the distribution of Canada's *ecoclimatic provinces* (broad landscapes in which there is a fundamentally similar ecological response to climate) were modeled using the 1981 GISS (Goddard Institute for Space Studies) 2xCO_2 scenario of climate change (Rizzo and Wiken, 1989). Substantial reductions in the areas of arctic, subarctic, and boreal ecoclimatic provinces were projected, with notable expansions occurring in the more southerly cool temperate and grassland provinces. It should be stressed that the intent of this investigation was to assess the sensitivity of Canada's ecosystems to climate change. There was no suggestion that the composition of ecological communities would remain the same in the future, though within different boundaries. Species react to change more individually. While some continue to survive in a particular area, others may die out, and not necessarily at the same time. In addition, the ability of species to invade new areas differs considerably, because of varying dispersal abilities, for example. Thus it is more likely that change will occur as a series of invasions and losses that result in entirely new communities, as appears to have happened over the past 10,000 years (e.g., Davis *et al.*, 1986; Webb and Bartlein, 1992) (see also the Biodiversity section (Paleoecology: past climates and ecosystem responses) and Wildlife section (Impacts of climate variability and change on wildlife) of this chapter).

During the past decade, there have been many studies on the implications of *future climate change* for Canada's ecosystems or components thereof. While presenting some of the general findings of those investigations, the primary focus of this review is on studies that document how *recent changes in climate* may already be causing ecological change in Canada. Most of these studies relate to a single terrestrial biome (such as forest, grassland, tundra) or aquatic system (freshwater; marine), but a few pertain to more than one biome. The section closes with a brief discussion of human adaptation strategies, and an identification of important gaps in knowledge.

Climate change impacts on Canadian ecosystems

Arctic tundra

Arctic ecosystems could be the most altered of all those in Canada since warming is expected to be greatest in higher latitudes (Maxwell and Barrie, 1989; Roots, 1989), and environmental conditions are close to the limits for life (Danks, 1992). Arctic plants have adapted to low temperature, low light, and a short growing season. Thus water and nutrients are often the most important limits to tundra productivity. Water stress may not be so important in wet low-Arctic communities, but it becomes very important in dry areas, which are more widespread in the higher Arctic.

Chapin *et al.* (1992a) summarized the possible effects of higher CO_2 and a warmer climate on arctic (particularly low Arctic) tundra ecosystems. They suggested that photosynthetic and growth responses to higher CO_2 and air temperature will be constrained unless nutrient limitations are reduced. One way for that to happen would be through an increase in soil temperature. That would foster decomposition, not only directly, but also indirectly by increasing the seasonal thaw depth, drainage, and aeration. Any resultant increase in nutrient availability would lead to accelerated plant growth. The growing season would probably lengthen under a warmer climate unless winter snowfall increased so much as to cause a correspondingly longer snowmelt period. Cloudiness and precipitation could increase, but there is a greater degree of uncertainty in this regard than with air temperature. Higher air temperature would enhance evapotranspiration, with varying consequences depending upon moisture availability at the site.

Changes in soil moisture resulting from climate change could be particularly crucial for arctic tundra ecosystems, especially for those that are presently very dry (e.g., dry heath) or very wet (e.g., moist tussock tundra). Evidence to support this comes from an experiment conducted to examine the consequences of increased winter snow accumulation on tundra vegetation (Scott and Rouse, 1995). Near Churchill, Manitoba, a double-ringed snow fence was installed on lichen-heath tundra in the summer of 1978, to act as a trap for drifting snow. The inner ring was 8 m in diameter, the outer, 13 m. Snow depths and densities were monitored during the 1978–1979 winter, and soil moisture and temperature measurements were acquired the following summer both inside and beyond the snow fences. A vegetation survey was done in August 1981, both within the snow fences and at a control site about 50 m to the east. The 1.3 m high fences trapped snow to the point that the inner fence was usually buried, with snow overflowing onto the tundra on the downwind (south) side. By way of comparison, maximum snow depth during the 1978-1979 winter on the adjacent tundra beyond the influence of the fences only averaged 0.05 m. During the winter, soil temperatures were considerably warmer under the deep snow inside the enclosure than in the nearby tundra. Over the summer, soil within the enclosure was much wetter and somewhat cooler. For the study period, which ended in 1992, air temperature and precipitation averages at Churchill were similar to the long-term mean. A resurvey of the vegetation in 1992 showed that all species which favoured snow-free and very dry conditions (e.g., the lichens *Cladina stellaris*, *Cetraria nivalis*, and *C. cucullata* and the shrub lapland rosebay) had disappeared while species more tolerant of wetter conditions (e.g., alpine bearberry and bog blueberry) had become established. The implication therefore was that higher winter snowfall would have a marked effect on vegetation communities, and wetter summers would probably accelerate the changes in vegetation.

If the primary effects of climate change in the low Arctic are warmer, drier soils, and more frequent fires, the vegetation would probably change to consist of more shrubs and less *Sphagnum*, with more trees in the longer term. In the high Arctic, one would expect more extensive plant cover with an invasion of low shrubs (soil conditions permitting, of course). This change in vegetation cover would produce a different response to climate change, making predictions of long-term ecological change even more difficult. For example, the new vegetation might be more responsive to higher CO_2 and air temperature. It might also provide denser shade over the ground, thereby lessening the amount of soil warming. Changes in plant cover would bring changes in herbivory, with the dominant herbivore replaced in some areas. Some feedback processes could affect climate. Changes in decomposition and productivity will alter CO_2 flux to the atmosphere. Arctic tundra has been a net sink for carbon dioxide in historic and recent geological times, but it could become a net source. There is evidence that this has already happened on the North Slope of Alaska (Oechel *et al.*, 1993). Changes in methane emissions are also possible. Warming of wet, poorly drained soils could increase emissions, while drying of soils could lead to the reverse (Chapin *et al.*, 1992a).

Non-arctic alpine ecosystems

A 500 m increase in altitude corresponds with an approximate 3°C decline in air temperature because of the adiabatic lapse rate (e.g., MacArthur, 1972). Climatic warming in mountainous terrain should encourage species to migrate upslope so long as there are no impediments such as increased winter snow accumulation or poor soil conditions. In the southern Canadian Rockies, treelines appear to have been higher from the 14th to the 17th centuries than today, and perhaps higher still about 1,000 years ago in response to more favourable climatic conditions (Luckman, 1994). In recent years, increases in tree seedling recruitment at or above the treeline have been documented in several countries including Canada (e.g., Graumlich, 1994). For example, Kearney (1982) identified two recent periods (middle 1940s to early 1950s, and late 1960s to early 1970s) as ones of major seedling establishment at timberline at three sites in Jasper National Park, Alberta. An analysis of climatic data revealed a significant association between above-average minimum summer temperatures and seedling establishment. Kearney suggested that the actual relationship was probably more complex, likely involving additional factors such as length of the snow-free period, and thermal conditions at germination.

Less land is available for a species to colonize at higher bands of elevation, and mountaintop-endemic species could disappear. Extinctions caused by upward movements in vegetation zones of 1,000 to 1,500 m since the last glacial maximum are known to have occurred in the past in Central and South America (e.g., Flenley, 1979, cited in IPCC, 1996b).

Forests

Forests are a key element in the carbon budget. Globally they hold about 80% of all above-ground terrestrial organic carbon, and about 40% of that below ground (e.g., Dixon *et al.*, 1994). The long life span of most trees causes forests to respond slowly to climate change. Tree migration entails the movement of seeds to new locations, establishment of seedlings, growth of individuals to reproductive maturity (which may take decades), and production of new seeds. For migration to occur, this cycle has to repeat itself. Numerous other factors can impede migration, such as absence of needed pollinators, unsuitable climate conditions for seed production or seedling establishment, and interference from strong competitors. Even if all goes well, many species may not be able to migrate at the rate demanded by climate change. With a warming of between 0.1 and 0.35°C/decade, for example, species would have to migrate poleward 1.5 to 5.5 km/year (or upwards 1.5 to 5.5 m/year in mountainous areas). Estimates of natural tree migration rates are far less, ranging from 40 to 500 m/year (e.g., Solomon *et al.*, 1984). A factor that must not be overlooked when considering the rate of forest response to climate change, however, is wildfire. As a disturbance, fire can play a key role in removing vegetation that is no longer suited to changed climatic conditions, opening the door to the invasion of better adapted species (Wein and Hogg, 1990). Warmer and drier conditions would favour the incidence of wildfire. Using $2xCO_2$ scenarios of climate change, it has been estimated, for example, that the average area of forest burned annually in Canada's Mackenzie Basin would double (Kadonaga, 1997).

Boreal

Boreal forests could be the most affected of all the world's forests because of the large temperature change expected in higher latitudes. In addition to soil conditions, the northern limit of tree growth is determined largely by energy-related factors, as reflected in measurements such as air temperature and net radiation (e.g., Bryson, 1966; Hare and Ritchie, 1972; Køppen, 1936), and there is considerable paleoecological evidence of climate-related shifts in the treeline since the last glaciation (e.g., MacDonald *et al.*, 1993; Payette *et al.*, 1989a; Ritchie and Hare, 1971). Northward and upslope movements of the treeline, and/or increased rates of tree growth seem likely under a warmer climate. The northern edge of the range of white spruce can be used as an indicator of treeline position as the two usually coincide (Danks, 1992). D'Arrigo and Jacoby (1993) have observed that white spruce seedlings are appearing further north and at higher elevations in western Canada and Alaska, suggesting that a migration of that species, and hence the treeline, is in progress.

While changes in air temperature have significant consequences for the northern boreal forest, changes in the water balance may be the most critical climatic factor in the southern boreal forest. Hogg (1994) undertook a study of the relationships between climate and vegetation in the boreal and parkland regions of the Prairie provinces (Alberta, Saskatchewan, and Manitoba). Both thermal (e.g., mean annual temperature, mean July temperature, growing degree days) and moisture (e.g., monthly moisture indices) aspects of climate were examined. For the southern boundary of the boreal forest, the strongest relationship was with a moisture index calculated by subtracting potential evapotranspiration from precipitation. Thus, it was suggested that either moisture shortage alone, or higher fire frequencies caused by the arid climate, has been the factor limiting conifer growth along the southern boreal boundary.

Indeed, the implications of wildfire have to be considered not just in the southern boreal forest, but throughout the zone, for wildfire is "the driving successional force in the boreal forest" (Hall, 1995). The warm, dry episodes that characterized the 1980s in large parts of Canada contributed to a marked increase in the number of fires, and area burned. While the 10-year running mean of area burned across Canada had been about one million hectares in the 1970s, it grew to 5.0 and 5.5 million hectares in 1981 and 1982, respectively (e.g., Wein *et al.*, 1994). At the Experimental Lakes Area near Kenora, northwestern Ontario, no major forest fires had occurred for over 100 years prior to the initiation of environmental monitoring and research around 1970. Then, within less than a decade, long droughts resulted in fires that burned significant parts of the area in both 1974 and 1980 (Schindler *et al.*, 1996a). On the other hand, there is evidence of decreasing forest fire frequency in at least a part of the southern boreal zone of Québec (Bergeron and

Archambault, 1993). Three-hundred year long fire and tree ring chronologies from the Lake Duparquet area (about 30 km northwest of Noranda) show such a decrease that began about 100 years ago. The explanation appears to be a decline in drought occurrence, attributable to changes in atmospheric circulation (northward migration of the polar front, allowing greater frequency of warm, humid air masses) (see also Archambault and Bergeron, 1992).

Grasslands

Climatic variables related to the water balance and water availability are of greatest importance in determining grassland distribution (Stephenson, 1990, cited in IPCC, 1996b) and production (e.g., Sala *et al.*, 1988, cited in IPCC, 1996b). Thus, the amount and timing of precipitation is crucial. Annual precipitation commonly accounts for 90% of the variance in primary production in grasslands (e.g., Sala *et al.*, 1988, cited in IPCC, 1996b) while temperature is the most important variable controlling decomposition (e.g., Burke *et al.*, 1989, cited in IPCC, 1996b). Fire and herbivory are among the factors causing periodic rejuvenation of grasslands, removing above-ground biomass and freeing up nutrients.

Wetlands

Freshwater

Climate change will affect wetlands most notably through changes in their hydrologic regimes. This can entail changes in water supply (e.g., precipitation) or loss (e.g., evapotranspiration). In higher latitudes, it can also involve changes in hydrology caused by the decay of permafrost. A variety of wetland types exist (e.g., bogs, fens, swamps and marshes), and the hydrologic conditions of one type vary markedly from that of another. Thus, while it is possible to offer some observations on climate change impacts for an individual type of wetland, it is difficult to generalize across types. For example, Poiani and Johnson (1993) modeled the effects of potential climate change on the hydrology and vegetation of semi-permanent prairie wetlands for a site in North Dakota. This type of wetland can cycle through different cover phases, depending upon moisture supply conditions. Poiani and Johnson (1993) used both the Goddard Institute for Space Studies projection of climate change (GISS85) and ten other sensitivity simulations that involved temperature changes of +2 and +4°C, and precipitation changes ranging from -20 to +20%. For the GISS scenario and nine of the ten sensitivity simulations, wetland cover changed from a roughly even split between emergent vegetation and open water to a closed basin condition with no open water. Prairie wetlands of the northern Great Plains serve as the "single most important breeding area for waterfowl in North America," and studies have shown that the most productive state of these wetlands for breeding waterfowl is one with approximately equal open water and emergent vegetation cover (Poiani and Johnson, 1993). Hence, the results of the GISS scenario and the sensitivity simulations used in this study do not bode well for waterfowl habitat quality in the Prairies.

Lowering of the water table could cause a wetland to change from a CO_2 sink to a source. For example, bogs are characteristically covered by peat that accumulates from partially degraded biomass in the waterlogged, anaerobic environment of the wetland. A lower water table would bring an end to peat formation, and also allow rapid aerobic decay of the existing peat, leading to release of CO_2. Methane trapped within waterlogged peat would also be released to the atmosphere, accentuating the emission of greenhouse gases (Brown, in press).

Coastal

When averaged around the globe, sea level has risen about 10 to 25 cm over the past century, and much of that may be attributable to a warmer climate (IPCC, 1996a). Some Canadian coastlines, notably the shores of Hudson and James Bays, continue to rebound following the loss of glacial ice cover (isostatic rebound); others, however, such as the those of British Columbia, Yukon, and much of Atlantic Canada are subsiding. In areas of subsidence, the survival of coastal wetlands will depend upon whether they can expand inland at a rate fast enough to compensate for loss due to flooding. Human-made barriers to such expansion, in addition to natural constraints, are a concern. In British Columbia, for example, dikes would have to be removed along the Squamish, Nanaimo, and Fraser rivers to alleviate the loss of wetlands (Beckmann *et al.*, 1997).

Consequences for wetland flora in areas of rising sea level could include changes in the spatial distribution of plant species, an increase in salt-tolerant species at the expense of freshwater ones, and a net loss in species diversity at the leading edge of wetlands (Latham *et al.*, 1991). This, in turn, would have consequences for many birds and other animals that rely upon specific wetland vegetation (see the Wildlife component of this chapter for further information).

Lakes and rivers

Seasonal ice cover is a characteristic of the majority of Canadian lakes and rivers. Ecological effects of lake ice cover include the attenuation of sunlight, reduced turbulence and mixing, and oxygen depletion which can lead to fish kills. Since about 1960, lake ice seasons have become shorter at several sites across much of Canada, in accordance with rising winter and spring season temperatures in many regions of the country (Environment Canada, 1995). In Nova Scotia, on the other hand, where there has actually been some winter season cooling in recent decades, the river ice season has lengthened about three weeks in at least some areas since the 1950s (Clair *et al.*, 1997).

Research conducted at the Experimental Lakes Area (ELA) near Kenora, northwestern Ontario, since about 1970 has provided important insights into the response of lakes and rivers to a warming climate (Schindler *et al.*, 1996a;Schindler *et al.*, 1990). From 1970 to 1990, air temperatures rose approximately 1.6°C and precipitation fell. Forest fires burned portions of the research basins in 1974 and 1980, as previously mentioned. Given these events, some of the observed changes in aquatic ecosystems were readily understandable. For example, with the warmer weather, the ice-free season on lakes increased about two weeks, and during the open-water season lakes became warmer and thermoclines deepened. Runoff fell more than 50%, and some formerly permanent streams became ephemeral. Lower runoff caused a decrease in the supply of many chemical constituents to the lakes. For example, exports of dissolved silica and dissolved organic carbon from land to water fell by over 50%. Nitrogen and phosphorus exports also decreased overall, though increases occurred for a few years following fires. With lower input of many substances, and longer water residence times, lakes became clearer. Lake water alkalinity increased as the ratio of base cations to strong acid anions rose. A slight increase in phytoplankton biomass and species diversity occurred, but primary productivity did not change. Higher water temperatures and deeper thermoclines pose a threat to species such as lake trout that require cold-water habitat. The cessation of lake trout recruitment in one lake may have been linked to such habitat change. In summary, it was suggested that these events "provide a preview of how climatic change may affect boreal lakes and catchments in the next century" (Schindler *et al.*, 1990).

In the Precambrian Shield of central Ontario, research indicates that drought can lead to remobilization of acid into lake water. Near Sudbury, Ontario, many lakes that had been acidified by atmospheric deposition of industrial SO2 emissions began to show improvement in the early 1980s because of lower emissions from local smelters. Monitoring at one of these lakes, Swan Lake, revealed a decline in pH to only 3.97 by 1977, followed by a substantial recovery to 5.8 by 1985 (Yan *et al.*, 1996). The years 1986 and 1987 were extremely dry, causing the lake surface area to shrink by 18%, leaving large areas of the lake littoral zone exposed to the air. Oxidation of reduced sulphur compounds in the exposed zone and elsewhere in the drainage basin ensued. The following year, 1988, was extremely wet, and sulphate was flushed into the lake, dropping its pH to 4.5. This was not an isolated case, as similar occurrences were observed in a number of other lakes in the region (e.g., Dillon and LaZerte, 1992; McNicol and Mallory, 1994). Since climate change scenarios suggest a trend toward lower soil moisture content in the continental interior, re-acidification of lakes in sulphur-enriched basins of the Precambrian Shield could be one of the consequences.

While climatological data for southern Canadian sites generally extend back a century or more, comparable record-keeping in most of the Canadian arctic archipelago only began within the last 50 years-all the more reason for exploring proxy data sources to investigate climate change. In one study, sediment core samples from three ponds on Cape Herschel, east central Ellesmere Island were analyzed for diatoms, for "If climate ameliorated even slightly, it would have had a dramatic effect on the diatom assemblages" (Douglas *et al.*, 1994). Analyses showed that while the assemblages were relatively stable for thousands of years, exceptional changes began to occur in the 19th century. The authors concluded that this could be attributed best to a change in climate, as opposed to other possible causes such as stratospheric ozone depletion or the long-range transport of pollutants. Only a slight amount of warming in this cold environment would be required to significantly lengthen the growing season and allow for the observed shift to more diverse and complex diatom communities. This reasoning is supported by the fact that similar changes in diatom assemblages have not been observed in nearby deep, ice-covered lakes.

Oceans

Climate change can cause changes in oceanic characteristics that include water temperature, salinity, sea level, ice cover, and oceanic circulation. Fish and shellfish respond directly to changes in water temperature, and faster growth rates are associated with warmer temperatures. For example, differences in bottom water temperature can explain 90% of the variance in growth rate of different stocks of Atlantic cod in the North Atlantic (Brander, 1995, cited in Drinkwater, 1997). In addition, year-to-year changes in temperature can affect growth rates within a single stock. Lower seawater temperatures since the mid-1980s are considered the cause of at least one-half of the recent decline in size-at-age of Atlantic cod on the northeastern Scotian Shelf (Campana *et al.*, 1995, cited in Drinkwater, 1997) and off Newfoundland (de Cárdenas, 1996, cited in Drinkwater, 1997). Growth rate dependence on water temperature has also been observed in several other species in the northwest Atlantic, and at various developmental stages including larvae. Laboratory studies have revealed that the growth rate–temperature dependency is caused at least in part by changes in feeding rates which drop off when water temperature is beyond the normal range of tolerance (e.g., McKenzie, 1934 and 1938, cited in Drinkwater 1997).

Water temperature, along with the availability of food and suitable spawning grounds, is a primary determinant of fish and shellfish distribution, since most fish species or stocks have a preferred temperature range. With a warming trend in the Gulf of Maine in the 1940s, there was a northward shift in the distribution and abundance of several species, including Atlantic mackerel and American lobster (Taylor *et al.*, 1957, cited in Drinkwater, 1997). Capelin, commonly found off Labrador and Newfoundland, spread as far south as the Bay of Fundy when temperatures fell in the 1960s, but shifted northward again as temperatures rose in the 1970s. With the most recent cooling that began in the late 1980s, capelin extended eastward and southward once more (Frank *et al.*, 1996, cited in Drinkwater, 1997). Other species known to have spread southward with this latest cooling include Arctic cod (Lilly *et al.*, 1994, cited in Drinkwater, 1997), and Atlantic cod (de Young and Rose, 1993, cited in Drinkwater, 1997).

Survival and growth of Pacific herring are sensitive to natural fluctuations in ocean climate. Ocean temperature influences herring survival and growth directly, and also indirectly by altering the abundance of herring predators, principally Pacific hake. Waters off the west coast of Vancouver Island undergo alternate warm and cool periods. Warm periods since 1976 have been intensified by strong El Niño events. During these warm periods, survival and growth of young herring are weak due to the abundance of Pacific hake and the high water temperature, frequently associated with El Niños. Strong El Niño events further reduce young herring survival because large numbers of Pacific mackerel migrate north into British Columbia waters and feed on herring, salmon, and other species during the summer. The result is a decline in spawning biomass of the West Coast Vancouver Island herring stock because fewer young herring survive to join the spawning stock. Conversely, survival and growth are relatively strong when the summer biomass of hake is low and the annual water temperature is cool, in the range of 10°C (Environment Canada, 1994).

Some fish migrations are known to be tied to specific water temperature ranges or thresholds. For example, Atlantic mackerel that overwinter off the Middle Atlantic Bight do not arrive along the coast of Nova Scotia or in the Gulf of St. Lawrence until waters warm to more than 7 or 8°C (Sette, 1950, in Drinkwater, 1997). Along the coasts of Newfoundland and Labrador, the timing and geographical distribution of Atlantic salmon are dependent upon the arrival of 4°C water (Narayanan *et al.*, 1995, cited in Drinkwater, 1997). On the west coast, there are two main migration routes for Pacific salmon returning to spawn in the Fraser River. When sea surface temperatures are warmer, such as during an El Niño event, salmon choose the north end of

Vancouver Island to approach the coast of British Columbia. Under cooler conditions, a more southern approach is taken (Groot and Quinn 1987).

Loss of sea ice in parts of the Arctic would be problematic for species that rely on ice as a platform for movement (e.g., Peary caribou), hunting (e.g., polar bear), or particular life-cycle stages (e.g., breeding and whelping for some species of seals). At the opposite end of the food chain, loss of sea ice would lead to a decline in ice algae, a food source for a number of amphipod species (Rose and Hurst, 1992). (See "Arctic Marine Food Webs" in the Biodiversity section of this chapter.)

Studies of a more general nature

Plant growth

Given that there has been an increase in atmospheric CO_2 of close to 30% since preindustrial times, one would expect to see evidence of increased plant growth under natural conditions (the so-called " CO_2 fertilization" effect). One avenue of investigation has been through the analysis of tree rings. At least 20 such studies have reported increases in alpine and boreal tree growth in North America and Europe compared with rates before 1850 (e.g., Innes, 1991). Rising CO_2 concentration and higher air temperatures are two of the possible causes of observed growth increases. D'Arrigo and Jacoby (1993) examined White Spruce tree rings from three areas near the North American treeline. The sites were located near Norman Wells, Northwest Territories, Churchill, Manitoba, and Bettles, Alaska. While a recent increase in tree growth was found, it was possible to attribute it all to changes in air temperature and precipitation. There were no residual trends of any consequence that needed further explanation. The Alaskan specimens have also revealed a greater sensitivity to precipitation since about 1970, perhaps an indication of greater moisture stress under warmer conditions (Jacoby and D'Arrigo, 1995).

With a moderate increase in air temperature, plant growth in most areas is expected to increase, mainly because of a longer growing season. In fact, analysis of radiometer data from satellites has provided evidence of an overall increase in terrestrial photosynthetic activity from 1981-1991 (Myneni *et al.*, 1997). The results suggest an increase in plant growth associated with a longer growing season. Greatest increases in photosynthetic activity occurred in the 45-70°N latitude belt, where the growing season is estimated to have lengthened by about 12 days, two-thirds of that coming in the spring. In Canada, largest increases in photosynthetic activity were in a wide band extending from the Yukon and British Columbia southeastward to the Great Lakes, then northeastward to Labrador. Particularly high values occurred in western and northern mainland Canada, consistent with observed trends in air temperature (especially warmer springs) and snow cover (earlier disappearance).

Phenology

Phenology is the study of the seasonal timing of life cycle events (Ratchke and Lacey, 1985, cited in Beaubien, 1993). Aspects of plant phenology such as bud break and first leaf can serve as sensitive and observable biotic indicators of climate change, since "Temperature appears to be the most important factor affecting the phenology of spring plant development in the temperate zone of the world" (Beaubien, 1993). Beaubien (1997) examined a 60-year record of dates of first bloom at Edmonton, Alberta, for three species, trembling aspen, saskatoon, and choke cherry. Overall, the annual mean of first bloom dates for the three species became eight days earlier over the 1936–1996 period, consistent with trends in air temperature.

"Plantwatch" is a program in which student and adult volunteers are observing and reporting the first and full bloom dates of plant species. Currently, the program tracks flowering times of up to eight plant species: common purple lilac (all over the world) and seven other plant species in North America (Beaubien, 1997).

Climatic characteristics such as mean summer temperature and season length can influence the life cycle of certain arctic insects, making them useful indicators of climate change. Phenological indicators could include the date when seasonal emergence begins, and the number of generations per year, or years per generation (Danks, 1992).

Permafrost

Wherever the heat lost from the surface of the ground in the cold months of the year exceeds heat gained in the warmer months, and the ground temperature remains below 0°C for at least two consecutive winters and the intervening summer, "permafrost," or perennially frozen ground, can occur. Climatic conditions across Canada have allowed for the occurrence of permafrost under about half of the nation's land surface (Natural Resources Canada, 1995). In the most southerly of these areas, permafrost occurs in isolated patches. Moving poleward, it becomes more common ("discontinuous"), eventually becoming continuous in extent. It also increases in depth at higher latitudes, from decimetres at southern limits to over 700m in the arctic islands. So long as its freezing point is not depressed too far by dissolved substances, water within perennially frozen soil turns to ice. In extreme cases (usually in fine-textured soils that have a high clay and silt or organic matter content), ice can comprise up to 50–70% of the top two to three metres of frozen ground. Medium to high ice content permafrost is particularly common in the Mackenzie Valley and adjacent lands, as well as on Banks and Victoria islands of the western arctic archipelago (Natural Resources Canada, 1995). Studies have also revealed areas of ice-rich permafrost in Northern Québec (e.g., Allard *et al.*, 1993).

It is in such ice-rich terrain that warming would have the greatest ecological consequences; for the thawing of ice-rich soil would lead, at a minimum, to subsidence of the land. That, in turn, could cause changes in the water table, alterations in vegetation, and even the formation of wetlands and shallow ponds. On sloping ground, the degradation of ice-rich permafrost could cause terrain instability resulting in mass movements such as landslides. Vitt *et al.* (1994) did an airphoto analysis of bog landforms in the discontinuous zone of Manitoba, Saskatchewan, and Alberta, east of the Rocky Mountains. They were able to categorize bogs into five types of surface physiography. In the south, most bogs lacked internal patterns, an indicator that they never had permafrost. In the most northern areas, the predominant type was peat plateau with extensive permafrost. In between, the dominant bog type was one with an internal "lawn" – an open, wet, *Sphagnum–Carex*-dominated area surrounded by a slightly higher wooded area. These lawns were deduced to be areas where ice-rich permafrost existed in the past but has since degraded – the likely consequence of a warmer climate since the end of the Little Ice Age, around 1850.

Human adaptation approaches and options

Climate is changing now, and no matter what the scenario for future anthropogenic greenhouse gas emissions, climate will continue to change into the foreseeable future (IPCC, 1996a). Thus, it seems inevitable that some amount of climate-induced ecological change will occur. However, there are fundamental uncertainties that hinder the assessment of how humans may adapt to such change. On the one hand, there is considerable doubt over how unmanaged ecosystems will respond to climate change, especially if the amount of change is toward the high end of the current range of projections. In the "Impacts on Biodiversity" section of this chapter, it is noted that "biological communities formed in response to past climate changes often have no analogue with modern-day species assemblages," even though there are cases where "similar environments exist today in similar climatic regions." Based on our knowledge of past ecological change, there is no guarantee that the structure and function of future ecological communities will remain the same.

Another major uncertainty relates to the consequences of potential human response to change in *managed* ecosystems. In the "Impacts on Wildlife" section of this chapter, it is pointed out that "changes in land and water use may have at least as much influence on the quantity and quality of wildlife habitat as changes induced directly by climate change." Consider the case of wetlands, for example. It is estimated that since 1800, one-seventh of Canada's wetland resource has been converted or lost through agriculture, urbanization, recreation, and other human-related uses (Government of Canada, 1991; Soil Conservation Society of America, 1987). Climate change may prompt responses in agriculture and other sectors that have further negative implications for wetland resources, unless measures are taken to avert such responses. The nature of those responses and their net impact on wetlands is not easily predicted, however.

A question that arises, then, in terms of human adaptation to change in unmanaged ecosystems is "Adaptation to what?" Suffice it to say that humans have a capacity to adapt. They will do so as necessary and to the extent possible. The uncertainties noted above make it all the more important to be proactive in trying to minimize the negative effects on ecosystems arising not only from climate change, but from other human-related stresses such as acidification and the long-range transport of toxic substances.

Knowledge gaps

Current predictions from General Circulation Models (GCMs) of fundamental climatic variables such as air temperature and precipitation are considered *unreliable at the regional scale* (i.e., they have a spatial resolution in hundreds, rather than tens, of kilometres). Major theoretical and practical challenges (e.g., how to deal with cloud physics; the need for greater computer power) have to be overcome before such finer-scale predictions from GCMs become possible – predictions that will allow scientists to say with greater confidence what the implications of climate change may be for specific ecosystems at the regional level.

Also lacking are reliable predictions of the frequency and magnitude of *extreme* climatic and hydrologic events such as heat waves, cold spells, severe storms, strong winds, droughts, and floods. Yet such events, occurring at vulnerable times of the year, may cause more ecological change at the local to regional level than many changes foreseen as a result of long-term climatic trends. For example, the effects of a single intense storm on coastal ecosystems may exceed those predicted as a result of climate-induced sea level change over a few decades. There is a crucial need for improved understanding of extreme weather events.

Long-term, multi-disciplinary monitoring and research on fundamental ecological conditions and trends, like that which has occurred at the Experimental Lakes Area in northwestern Ontario, is rare in Canada, and even worldwide. It must continue where it exists and be expanded into non- or poorly represented ecosystems, to resolve the many remaining questions about what is happening in Canadian ecosystems, and why such things are happening. The Ecological Monitoring and Assessment Network (EMAN), coordinated by Environment Canada's Ecological Monitoring Coordinating Office, is striving to make this happen (Environment Canada, undated). Key indicators need to be identified and monitored as part of this initiative. For example, a suite of bioindicators could be monitored that integrate the phenology of plants with that of other organisms (Beaubien, 1993).

For the oceans, an improved understanding of changes in basic physical parameters such as water temperature, salinity, and ocean currents is needed (Beckmann *et al.*, 1997). Consider, for example, the present level of understanding of the dynamics of North Atlantic Ocean circulation and its role in climate change and variability. Sy *et al.* (1997) report on the spread of cold water masses across the North Atlantic from their source in the Labrador Sea at a rate "three to four times faster than previously estimated, with associated consequences for the North Atlantic thermohaline circulation." Further research may indeed turn up more of these unexpected results. More complete information on species life histories is also needed, to make better predictions of the impacts of climate change and variability on fish and other marine organisms (Drinkwater, 1997).

Experimental approaches to the study of the effects of elevated CO_2 on ecosystems range from the use of enclosed or open chambers to free air CO_2 exchange experiments. In the latter, CO_2 is applied to vegetation without enclosure in any type of chamber. For low-stature ecosystems such as grasslands and tundra, experiments may have to be run for ten years or more to detect some of the important responses. Even longer experiments are needed to study forest response to higher CO_2 levels (Pitelka, 1994).

Plant–herbivore and other trophic-level interactions require more study. Insects are known to respond to plant nutrient concentrations and the levels of chemical defenses. Most studies have revealed changes in carbon:nitrogen (C:N) ratios under increased CO_2; hence changes in insect behaviour should be expected. Also, most experiments have considered only leaf-chewing insects, ignoring sucking insects that consume more than the chewing ones (Pitelka, 1994).

More needs to be known of the mechanisms regulating biogeochemical cycling and biological productivity. By way of illustration, the understanding of biotic interactions and feedback processes (e.g., feedbacks between plants and soil, and between herbivores and plants) in tundra ecosystems needs to be improved. The links between photosynthesis and growth in the Arctic deserve more study, especially for mosses and lichens (Chapin *et al.*, 1992a).

Research has to consider not only the direct ecophysiological effects of changes in climatic variables, but also any modifications to those effects caused by soil feedbacks and biological interactions between different organisms. Many studies dealing with the impacts of climate change on ecosystems are limited by their failure to consider some of these important interconnections.

IMPACTS ON BIODIVERSITY

Introduction

Objectives

The objectives of this component of the chapter are to provide an overview of the ways in which biodiversity in Canada may be affected by global climate change and explore cases where changes in biodiversity may have already taken place.

Biodiversity is a complex phenomenon that both responds to, and is the cause of, changes in climate. The scientific understanding of what biodiversity is and how it is maintained is still in its infancy (Wilson, 1992). Because of the complex web of interactions linking species to ecosystems to climate, isolating the direct cause-and-effect relationships between climate change and biodiversity is often impossible. Consequently, this chapter reviews the major ways in which the biological processes and patterns linked to biodiversity might be affected by climate change. As well, the biological responses to past climate change detected in the paleoecological record will be discussed as a guide to potential future impacts.

Definition of biodiversity

The conceptual basis of biodiversity has been developed since the late 1980s to include the variety of living forms and their abundance in a biological community and is a characteristic of biological systems at all levels of organization (Noss, 1990a). Variation exists among genes, species, populations, communities, ecosystems, and landscapes (Reid and Miller, 1989; Wilson, 1992; Solbrig, 1991).

These concepts were formalized in the definition of biodiversity adopted at the United Nations Conference on Environment and Development (UNCED), the Earth Summit, in Rio de Janeiro in 1992. Biological diversity, or biodiversity, is defined in Article 2 of the Convention on Biological Diversity (UNEP, 1992):

"*Biological diversity*" means the variability among living organisms from all sources, including *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems."

Understanding biodiversity requires more than simply enumerating the variety in living things over time. It requires a knowledge of the structures and processes that maintain this diversity (Noss, 1990a).

The incorporation of multiple levels of biological organization can make the assessment of biodiversity difficult to apply because diversity at one level does not necessarily entail diversity at another (Franklin, 1993; Angermeier, 1994). Sometimes, preservation of biodiversity at one spatial, temporal, or organizational scale may conflict with the preservation of diversity at another scale. For example, species diversity is often best maintained under conditions of intermediate disturbance (Huston, 1979; Connell, 1978). However, the migration and dispersal associated with this disturbance can lead to a mixing of genotypes across the landscape, breaking up of co-adapted genotypes that permit adaptation to local conditions, and hence reducing the genetic diversity within a species (Hobbs and Huenneke, 1992).

Paleoecology: past climates and ecosystem responses

The paleoecological record reveals the repertoire of past climate responses in particular regions to changes in global climate (e.g.: Dansgaard *et al.*, 1993; Dorale *et al.*, 1992). The link between climate and regional vegetation zonation is well established (COHMAP Members, 1988). For example, paleobotanical evidence has revealed Holocene (10,000 years before present) changes in treeline position that are believed to reflect climatic variations associated with the shape and position of the Arctic frontal zone (MacDonald *et al.*, 1993; Moser and MacDonald, 1990; Ritchie, 1987).

What happened to biodiversity in Canada during previous periods of climate change, particularly in the Holocene, can provide us with clues to the kinds of changes that might be expected under current climate change forecasts (Liu, 1990; Huntley and Webb, 1989; Payette *et al.*, 1989a; Ritchie, 1985, 1987). Of particular interest is how fast climate change can occur and how quickly the ecosystems appeared to respond to changing conditions. Because of the space restrictions, only a brief overview of some major findings in the paleoecological literature will be discussed here.

Examination of the paleoecological and ice-core literature revealed two themes:

1. Climate change can occur much more rapidly than was previously expected. Paleoclimate data from ice cores and sediments have revealed that the climate system is capable of rapid switching between significantly different modes. Climate variability over decades to centuries has been documented for the Holocene (Hoffert and Covey, 1992), along with abrupt switching behaviour (Taylor *et al.*, 1993; Dansgaard *et al.*, 1989; Flohn, 1987; Cook and Mayes, 1987). Even subtle changes in global average temperature or precipitation can result in abrupt and large-scale disruptions of the disturbance regimes characteristic of particular regions (Woodmansee, 1988). Hence, at least some regions in Canada likely will experience abrupt changes in climate which will alter the pattern of normal disturbance regimes for the area and create levels of disturbance sufficient to disrupt extant communities and allow rapid invasion by southern migrants (Clark, 1991; Campbell and McAndrews, 1993). However, the

potential for rapid invasion does not necessarily mean that new, stable community types will quickly become established. Biodiversity may not be able to respond as fast as economic or social forces desire. For example, the fastest response time of forest biodiversity to equilibrate to new climate conditions appears to be on the order of centuries (MacDonald *et al.*, 1993; Pellatt and Mathewes, 1994; Ritchie, 1987; Davis, 1981). Therefore, based upon past experience, we should expect significant lag times in the establishment of new, stable biological communities associated with the changed climate.

2. The second theme is that the biological communities formed in response to past climate changes often have no analogue with modern-day species assemblages (Davis, 1981; Anderson *et al.*, 1989). For example, Bennett's (1990) survey of biotic responses to climate change brought about by periodic fluctuations in the Earth's orbit (Milankovitch cycles) concluded that present-day terrestrial and freshwater communities lack a long history and that each species has responded individually to the climatic and other environmental changes brought about by the global climate change. Ritchie (1987) reached a similar conclusion in his investigations into how North American forest communities evolved following the last ice age. In his analysis of pollen found in sediment cores, he discovered tree communities existing 9,000 to 3,000 years ago that have no modern analogues. This despite the fact that similar environments exist today in similar climatic regions. The discovery of past vegetative communities without modern analogues makes predicting specific ecosystem responses under anticipated global warming more difficult (Liu, 1990; Anderson *et al.*, 1989).

Biodiversity responses

Threats to Canada's biodiversity will be discussed within each of the three levels of biological organization that comprise it — genetic diversity, species diversity, and ecosystem diversity. Where possible, both direct and indirect effects of climate change on biodiversity will be discussed. Due to space limitations, only a few representative examples will be discussed.

Direct effects of climate change on biodiversity include immediate or delayed responses to factors such as temperature, precipitation, insolation, and storm frequency and intensity (McAllister and Dalton, 1992). These effects can occur on all spatial and temporal scales and over all three levels of biological organization (Peters and Lovejoy, 1992).

Indirect effects are those that are mediated through other biological interactions. Consequently, they can span the entire spectrum of ecological processes and might be manifested through alterations in the availability of resources, changes in competitive abilities, dispersal rates, predation, disease, community structure, etc. (McAllister and Dalton, 1992). For example, in forests, physiological damage to trees brought about by drought can result in increased susceptibility to insect attack and fire, resulting in changes in community structure (review in Klein and Perkins, 1988).

Genetic diversity

Genetic diversity refers to the diversity of genetic information within a population (Noss, 1990a; Solbrig, 1991). The genetic diversity present today is the result of evolutionary processes occurring over thousands of generations; as such, it cannot be immediately replaced, even through introductions of exotic species or artificial breeding (Angermeier, 1994).

The extent and kind of genetic diversity present is critical because ultimately the genes are the source of new variations which allow adaptation by a species, and eventually ecosystems, to altered climates and new environmental conditions. The degree of genetic diversity present in a population is also of immediate importance as it directly influences reproductive capacity and resistance to disease (Lande, 1988).

Genetic diversity can be measured in many ways, including diversity at the level of the primary products produced (enzymes), or at the DNA level, such as RFLPs (restricted fragment length polymorphisms), RAPD (randomly applied polymorphic DNA), or microsatellites (Giles, 1994).

There is relatively little knowledge of the natural range of genetic diversity in wild Canadian populations, especially for soil invertebrates and nonvascular plants, many of which are still unnamed (Biodiversity Science Assessment Team, 1994). Even for species that are well studied, such as mammals, birds, and vascular plants, knowledge of their genetic diversity has only recently been acquired. Because of the high effort and expense needed to measure genetic diversity in wild populations, genetic studies tend to be performed on species already receiving conservation attention, such as the beluga, or white whale (e.g., Smith, 1990), or those that are commercially exploited, such as salmonoid fish (e.g., Grewe and Hebert, 1988).

There are increasing numbers of studies of genetic diversity in wild Canadian populations, including Lesser snow geese (e.g., Quinn and Cooke, 1987), collared lemmings in the Arctic (e.g., Borowik and Engstrom, 1993), arctic crustaceans (Hebert and Hann, 1986), red-winged blackbirds (e.g., Gibbs *et al.*, 1990) and meadow voles (Plante *et al.*, 1989).

The consequences for genetic diversity from global climate change will be reviewed by examining its influence on the patterns and processes that are known to create and maintain genetic diversity, including such factors as habitat change, habitat fragmentation, and the invasion of alien species and genotypes.

Habitat change

Increasing temperatures will lead to a reduction in some forms of habitat, notably the volume of cold water in lakes and the area of alpine zones. Loss of habitat can result in loss of genetic diversity through the loss of locally adapted genotypes, particularly for species that have limited migration capability. For example, study of the perennial herb, *Polygonum viviparum*, revealed that high Arctic, low Arctic, and alpine populations had no genotypes in common (Bauret, 1996). Alpine populations contained less genetic diversity, probably owing to restrictions in migration across unsuitable habitat between peaks. The genetic diversity of montane populations of this species can expect to be lost as habitat shrinks upwards and propagules fail to make it to suitable habitat further north. As well, migration of low-Arctic genotypes into high Arctic zones will probably disrupt locally coadapted genes (Bauert, 1996).

Habitat fragmentation

Climate change can create fragmentation of habitat in many ways. For example, increases in storm intensity and frequency expected to accompany climate change in Canada could lead to more frequent and intense fires caused by lightning strikes (Johnson and Larsen, 1991). Where habitat is already partly fragmented with patches linked by corridors, fire could sever those links, causing even greater fragmentation and consequent disruption of migration pathways. Increased flooding (Knox, 1993) can create habitat islands surrounded by washed out mudflats. Drought may dry up prairie pothole wetlands, leaving fewer habitat patches on the landscape for waterfowl (Poiani and Johnson, 1993).

Fragmentation of habitat can result in reduced gene flow across the landscape, as well as population declines within the remaining patches (Saunders *et al.*, 1991; Fahrig and Merriam, 1994). Both of these factors can contribute to a reduction in genetic diversity within a population by lowering the effective population size and increasing the loss of rare alleles due to drift and extinction of local populations (Hartl, 1988). Even if recolonization to extirpated patches occurs, the net effect is still a reduction in overall genetic diversity (McCauley, 1991).

Invasions of new species and genotypes

Biological invasions have already contributed substantially to a loss of genetic diversity and species extinction worldwide (Vitousek *et al.*, 1996). Introductions of exotics affect the indigenous gene pool either directly, through introgression (gene flow), or indirectly, such as reductions in the effective population size, making the indigenous populations vulnerable to the effects of inbreeding and drift.

In Canada, invasions of exotic species or genotypes have already created problems for native species (e.g., Billington and Hebert, 1991). Examples of negative genetic consequences resulting from exotic introductions in fisheries include the Florida largemouth bass (Philipp, 1991) and nearly all the native salmonids (Krueger and May, 1991). In the latter case, the exotic species that have been introduced (e.g., brook trout) have led to hybridization with native species resulting in a contamination of the gene pools of native species.

Species diversity

Species diversity, or species richness, refers to the variety of different kinds of organisms to be found within an area. The degree of species diversity present in an area has been shown to be important for ecosystem function, resistance to invasion, and recovery from a disturbance (e.g., Tilman, 1996; Richardson and Cowling, 1993; Naeem *et al.*, 1994,1996; Lodge, 1993). Species diversity is also important for Canadian society, as it is the source of much of our food (e.g., marine fish and shellfish) and recreation.

Species diversity is influenced by a wide variety of ecological and environmental processes, including habitat size (e.g., MacArthur and Wilson, 1967), disturbance regimes (e.g., Hobbs and Huenneke, 1992), habitat heterogeneity (e.g., Franklin, 1993), invasion history (e.g., Lodge, 1993), and rate of evapotranspiration (e.g., Currie, 1991). It is impossible in this short chapter to detail all the direct and indirect ways that species diversity in Canada could be affected by climate change. There are extensive reviews on the maintenance of biodiversity (e.g., Ricklefs and Schluter, 1993) and how it might be threatened by environmental change (e.g., Barker and Tingey, 1992; Chapin *et al.*, 1992b).

Species-rich areas in Canada are currently found in habitats such as the coastal temperature rain forest, rich fens and other wetlands, estuaries, old growth forests, and patches of relict habitat (e.g., Niagara Escarpment) (Biodiversity Science Assessment Team, 1994). However, the full extent of biodiversity in Canada is still poorly understood. Even in major ecosystems (e.g., boreal forest, grasslands) biodiversity remains largely unassessed, especially for hyperdiverse groups of organisms like arthropods.

Threats to species diversity from global climate change will be reviewed by examining a few of the direct and indirect threats to the patterns and processes that are known to create and maintain species diversity.

Habitat change

Climate change can lead to direct habitat loss through such means as changes in water levels, forest cover, snow cover, and water temperatures in lakes and streams. Decreases in habitat size lead to increased risks of extinction of populations (Pimm *et al.*, 1993; 1995). Two examples where reduction in habitat occurs as a direct consequence of climate change are found with cold-adapted freshwater fish (Regier and Meisner, 1990) and montane habitats (Harte and Shaw, 1995; MacDonald and Brown, 1992).

Brook trout prefer summer stream water temperatures to be around 12–18ºC (Meisner, 1990a). Projections of the suitable habitat available to them after a global warming scenario reveal that their breeding range in Canada will be severely restricted as groundwater warms up (Meisner, 1990b). Although they will benefit by increasing winter temperatures, they will suffer population declines through reduced egg hatching success due to lower dissolved oxygen concentrations on their warmer spawning beds (Meisner, 1990a). This same scenario will be faced by other salmonids (Regier *et al.*, 1990).

The natural habitat islands of alpine zones on mountain peaks are especially susceptible to shrinkage as climate warming moves their boundary upwards. MacDonald and Brown (1992) modeled the rate of loss of mammals in montane habitats as a function of the size of the habitat. They predicted that an increase of 3°C would result in the loss of species ranging from 9% to 62% on each mountain top.

Migration of climate zones northward may leave current reserves and parks as habitat islands. They could suffer species losses, both as a consequence of their size and isolation (Malcolm and

Markham, 1996), as well as due to a shrinkage of suitable habitat (Singh and Wheaton, 1991), since the protected pockets no longer experience the climatic conditions necessary for the preservation of the previously intended species (Myers, 1993).

Species invasions

Species invasions have been a regular occurrence in Canada since the arrival of Europeans and they have been associated with the decline or loss of many native species (e.g., Crossman, 1991). Invasion of southerly species into Canada is expected to occur as favourable climate conditions migrate northwards. The consequence of this invasion on the status of native species diversity is hard to predict. In general, species invasions have proven to be one of the biggest threats to global biodiversity (Vitousek *et al.*, 1996), and so some losses in Canada can be expected as a result.

There is as yet little unequivocal evidence that species ranges are expanding northward into Canada solely as a consequence of climate change. Most studies concentrate on the movement of individual sub-populations and fail to take into account the movement of the whole species range. However, Parmesan (1996) examined changes in the entire distribution of Edith's checkerspot butterfly and concluded that the species is moving its range northwards into British Columbia as southerly populations disappear and new ones arise on the northern border of its range.

Staniforth and Scott (1991) studied the invasion of southerly "weed" species into the subarctic zone around Churchill, Manitoba. The number of species and their local distribution has increased over the past 30 years. Of the 106 introduced weed species identified, 28% persisted locally by vegetative propagation or seed input. Most of these were confined to human-disturbed habitats around the town, particularly on the refuse tips. Establishment in natural areas was non-existent, but they predicted that more southerly weeds will become established in natural areas as the climate warms up.

Change in snow cover and other environmental conditions

Species richness in a region develops within a bounded range of climate patterns (e.g., Larsen, 1971). Changes in any one of the environmental variables related to the climate pattern could conceivably alter species diversity. Snow is one important environmental variable that serves to determine the abundances of many species in the Arctic and boreal zones in Canada (Walsh, 1987).

Climate change in the boreal region is expected to result in significantly more snowfall (CCC92 — Canadian Centre for Climate Modelling and Analysis 2nd Generation model). This will have significant impacts on many species. For example, the importance of snow cover in the composition of Arctic vegetation communities has been demonstrated by several authors (Schaefer and Messier, 1995; Scott and Rouse, 1995; Walker *et al.*, 1993). Scott and Rouse (1995) experimentally altered the amount of snow cover on upland tundra by positioning snow fences on experimental plots. They found a rapid change in plant community composition as a result of greater snow cover, particularly if it were to be accompanied by increased summer rainfall.

Ecosystem diversity

Ecosystems are non-linear, non-equilibrium, open systems that are capable of surprising behaviour (Woodley *et al.*, 1993). The importance of maintaining ecosystem diversity as a goal in preservation of biodiversity has recently been gaining wider acceptance (Schmidt, 1996), particularly because ecosystem functions control the fluxes of energy and materials across the landscape upon which species diversity relies (e.g., Pickett and Cadenasso, 1995)

Ecosystems are involved in feedbacks with the species that comprise them and there is now growing evidence that ecosystem functioning depends upon the species diversity it contains (e.g., Tilman, 1996; Tilman and Downing, 1994; Wedin and Tilman, 1996). For example, ecosystems able to show fluctuation in individual species contributions to the net biomass varied less in year-to-year changes in productivity (Tilman, 1996). Tilman further found that differential species responses to a fluctuating environment ensured stability at the ecosystem level, though not at the species level. Preservation of ecosystem diversity thus appears linked to the preservation of species diversity.

Ecosystem-level responses to climate change are probably the most difficult to determine because of their large temporal and spatial scales and complex dynamics. In addition to direct alterations of the landscape and ecosystem, the changes in diversity at the level of the genes or species brought about by climate change can also cause changes in the emergent behaviour at higher levels of organization (SCOPE, 1996). This complexity means that ecosystem responses may never be predictable and that "surprise" should be anticipated and planned for (Myers, 1995; Holling *et al*, 1995).

The surprise element comes from the non-linearities in the system. Ecosystems can absorb stresses over long periods without much outward sign of injury, then reach a catastrophic point at which the cumulative stresses finally reach critical proportions (reviewed in Myers, 1995; Carpenter *et al.*, 1995).

Some surprises to be wary of are a rapid re-sorting of ecosystems and landscape modification (Malcolm and Markham, 1996). Also likely are feedback processes that will lead to sudden and unpredictable trophic cascades and species shuffling (e.g., Chapin and Korner, 1994). As well, changes to keystone species resulting from climate change may be more important for ecosystem functioning than changes to overall species diversity (e.g., Stirling and Derocher, 1992, 1993; Srivastava and Jefferies, 1996).

Because ecosystems are prone to surprising shifts in their structure and composition, some argue that the emphasis should shift from the protection of diversity to the preservation of ecological integrity (e.g., Noss, 1990b; Woodley *et al.*, 1993; Angermeier and Karr, 1994). Ecological integrity, or *health*, reflects the ability of an ecosystem to self-organize itself over a broad range of organization levels and spatiotemporal scales (Kay and Schneider, 1992). Concepts of integrity emphasize preserving the adaptability and function of ecosystems rather than their current structure.

Unfortunately, while the concept of ecological integrity is intuitively understood by almost all ecologists, coming up with a universally agreed upon operational definition has proven challenging (Shrader-Frechette, 1994). Ultimately, however, most agree that a concept of biodiversity that encompasses both species richness and ecological function is necessary.

Some Canadian ecosystems that have been studied with respect to climate change scenarios include boreal lakes (e.g., Schindler *et al.*, 1990, 1996b), Arctic coastal marshes (Jefferies *et al.*, 1995; Ruess *et al.*, 1989), tundra–treeline dynamics (e.g., Payette *et al.*, 1989a), and Arctic marine food webs (e.g., Conover *et al.*, 1986; Stirling and Derocher, 1992, 1993).

The ways in which ecosystems might be affected by climate change will be discussed in the context of three Canadian examples.

Desertification of a subarctic saltmarsh

The salt marshes and lesser snow goose colony at La Perouse Bay, on the shores of Hudson Bay near Churchill, Manitoba, have been studied extensively for over 25 years (Cooke, 1987). A complex picture relating herbivory, nitrogen cycling, wildfowl migration, and the indirect impacts of climate change on an ecosystem has emerged.

A resident population of lesser snow geese, as well as migrants, use La Perouse Bay as a feeding site during spring migration. When the snow goose population pressure was low, the grazing by the geese in spring and summer stimulated the production of above-ground biomass of swards creating a positive feedback that encouraged plant growth and soil productivity (reviewed in Chapin *et al.*, 1992).

Increased winter survival due to a decline in hunting along their migration routes and changes in agricultural practices in their wintering range in the southern United States have helped fuel a population growth of snow geese averaging 8% per year. Snow geese are now feeding on winter wheat crops throughout their range, which increases juvenile survival. Since the mid-1950s, the mid-continental population of Snow geese has grown from 500,000 to 4,000,000 birds (Jefferies *et al.*, 1995).

A combination of greater population density on the migration routes northward combined with bad spring weather on the northern breeding grounds is delaying the passage of Lesser snow geese migrating to breeding grounds further north. The migrants now stage in La Perouse Bay, along with the resident geese returning to nest. As a consequence, the herbivory pressure is intense on the salt marshes during the time when there is little above-ground biomass to graze. Instead of grazing, the geese grub for rhizomes and shoots, which results in destruction of the salt-marsh swards and the exposure of bare sediments. Increased rates of evaporation in the frequently dry and warm summers on disturbed swards result in high soil salinities, which hinder establishment and growth of new vegetation (Srivastava and Jefferies, 1996). A positive feedback results between herbivory, plant growth, and salinity, leading to the desertification of the Arctic salt-marsh community.

Along with the salination, overall rates of soil nitrogen remineralization are reduced because of reductions in the biomass of swards. Soils around La Perouse Bay are limited by nitrogen, not phosphorous, so this exacerbates an already nitrogen-limited environment (Wilson, 1993). Coincident with the desertification has been a decline in populations of soil invertebrates, shorebirds, and some species of duck, such as widgeon, which are grazers (Fred Cooke, unpublished data).

Treeline dynamics and fire

Fire, both in its intensity and frequency, is a major determinant of the community structure in the boreal forest (e.g., Johnson and Fryer, 1989). The increase in warm and dry weather conditions predicted by (GCMs) should result in increased frequency and severity of fires throughout much of Canada's western boreal forest (e.g., Johnson and Larsen, 1991; Flannigan and Van Wagner, 1991). This could have significant impacts on species compositions and ecosystem functions, but the local effects on species diversity are dependent upon weather, soil conditions, and other disturbances (e.g., Mackay, 1995).

For example, the position of the treeline has been shown to depend sensitively on the dynamics of fire (e.g., Landhausser and Wein, 1993; Payette *et al.*, 1989a). Treeline dynamics can play a major role in determining ecosystem structure. Past treeline movements in the north have been associated with significant changes in species composition and phenology (Moser and MacDonald, 1990), including invertebrate community structure in the associated lakes (Walker and MacDonald, 1995) and herbaceous vegetation (Ritchie, 1987).

In the western boreal forest, climate change is expected to lead to warmer, drier summers (CCC92) and more frequent lightning storms, resulting in greater frequencies and intensities of fires (Shaver *et al.*, 1992). It is expected that warming conditions in the west will lead to a migration of the treeline northward despite the fires.

Increased fire frequency and intensity will also occur in the eastern boreal forests of Northern Québec. However, climate projections call for cooler weather throughout this region (CCC92). Increased fire frequency will cause the treeline to retreat farther south in this region since the black spruce forest is unable to regenerate as fast as tundra after a fire under the cooler conditions (Arseneault and Payette, 1992; Cook and Cole, 1991).

Arctic marine food webs

The Arctic food web has a complex structure which is based on overall marine productivity. There are five distinct levels culminating in the top carnivore, the polar bear (Welch *et al.*, 1992). Climate-induced changes to marine productivity will eventually be manifest in the top of the food chain causing changes in the reproductive performance and distribution of polar bears (Stirling and Derocher, 1993; see also Diamond, section 3 of this chapter).

There are numerous risks to this system from climate change including and perhaps foremost the impacts on sea ice and snow cover. In Hudson Bay, it is expected that the ocean will gradually warm and that the amount and duration of ice cover will decrease (CCC92). This has several consequences for productivity. First, there is extensive growth of algae under the polar ice which serves as the major food source for a diverse variety of zooplankton and crustaceans (Conover *et al.*, 1986). The melting of the ice reduces the substrate available to the algae, and the algae then are no longer present as a food source for the ice-associated zooplankton and crustaceans. The melting ice also decreases the salinity of the upper water column. An increased salinity gradient will decrease the rate of vertical flow of seawater that brings nutrients from deeper water up to the surface (Conover *et al.*, 1986), further reducing the productivity of phytoplankton.

With a decrease in primary productivity, the ocean will not be able to support existing levels of crustaceans and eventually fish (Conover *et al.*, 1986), upon which the seal populations depend (Welch *et al.*, 1992). Fewer seals means fewer polar bears (Derocher and Stirling, 1995). Arctic foxes which frequently follow polar bears onto the ice, feed on the scraps that the bears leave behind (Welch *et al.*, 1992). With fewer seal scraps to eat, the foxes may be forced to increase predation on nesting birds in summer, putting additional pressure on their populations.

Research needs

We need to know what our biodiversity is before we can assess the impacts that climate change may have on it. Currently, we know about 20% of the species that make up Canadian ecosystems and we know even less about their function. There is very little knowledge of the hyperdiverse groups (e.g. fungi and arthropods) that constitute over 80% of our biodiversity and form the infrastructure that drives ecosystem dynamics. We need a baseline knowledge of species-level biodiversity in Canadian ecosystems before we can adequately determine the response of the biological community to climate change.

There is a lack of data on the pattern of genetic diversity found in wild, healthy populations, particularly in those species that are not commercially exploited. We need to know more about natural patterns of genetic diversity before we can detect whether it has been reduced as a consequence of climate change.

The diversity and sensitivity to climate change of soil microbes and nonvascular plants requires more attention, as these may be highly significant in determining future ecosystem function.
Predicting responses of biological communities and ecosystem processes to changes in climate will depend in part upon knowing the kinds of dynamical behaviour that are possible. There is a need for integrative studies of ecosystem-level behaviours.

Conclusion

The sudden changes in climate to be experienced in Canada bring with them opportunity as well as loss for biodiversity. However, it will be impossible to make exact predictions of which species assemblages will form and how diverse they will be. If the integrity of the landscape and ecosystem processes are preserved, then perhaps biodiversity can be maintained or even enhanced in response to the changes in the environment brought about by climate change in Canada.

However, nature has a profound capacity to surprise us, and so we must be cautious in making any predictions of how biodiversity will respond to climate change. There is also a clear warning in the paleo record that catastrophic changes in climate have often been associated with past periods of mass extinction (Crowley and North, 1988; Signor, 1990).

IMPACTS ON WILDLIFE

Introduction

Scope of wildlife in the chapter

Wildlife is defined in *A Wildlife Policy for Canada* as "all wild organisms and their habitats — including wild plants, invertebrates, and microorganisms, as well as fishes, amphibians, reptiles, and the birds and mammals traditionally regarded as wildlife" (Wildlife Ministers' Council of Canada, 1990).Two points need to be made about this definition." First, it includes groups of organisms traditionally considered as consumable resources (e.g., fish and forest trees), which are therefore treated as separate economic sectors within the Canada Country Study: Climate Impacts and Adaptation; these related sectors will be referred to as appropriate, but they will not be treated in detail. Second, it does not necessarily focus on those groups which are hunted, either for sport (the majority), for subsistence food, or for their fur. In both these respects, the modern use of the term "wildlife" goes far beyond traditional uses of the term, though these traditional uses are still strongly reflected in Canadian policies, laws, and government structures.

The emphasis in this chapter is on characteristics of wildlife populations which have been identified as vulnerable to climate variability and change. Most wildlife populations are driven, first and foremost, by the quality and quantity of their habitat; accordingly, effects of climate on habitat are likely to outweigh those of any other forcing agent. Habitat is treated in depth elsewhere in the Canada Country Study: Climate Impacts and Adaptation, under at least three other headings, namely unmanaged ecosystems, biodiversity, and changing landscapes. In this chapter, the emphasis will therefore be on direct effects of climate on populations, rather than on habitats themselves. Nonetheless, indirect effects acting through habitat changes cannot be ignored if a full understanding of climate impacts is to be achieved. Some overlap with other sections is thus inevitable.

Non-climate influences on wildlife

While recognizing that wildlife populations are driven primarily by quantity and quality of habitat, competitive, predator–prey, and host–parasite relationships, as well as contamination by toxic or other harmful chemicals, nonetheless play important roles. Climate will affect these other components of the community, in addition to its effects on the wildlife population of interest. Any factor driving these influences will, therefore, also affect this population. In such an interlocking complex of potential influences, teasing out the possible effects of climate represents a major scientific challenge.

Added to these environmental shaping forces are those imposed by human society. Government wildlife management policies are driven by the "hunting paradigm," which assumes that populations are controlled by mortality of adults and therefore manipulates the hunting component of that mortality through regulating the numbers to be killed by hunters. Yet wildlife managers generally agree that quality and quantity of habitat generally has more influence on the long-term size of wildlife populations than does hunting mortality. Habitat quality and quantity are land-use issues and thus involve a much wider public than wildlife managers alone. Wildlife legislation in Canada does not adequately reflect the need to influence habitat more than hunting mortality, leaving inadequate tools for direct management of most wildlife populations.

Links to other sectors and chapters in the Canada Country Study: Climate Change Impacts and Adaptation

The other sectors to which wildlife populations are most closely linked are forestry (both as wildlife habitat, and as being comprised of wildlife species — i.e., plants and other organisms), agriculture, fisheries, and biodiversity, which was dealt with earlier in this chapter forestry and agriculture together determine land use — and therefore wildlife habitats — across a large proportion of the land area of Canada, and wildlife populations are the building blocks of biodiversity, of forests, and of fisheries; to treat them separately may help to organise discussion, but it is conceptually arbitrary.

An example of linkages to agriculture is given later (see "Changes in population size — prairie ducks, drought, and agriculture"). An example in forestry involves possible northward movements into the boreal forest of spruce budworm as the climate warms. Several species of insectivorous bird —mainly warblers, family *Parulidae* but also evening grosbeak (Crawford *et al.*, 1983) — are important natural predators of spruce budworm (Holling, 1988). Significant declines in some of these species, particularly the neotropical migrant warblers, have been detected recently (Kirk *et al.*, 1997), though it is unclear how much of the declines is attributable to loss of tropical forest habitat in their winter quarters, and how much to events (including harvesting) in their boreal forest breeding grounds. "Neotropical migrants couple boreal regions to tropical regions and, through their effects on insect outbreaks, are an example of the unexpected control that animals exert over ecosystem functioning" (Pastor, 1996).

Links to cross-cutting issues

The cross-cutting issues of most obvious relevance to wildlife are changing landscapes, since these define the habitats available to wildlife; extreme weather events, and integrated air issues, both describing atmospheric impacts on wildlife populations; and extra-territorial influences, particularly in the case of migratory species (mostly birds) which spend significant parts of their life cycles outside Canada's political jurisdiction.

Regional biases

Climatic influences are sometimes most obvious where climate is most extreme. Accordingly, much of the literature on climate impacts on wildlife comes from the Arctic, or from the prairies, where cold and drought, respectively, have dramatic effects on wildlife. In parts of the country more dominated by the built environment, or with more moderate climates, possible impacts of climate tend to be overlooked and are consequently less commonly investigated.

Impacts of climate variability and change on wildlife

The ability to assess possible impacts of climate variability and change on wildlife is constrained by a limited knowledge of the effects of climate on wildlife (Diamond, 1990). Relationships between climate variables and wildlife responses abound in the literature (Whyte and Ignatiuk, 1989), but there have been few attempts to integrate this piecemeal information to describe general relationships between climate and wildlife (but see Root, 1988a, b).

While impacts of climate on wildlife habitats are covered in more detail elsewhere, a few points need to be made to set the scene. The first is that the mixes of species that make up the plant communities with which we are familiar, are not fixed communities that will respond synchronously as a whole to changing climates; rather, they are temporary associations of species that share a tolerance for environmental conditions that are currently coincident. Many of these species have slightly different climatic optima, and will persist for different periods, and migrate at different rates, as the climate shifts; accordingly, changes in climate will cause them to disassociate and re-sort into different combinations of new plant and animal species (Van Devender and Spaulding, 1979; Peters, 1990). Thus, the inter-specific relationships within present-day communities, which affect our current understanding of the environmental tolerance of a species, may not persist in future climates.

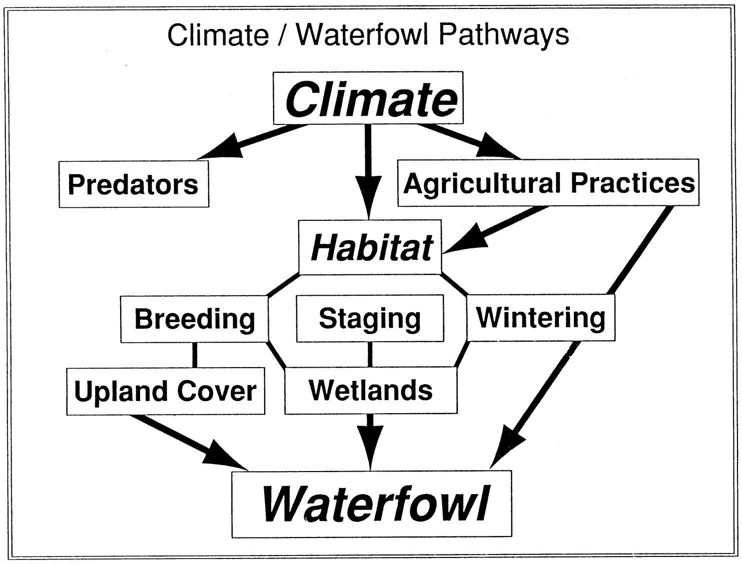
Changes in habitat distribution

The current distribution of biomes, ecozones, and plant associations is driven by interactions between climate and soils, with the climatic influence clearly reflected as bands of major habitat types (e.g., tundra, forest, and grassland) arranged in a roughly latitudinal zonation around the planet. As a broad generalization, a rise in average global temperature can be expected to drive these zones towards the poles (Flohn, 1979); however, major uncertainties remain. These include both the likely extent (northern and southern limits) of each major habitat type, as well as its composition. For example, will boreal forest as we currently recognize it retain the mix of species with which we are familiar? Or will species re-sort themselves, as suggested above, into entirely different communities? One attempt to model these changes (Rizzo and Wiken, 1992) predicted not only major changes in ecological boundaries, but also significant internal changes in the composition of these ecosystems. Lenihan and Neilson (1995), using the Canadian Climate–Vegetation Model (CCVM), queried two doubled- CO_2 scenarios and found that they both predicted reduced extent of tundra and subarctic woodland formations, northward shifts and increased extent of boreal and temperate forest, and expanded dry woodland and prairie vegetation. Both scenarios were also accompanied by considerable changes in the composition of some vegetation types. The CCVM is driven by climatic parameters that influence the distribution of vegetation more directly than those usually employed in general circulation models (GCMs), and so is likely to give more realistic results than predictions based on conventional GCM outputs.

It also needs to be recognized that the current suitability as wildlife habitat of most ecosystems in Canada is determined as much by human management of those habitats (especially through agriculture, forestry, and fisheries) as it is through natural characteristics of those systems. It follows that human changes in land and water use may have at least as much influence on the quantity and quality of wildlife habitat as changes induced directly by climate change.

The major pathways by which climate change will affect wildlife habitat are illustrated for waterfowl in Figure 2.1 (from Diamond and Brace, 1991); the same principles can be applied to other groups of wildlife. These pathways emphasize that climate variability and change will affect agricultural practices which in turn will affect habitat, in parallel with - and probably exceeding - direct responses of the habitat to the changing climate. Since most wildlife habitats outside the arctic are now managed, at least to some extent, it follows that changes in management practices will affect wildlife habitat, in addition to effects induced directly by climate change. For example, the Canadian prairies are now predominantly agricultural, and their future suitability for wildlife will depend on how farmers respond to changing climate. A change from wheat to dryland pasture will favour wildlife characteristic of short-grass habitats, for example (see Owens and Myres, 1973; Diamond, 1993). Similarly, at least half the forested lands of Canada are managed for forest products (timber and pulp), not just by logging but by fire suppression and the fragmentation and road-building that accompany logging; the changes brought about in forestry practices will have probably as much influence on forest-wildlife habitat quality, as will the changes induced directly by the changing climate. That is, human responses to climate change may affect wildlife populations as much as the change itself. A further point to keep in mind is that many wildlife species are able to adapt to some change in habitat conditions, including that which may occur as a result of climate change.

Figure 2.1 Major pathways through which climate may affect waterfowl populations



Leaving aside changes in distribution in vegetation types for detailed treatment by other chapters, there remain three habitats at risk that are not defined principally by their vegetation. These are low-lying offshore islands, coastal mudflats, and marine ecosystems.

Coastal mudflats

Many species of shorebird (plovers, sandpipers, and phalaropes) breed in the Canadian Arctic and migrate to wintering grounds in tropical or temperate South America each fall. To fuel that migration, they depend on abundant food supplies in safe foraging sites en route. The most important such staging grounds in Canada have been identified as James Bay (Ontario), the Bay of Fundy (New Brunswick and Nova Scotia), and the Fraser Delta (British Columbia). All these include large expanses of coastal mudflats rich in invertebrates (e.g., *Corophium volutator* in the Bay of Fundy) and protected from terrestrial predators by large stretches of mud. In the Bay of Fundy, for example, between 50% and 90% of the world population of semipalmated sandpiper migrates through the site en route from the Arctic to South America each fall (Mawhinney *et al.*, 1993). During their stay of about 15 days in the Bay of Fundy, semipalmated sandpipers nearly double their weight (from 20–25 g to about 40 g) before departing on a non-stop trans-oceanic flight of 60–70 hours to their wintering grounds 4,000 km away in Suriname (Hicklin and Smith, 1984, Stoddard *et al.*, 1983). Clearly the loss of this habitat, or serious reduction in its extent, could have very serious consequences for the population of over two million birds (Mawhinney *et al.*, 1993) that currently use this site.

All these sites are coastal mudflats that are liable to be destabilized, and eventually inundated, by a rise in sea level. Although flat areas immediately inland will then provide potential future mudflats to replace them, these lands are currently heavily used for agriculture or other forms of development that will not lightly be given up for shorebird habitat. Significant changes in the characteristics of the Bay of Fundy mudflats, their invertebrate densities, and their use by shorebirds, are already evident, though the extent to which these changes may be related to sea-level rise is unclear (Percy *et al.*, 1996).

Marine ecosystems

This section refers to seabirds and their marine prey; fisher and marine mammals are treated separately. Dunbar (1973, 1976, 1985, Dunbar and Thompson, 1979) has reviewed some changes in marine life attributed to climate in the Canadian Arctic and nearby regions.

Marine ecosystems show global, regional, and local patterns of zonation, much as terrestrial biomes do. Marine ecozones are characterized by physical properties, notably temperature, salinity, and current speed and direction (Ekman, 1967). Each zone has characteristic communities of plants and animals, again as terrestrial ecozones do. Distributions of seabirds throughout the world are related to these distinct patterns (Murphy, 1936), chiefly by association with particular species or communities of prey (plankton, krill, squid, and fish). Impacts of climate change on seabird populations are likely to be mediated chiefly through responses of their prey to changes in the distribution of water bodies in the sea.

In Atlantic Canada, for example, the cold Labrador Current will likely extend further south as the Greenland ice cap melts and provides increased inputs of cold, fresh water to Baffin Bay (Conover, 1995). Since this current dominates the regional climate, global warming actually produces local cooling in Atlantic Canada (see Atlantic Region report). Lower water temperatures in Atlantic Canadian waters in recent years may be partly a result of this process, and have been linked by some with the collapse (or lack of recovery) of Atlantic cod stocks. Concurrently, some typically cold-water seabirds have extended their breeding range southwards, including Northern Fulmar, which colonized southeast Labrador and eastern Newfoundland in the 1970s (Brown and Nettleship, 1984), black-legged kittiwake, which colonized the Bay of Fundy in the late 1980s (Kehoe, 1994), and razorbill, which very recently established a new site in the Bay of Fundy (Mawhinney and Sears, 1996).

Recent changes in distribution of marine fish and invertebrates off Atlantic Canada suggest that all levels of the marine food chain may be responding to southward extensions of colder waters; whether these are attributable to long-term global warming, or to short-term cycling of warm and cold periods, remains to be seen (Conover, 1995).

The distribution of seabird breeding colonies in the Arctic is closely tied to polynyas and coasts where the sea ice breaks up early: southwest Greenland, Hudson Strait, and the North Water polynya at the top of Baffin Bay (Brown, 1991). Global warming is likely to benefit these seabirds by melting sea ice earlier, giving the birds access to feeding areas; by extending the growing period for phytoplankton and thus for the whole very short marine Arctic food cycle; and the earlier melting of snow will give birds nesting on cliff ledges and in boulder screes earlier access to nest sites (Brown, 1991). However, if warming proceeds to the point of severely reducing the extent of sea ice, overall food supplies may decline, as much of the Arctic food web depends on algae living under the ice (Bradstreet and Cross, 1982).

Other consequences of a reduction in Arctic sea-ice cover may be negative for a variety of marine mammals. The distribution and numbers of Arctic seals are strongly dependent on ice cover and if this is reduced so, ultimately, will be seal populations; as long-lived animals with low reproductive rates they may be slow to adapt (Stirling and Derocher, 1992). Seals are also the main prey of polar bears; at the southern edge of their range, in James and Hudson Bays, polar bears already have to fast for four months when the sea ice melts in the summer. Prolonging the ice-free period will increase nutritional stress on the population until they are no longer able to store enough fat to survive. Early signs of impact will include declining body condition, lowered reproductive rates, reduced survival of cubs, and an increase in polar bear–human interactions. Although most of these parameters are currently detectable in the polar bears of western Hudson Bay, it cannot yet be determined whether or not climate change could be involved. Should the Arctic Ocean become seasonally ice free for a long enough period, it is likely polar bears would become extinct (Stirling and Derocher, 1992).

Close correspondence between trends in weather, abundance of plankton and herring, and several reproductive parameters of a marine gull (the black-legged kittiwake *Rissa tridactyla*), were found over a 33-yr time period in the North Sea (Aebischer *et al.*, 1990). It is not clear from this remarkable study whether the similarity in patterns is due to causal linkages up the food chain, with the base of the food-chain driven by weather; or to independent climatic forcing of each level. Likely the mechanisms involved are more complex than either of these alternatives. That the weather signal is strong enough to be reflected at all trophic levels, argues strongly for the potential of marine food webs to provide clear signals of global climatic change.

Changes in population distribution

Although most changes in wildlife distribution are likely to result primarily from changes in distribution of habitat, changes in climate may also drive changes in distribution more directly. Homeothermic (loosely, "warm-blooded") animals are less likely to show such effects than poikilotherms ("cold-blooded" animals), but even birds respond directly to climate despite their highly efficient insulation.

The climatic relationships of winter distributions of birds in North America have been analyzed by Root (1988a, b), using many decades of data from the Christmas Bird Counts made by volunteers since the early 1900s. The winter range of most species of songbird in North America is determined mostly by habitat distribution; but once that is taken into account, the northern boundary of the winter range of many species of songbird coincides with January isotherms reflecting daily energy requirements of about 2.4 times the Basal Metabolic Rate (Root, 1988a, b). Assuming this relationship is causative, winter warming would be expected to lead to northward shifts of the winter range of many songbirds.

Similarly, comprehensive analyses of summer distributions of birds have not been undertaken, though the digital data do exist (Price *et al.*, 1995) and have been used to look for trends over the last 30 years (Sauer *et al.*, 1997). A detailed analysis by James and Shugart (1974) of the start of the laying season of the American robin, using a Principal Component Analysis of seven climate variables, showed that a combination of April wet and dry bulb temperatures was the best predictor of the beginning of the nesting period. The authors proposed that their graphic model of the "climate space" of American robins could be extended to predict the geographic range of the species, and changes in that range according to changes in climate (particularly, in this case, April temperatures). The potential for this approach to be applied more widely to North American breeding birds has not been realized, but the possibility of relating breeding phenology (timing) and success to climate change is being explored currently using an aerial insectivore, the tree swallow (Hoyt, 1996).

Birds that feed on insects in flight — aerial insectivores — are particularly vulnerable to weather in the spring and early summer. Mortality of adults from cold snaps in April and May are relatively common (e.g., Erskine, 1978; Henny *et al.*, 1982; Krapu, 1986; Sealy, 1966), and growing young are vulnerable in June when adults must spend most time catching food rather than brooding the chicks. Cold and rain at this time, such as occurred in 1993 in southern Saskatchewan, can lead to mass mortality of chicks because the adults have to spend more time trying to find food and cannot keep the young warm (Hoyt, 1996). Increased frequency of such extreme events may cause enough mortality to lead to a shift in distribution away from regions experiencing such weather patterns. Some other aerial insectivores, particularly swifts (family *Apodidae*), are metabolically better adapted to cold, wet summer weather; the chicks have variable growth rates and can go into torpor to conserve energy through lean periods (Lack, 1973).

Changes in productivity and survival

Productivity

Tree swallows (above) offer an example of a species which is vulnerable to lowered productivity from extreme summer weather events. Increased summer precipitation will likely have negative impacts on a wide variety of birds to the extent that it reduces time available for feeding; but to the extent that (especially combined with warmer temperatures) it may increase primary and secondary productivity, the effect may be beneficial. As a generalization, an increase in average summer precipitation might be expected to enhance bird productivity in general, but increased frequency of summer storms may not be, especially if they occur at critical times in the breeding cycle. A sudden rise in water levels can be devastating for birds nesting close to water; diving ducks, and especially common loons, which nest within centimetres of the water surface, are especially vulnerable. Heavy rain associated with the passage through the Maritimes of tropical storm Bertha in mid-July 1996, for example, raised water levels in southwestern New Brunswick very suddenly and washed out several loon nests within a few hours (Benjamin and Diamond, 1996). The same storm washed most nests of the recently established kittiwake colony described by Kehoe (1994) off the cliffs of their nesting island, and caused significant mortality of chicks of four species of seabird on Machias Seal Island in the Bay of Fundy (Amey, 1997).

Survival

Most species of wildlife breed during summer rather than winter, so changes to the winter climate will affect survival rather than productivity. Changes to Canadian winter temperatures alone will likely have little effect, but ice storms and freezing rain — likely to become more frequent with warmer winters — can have serious effects on a variety of organisms. When buds, fruits, and bark are made inaccessible to small birds by a coating of ice, they cannot meet their energy needs (many really small birds, such as chickadees, need to feed virtually throughout the daylight hours to meet their energy needs in winter). Layers of ice above the snow make lichen and other vegetation inaccessible to peary caribou in the Arctic islands; recent population declines of some of these herds have been linked to increased frequency of freezing rain in winter (Miller *et al.*, 1977, 1982).

Winter snow depth is well known to affect the distribution of many mammals, especially ungulates and wolves, at both local and geographic scales (Formozov, 1946; Telfer and Kelsall, 1984). Ungulates differ in their structural and behavioural adaptations to snow. At the extremes are bison, with their chest close to the ground, heavy body and small feet, liable to bog down in deep snow and to break through a shallow crust, and restricted to feeding on plants growing beneath the snow; and caribou, with a chest relatively high above the ground, light body weight, and wide snowshoe-like feet enhanced by highly developed dew claws. Current distributions of ungulate communities correspond well with their adaptations to type and depth of snow in the regions in which they occur. Shifts in winter climate will likely lead to shifting suitability of ranges for these species. Such changes occurred between the Little Ice Age (1300-1850), when moose and caribou occupied Nova Scotia, and the period after 1850, when milder winters allowed white-tailed deer to recolonise the province at the expense of caribou (Telfer, 1967). Predator-prey relations will shift, too, with changing distributions of snow types; wolves flounder in deep snow that caribou can cross, but can follow moose which are no better suited to travel through soft snow (Telfer and Kelsall, 1984).

Changes in population size

Many species of wildlife show cyclic changes in population size (e.g., Steen *et al.*, 1990). Much research has been devoted to possible drivers of these cycles (in addition to confirming whether or not the cycles are really predictable rather than random fluctuations). Recognition of the possible role of climate as a driver of these cycles is relatively recent.

Lynx and long-term climate cycles

Perhaps the best-known such population cycle is that of lynx, a predatory mammal of northern forests (Sinclair *et al.*, 1993; Scott and Craine, 1993). Population cycles of lynx commonly follow the approximately 10-year cycle of their principal prey, the snowshoe hare. Using tree-ring growth data from Churchill (Manitoba) as a climate proxy, Scott and Craine (1993) related long-term phases of the lynx cycle to three phases in the general atmospheric circulation. They suggested that reduced prey populations during cool periods lead to specialization by lynx, leading in turn to the initiation of a population cycle; in warmer climates, the predators are able to switch to a wider range of prey and lynx populations no longer cycle.

Prairie ducks, drought, and agriculture

Less widely known are the fluctuations of prairie ducks (family *Anatidae*), whose numbers oscillate approximately every five to ten years, more or less in synchrony with the number of ponds available in spring (Kiel *et al.*, 1972, Diamond and Brace, 1991). Ducks require wetlands to feed in, and permanent vegetation close by in which to nest. Extreme drought in the principal breeding grounds on the prairies can displace ducks to the north, into the boreal forest or even Arctic tundra biomes (Hansen and McKnight, 1964). Steep declines in duck numbers in the 1980s led to the establishment of the North American Waterfowl Management Plan (NAWMP) (Nelson *et al.*, 1991), designed to restore nesting habitat to waterfowl throughout North America, but especially in the prairies, where most of the continental population breeds (Batt *et al.*, 1989). Much debate has centred around the relative contributions of intensified agriculture (through loss of nesting habitat and drainage of wetlands) and climate to declines in duck populations (e.g., Turner *et al.*, 1987, Johnson and Shaffer, 1987, Diamond and Brace, 1991). The relation between long-term changes in land use and climate, and duck abundance over 30 years, was examined by Bethke and Nudds (1995). They used duck counts from annual aerial surveys, corrected by ground counts, and precipitation records, to relate indices of abundance of 10 species of ducks to indices of wetland conditions from 1955 through 1974. They then used these relationships to predict the abundance of each species from 1975-1989, and attributed "deficits" (i.e., actual populations below predicted ones) to the effects of intensified agriculture. They found that the effects of agriculture were negligible in the eastern prairies, where intensive agriculture had already destroyed most waterfowl habitat before 1951, and increased towards the west and north, where much more waterfowl habitat still remains.

Two points about this study are particularly notable: (1) the authors went to great pains to find the most appropriate combination of climate variables (Conserved Soil Moisture, which includes precipitation over the previous 21 months and weights winter precipitation more heavily than summer (Williams and Robertson, 1965)); and (2) this study is unique in bringing many different sources of data (waterfowl, climate, land use) to bear on one problem and, in so doing, considerably increasing our understanding of how they interact in a complex ecosystem. In so doing they have brought modern computing power to bear on concepts whose fundamentals were developed much earlier (Boyd, 1981, 1985) but were intractable without sophisticated analytical and computing resources.

This case illustrates not only the potential for using existing data to disentangle complex interactions between human land-use, climate, and wildlife populations, but also that the particular climate variables important in each situation need to be defined carefully. In this case, the accumulation of water in the soil over a period of nearly two years proved to be the major driver of responses by an important component of the wetland ecosystem.

Arctic-nesting geese[1]

At most latitudes in the Canadian North, the west is warmer than the east; the treeline reflects this, reaching the Arctic Circle in the northwest but not above 53°N in Northern Québec. Yet most geese breed in the eastern Arctic, and their greatest recent increases in numbers have been in northern Keewatin, south of Queen Maud Gulf, and northwestern Baffin Island, both areas where snow usually clears later than further north or south. This increase in goose populations in the central Arctic has come about with an increase in mean summer temperature at the rate of 0.1°C per year during 1977–1988 (Etkin, 1991), and may have more to do with changing agricultural practices and hunting pressures in the south than with temperatures in the north.

Changes in timing and success of breeding[1]

In many Arctic birds, breeding is initiated at or shortly after snow melt; late melt delays breeding and often lowers breeding productivity as well, either for energetic reasons (e.g., Atlantic brant (Barry, 1962), lesser snow geese (Davies and Cooke, 1983), Ross's goose (Ryder, 1967)), or through increased predation (e.g., Byrkjedal, 1980). In extreme cases, a late spring may encourage geese to move to entirely new breeding areas (McCormick, 1988), or lead them to abandon attempts to breed that year. For long-lived birds such as geese, it is important for adults not to endanger their own survival by nesting so late that they might be unable to complete regrowth of flight feathers before the onset of winter.

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[1] based on Boyd, 1988

Some snow cover at the time of arrival can also be beneficial to some species such as pinkfooted geese because it protects their food plants from damage by frost during early stages of growth, when they are of highest nutritional value (Fox *et al.*, 1991). These geese crowd to feed at the edges of melting snow patches, not using the frosted shoots on open ground. There is thus a balancing of risks and benefits to nesting geese in the timing of snow-melt, with very early melting reducing the amount of high-quality food and so being unhelpful to geese trying to improve their condition before nesting. Similar dependence on plants emerging from melting snow patches has been seen in white-fronted and Canada geese at their breeding sites on the Kent peninsula, Northwest Territories in late May and early June (Boyd and Diamond, 1993).

The influence of date of snow-melt on the timing of breeding has been documented in the Hudson Bay region, where nesting dates of three populations of two species of goose were earlier in the 1970s and 1980s than in the period 1964–1970, when temperatures were much colder (Boyd, 1982, MacInnes *et al.*, 1990).

The breeding success of Arctic-nesting geese and shorebirds often varies in parallel among species from the same geographic region. How much of this variation is caused by weather on the breeding grounds (e.g., Boyd, 1987), or by cycles in predators (such as arctic fox) and their alternative prey (mostly voles and lemmings) (e.g., Summers and Underhill, 1987) remains controversial; both factors are probably important (Dhondt, 1987).

Breeding in many Arctic shorebirds is timed so that chicks hatch at the same time as their insect food supply (Holmes, 1966); uncoupling of the current linkages between temperature, snow-melt, and the physiologies of shorebirds and insects could have significant effects on breeding success (Green *et al.*, 1977). High summer temperatures may increase the productivity of the ecosystem, but may also have a negative impact on incubation behaviour and the growth and survival of the young of many species of high-latitude birds which are ill adapted to predicted daily maxima of 30°C and above.

When annual indices of breeding success in goose populations are correlated with measures of spring conditions (such as mean June temperature, decreasing snow depth, or the date when daily temperature rises above 0°C), statistically significant relationships are often found (Boyd, 1988). Typically, the responses are asymmetrical; low temperatures and late snow cover are associated with poor breeding success, but above average temperatures, or unusually early snow clearance, are not especially strongly linked to good breeding success.

In many seabirds, both breeding distribution and the timing of breeding are related to sea-surface temperatures (Harris and Wanless, 1989). Since these temperatures are likely to change as the climate warms, noticeable changes in distribution and breeding success of seabirds can be expected. Climatic fluctuations in the northwest Atlantic over the last few hundred years, and their effects on fish and seabird populations, were reviewed by Dunbar (1985) and Dunbar and Thompson (1979).

Changes in migration patterns

The timing of migration is well known to correlate closely with weather conditions; the departure of snow geese from winter quarters, for example, is triggered by temperatures above 18°C (Flickinger, 1981), and the northward progress of Canada geese on spring migration is correlated with the 35°F (1.7°C) isotherm (Lincoln, 1979). In general, weather systems, rather than actual temperatures, probably govern the timing of migration; peak waterfowl migration in fall usually occurs shortly after the passage of a cold front (Hochbaum, 1955) whereas in spring, migrants move north on the warm sector of low pressure systems (Lincoln, 1979). Thus the distribution of air masses is at least as important as temperatures and wind strengths (Blokpoel and Gauthier, 1975).

Timing of many events in a bird's annual cycle, including migration, breeding and moult, is frequently triggered by changes in daylength (Murton and Westwood, 1977). This timing mechanism may prove maladaptive in a changing climate, when the linkage between daylength and changing food supply, habitat availability, movement of air masses etc. becomes uncoupled as these factors change while daylength does not.

The importance of coastal mudflats as staging grounds for shorebirds has been mentioned already ("Changes in habitat distribution — coastal mudflats"), and the most important such areas in Canada identified. Loss of these sites is potentially catastrophic for shorebirds, unless they are replaced by others, for which there are no obvious candidates that are not equally vulnerable. However, on the bright side, most of the shorebirds that pass through the Bay of Fundy in the fall, use alternate routes through the centre of the continent in spring. Some of the sites they use then, such as the Quill Lakes in Saskatchewan (Alexander *et al.*, 1996), may offer alternatives to the Bay of Fundy in fall also. However, if a general drying trend occurs in the Canadian prairies and the Great Plains, as most models predict (Mc.G. Tegart *et al.*, 1990), staging habitats will decline in quantity, and probably in quality. Increased water temperatures and salinity in the remaining prairie wetlands could well lead to increased frequency and severity of disease outbreaks, especially of botulism and avian cholera (Wobeser, 1994), with potentially important impacts on geese, ducks, and shorebirds.

While a change in migration route from coastal to inland may seem unlikely, there have been recent demonstrations of the ability of birds to change their migration patterns very quickly in response to changes in resources, *viz.* the switch in migration routes and wintering areas by several species of diving duck in both Europe and North America to take advantage of colonisation of inland waters by zebra mussels *Dreissena polymorpha* (Wormington and Leach, 1992; Stanczykowska *et al.*, 1990).

Arctic-nesting geese are affected by agricultural practices in their spring staging areas in the prairie provinces and the northern United States. Snow geese moving north lay down fat stores for breeding by feeding on corn and grain residues in the Canadian prairies; harvesting weather in the previous fall can affect the amount of food left in the fields over winter, to be exploited by northward-migrating geese next spring (Alisauskas and Ankney, 1992). Davies and Cooke (1983) suggested that soil moisture conditions in spring may influence the spring carbohydrate nutrition and fat storage of snow geese, by affecting the start and the speed of new plant growth. Alisauskas and Ankney (1992) found that snow geese in farmed staging areas in spring fed largely on waste corn from the previous fall, not on green plants. New growth is likely to remain important in staging areas north of intensively farmed land and in breeding areas.

International linkages

Many shorebirds migrating north in spring time their migration to coincide with the spawning of horseshoe crabs in Delaware Bay, feeding on the nutrient-rich eggs laid by the crabs on the shoreline. Delaware Bay thus plays a similar role in the life cycles of migratory shorebirds in spring as the Bay of Fundy does in fall; it is an essential staging ground where birds feed to fatten up for the next leg of the migratory journey (Lester and Myers, 1989). Should climate change alter the timing of either the shorebirds or the crabs, the relation between the two would become uncoupled, with potentially serious consequences for the shorebirds.

Migratory species emphasize the point that climate change is a global phenomenon with causes and consequences that go far beyond any nation's borders. An example involving migratory birds in the Old World, for which there is not yet any parallel in the western hemisphere, is the decline in Europe of the common whitethroat These small insectivorous songbirds were once one of the commonest species in the British countryside; they birds winter in the sahel zone of West Africa, which was the victim of serious drought in the 1970s. Many whitethroats must have been unable to survive the arid conditions which persisted for several years, because they did not return to Europe and the breeding populations have still not recovered to pre-drought levels (Winstanley *et al.*, 1974; Elkins, 1983).

Extreme events

Storms at any time of year can have severe effects on birds. Cold snaps in late spring frequently cause large-scale mortality in small birds (see "Changes in population distribution"), and summer storms can kill shorebirds on their breeding grounds (e.g., Morrison, 1975). Observations of such extreme events are usually descriptive, and it is uncertain what role they may play in determining long-term population levels.

In the case of Arctic-nesting geese, however, there are well-documented cases of the impact of extreme winter cold. In the southern Unites States, cold spells reduce the availability of green vegetation in ploughed and stubble fields and drive wintering snow geese into pasture, fallow fields or their ancestral habitat, coastal marshes (Alisauskas *et al.*, 1988). More dramatically, in the very hard winter of 1976–1977, two-thirds of the 125,000 brant wintering on the United StatesAtlantic coast starved and froze to death (Rogers, 1979). Yet the most important outcome of the disaster was a positive one for the survivors. Driven from their normal feeding on *Zostera* and other algae in the intertidal zone by the freezing of the foreshore, they moved inland to short grasses on airfields, golf courses and suburban lawns. Their descendants now turn regularly to short inland grasslands in late winter, when foreshore foods are depleted. There are other examples in Europe of lasting changes in distribution resulting from movements forced by exceptionally hard weather. For example, in the cold winter of 1978–1979 about 5,000 Canada geese, from the Swedish breeding population, visited northern Germany for the first time. This has led to the establishment of a wintering tradition, with 3,000–4,000 remaining in Germany each year (Prokosch, 1991).

Adaptation Approaches and Options

The wildlife populations most likely to be at risk from climate change and variability are those already under stress or threat from other factors. Of the staging grounds of migratory shorebirds, for example, Delaware Bay is already threatened by coastal development, and the Bay of Fundy mudflats by changes in tidal patterns arising from damming of freshwater inflows, and from harvesting of baitworm (the polychaete *Glycera dibranchiata*) (Percy *et al.*, 1996). Much has been done to secure important staging grounds for shorebirds under the Western Hemisphere Shorebird Reserve Network (Myers *et al.*, 1987), but any conservation strategy that relies on protected areas "will enter a phase of dubious application. Protected lands will become uninhabitable by the very species, habitats, and communities they were designed to preserve because of the shifting climatic conditions (Peters and Darling, 1985)" (Lester and Myers, 1989).

In the worst cases, where populations decline steeply and are evidently at risk of extinction, management will have to become increasingly intrusive if it is to succeed. Peters and Darling (1985) suggested that options to be considered seriously might include: more and larger protected areas, connected by corridors; transplantation programs; selective breeding of parts of the population best adapted to the new climate; and off-site storage of genetic material, making up an increasingly aggressive field of "salvage ecology". Additional considerations could include protecting future key areas, such as areas that are likely to be flooded, and managing at a landscape level so that human activities such as forestry and agriculture can be integrated with the oveall habitat considerations.

Knowledge gaps

Interest in effects of climate in the research community is relatively recent (but note, e.g., James, 1970, James and Shugart, 1974). In Canada, a workshop on Climate Change and Wildlife held by Canadian Wildlife Service in 1989 (Canadian Wildlife Service, 1989) has not led to any noticeable change in policy or research priorities. Although much information on effects of *weather* — especially extreme events — finds its way into the literature, there has been no attempt to integrate these disparate sources into an evaluation of the overall effects of *climate*. Information remains scattered and disjointed. There is a clear need to integrate this information as a first step towards designing a research strategy. The point that climate needs to be included in any model that seeks to explain population dynamics of any species, is still not widely accepted by population biologists, despite the numerous examples presented in this chapter. If climate is an important driver of many populations (as the example of prairie ducks clearly shows), then clearly wildlife biologists need a better understanding of its effects, if only to improve current population models.

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APPENDIX 2A: COMMON AND SCIENTIFIC NAMES OF SOME SPECIES REFERRED TO IN THE TEXT

Mammals

polar bear: *Ursus arctos*
peary caribou: *Rangifer tarandus*
snowshore hare: *Lepus americanus*
lynx: *Lynx canadensis*

Birds

Atlantic brant: *Branta bernicla hrota*
northern fulmar: *Fulmarus glacialis*
northern gannet: *Morus bassanus*
lesser snow goose: *Chen caerulescens caerulescens*
pinkfooted goose *Anser brachyrhynchus*
Ross's goose: *Chen rossi*
evening grosbeak: *Coccothraustes vespertinus*
black-legged kittiwake: *Rissa tridactyla*
common loon: *Gavia immer*
common murre: *Uria aalge*
razorbill: *Alca torda*
American robin: *Turdus migratorius*
semipalmated sandpiper: *Calidris pusilla*
tree swallow: *Tachycineta bicolor*
common whitethroat: *Sylvia communis*
widgeon: *Anas americana*

Fish

Atlantic cod: *Gadus morhua*
brook trout: *Salvelinus fontinalis*

Insects

spruce budworm: *Choristoneura fumifera*
Edith's checkerspot butterfly: *Euphydryas editha*

Plants

trembling aspen: *Populus tremuloides*
alpine bearberry: *Arctostaphylos alpina*
bog blueberry (or alpine): *Vaccinium uliginosum*
choke cherry: *Prunus virginiana*
lapland rosebay: *Rhododendron lapponicum*
saskatoon: *Amelanchier alnifolia*

CHAPTER THREE

CANADIAN INLAND WETLANDS AND CLIMATE CHANGE

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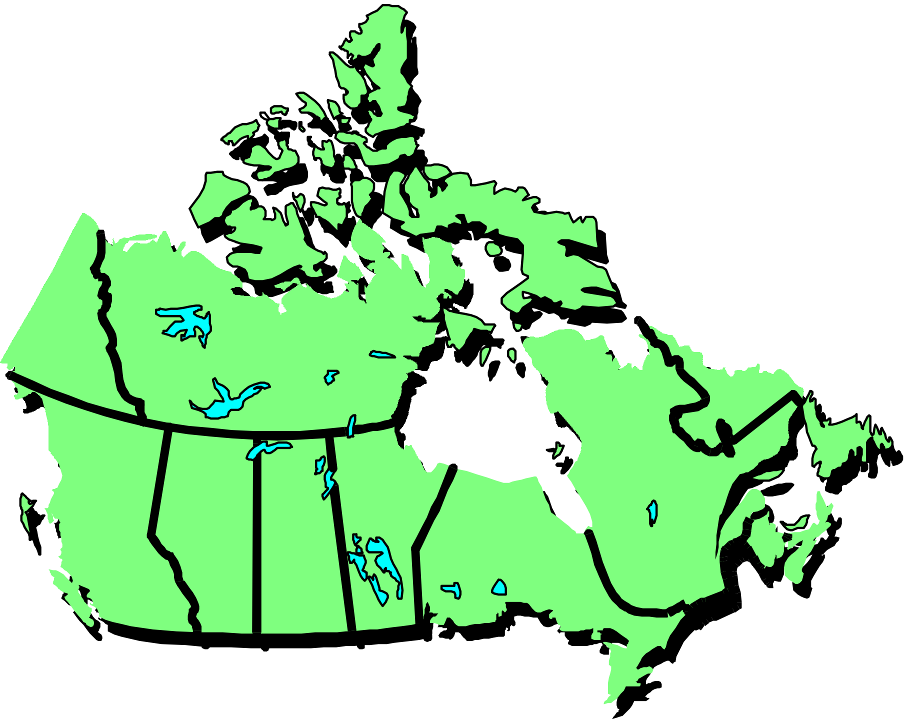

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EXECUTIVE SUMMARY

Wetlands, including marshes and peatlands cover 14% of Canada's land area. They are a critical resource providing habitat for important species, storage of atmospheric carbon, links in cycling of nutrients and minerals, buffering against pollution, and functions related to stream flow and water storage. Wetlands support food chains by recycling nutrients, produce plant material as food for other organisms and provide habitat for a diversity of wildlife species. Prairie wetlands constitute the most important waterfowl breeding area in North America and the Prairie region annually produces 50 to 80% of the continent's total duck population. Wetlands around the Great Lakes also provide important migration and staging habitats for approximately three million waterfowl. Many of Canada's rare, threatened or endangered species survive in habitats found only in wetlands. These habitat functions also support a wide range of recreational and tourism activities.

Northern peatlands act as water catchment and storage areas and, although they support a much simpler fauna, many species pass through them obtaining food and shelter there. Peatlands are significant carbon sinks by virtue of the carbon contained in layers of peat, which may be metres thick. Export of this carbon as dissolved organic carbon (DOC) in outflows from peat areas is an important source of carbon for streams and lakes. Peatlands are mined for peat for horticultural use and may also be used for fuel.

Hydrological functions include: flow stabilization, groundwater recharge and discharge, and erosion control, and wetlands provide benefits in flood control, contaminant reduction and water conservation. Hydrology is a key factor in determining wetland ecology. For example, most prairie pothole wetlands are closed basins that receive water primarily through snowmelt runoff and spring storm events. During the summer and fall, evaporation and transpiration from wetland vegetation usually exceeds precipitation causing water level declines. Wetland vegetation changes in response to these water level changes and drying basins may become covered by interspersed or closed stands of vegetation in the summer. Annual water levels fluctuate seasonally and annually due to the climate variability in the Great Plains; as a result prairie wetlands vary significantly in water permanence and water quality. Peatlands also depend on the water regime: the level of the water table is the main controlling factor in the decomposition of peat. Peat exposed to air oxidizes fairly quickly, releasing carbon dioxide (CO_2) in the process. Water-saturated peat decomposes slowly – usually slower that the rate of peat accumulation – and releases more methane (CH_4) in the process.

Climate change scenarios suggest a warmer climate accompanied by changes in regional and local precipitation patterns. A warmer climate will affect inland wetland hydrology, geochemistry, ecological functioning and water quality as well as groundwater systems interconnected with wetlands. The results of simulation models suggest that an increase in spring precipitation and snowmelt runoff amounting to 10% of the total growing season precipitation would be necessary to compensate for increased water loss from evapotranspiration due to a warmer summer climate. These simulations suggest semi-permanent wetlands could change from open-water basins to completely vegetated areas even under the wide range of changes in precipitation projected for the Great Plains Region. Another major effect of simulated increases in temperature and decreases in precipitation would be to significantly increase wetland salinity.

Climate changes that results in lower water levels could significantly alter the quantity and quality of wetland habitats for waterfowl. Simulations indicated that a 3°C increase in temperature would result in a 56% decline in the number of wet basins in the parkland region and a 15% decline in the Canadian grassland region. A 10% increase in precipitation nearly balanced the 3°C increase in temperature in the grassland region but parkland basins still showed a decline of 39%. Decreasing precipitation coupled with increasing temperature generated an even higher loss of wetland basins.

A warmer, drier climate could lower waterfowl production directly by increasing the frequency of dry basins and indirectly by producing less favourable cover ratios and encouraging denser growth of emergent vegetation, which generally provides lower quality waterfowl habitat. Wetland response to the conditions depends on the type of wetland and its geomorphology and water depth. The response of the plant community depends on factors such as past plant distribution, vegetative spread, germination conditions, survival rates under flooding and drought and dispersal mechanisms. Other important aspects of wetland structure and function which may be affected by climate include: algal production, decomposition, nutrient and mineral cycling, and food-chain dynamics. With rising temperatures however, prairie habitat may expand northward and offset some of the anticipated loss in other parts of the region.

Lake and river shoreline wetlands would also be affected by lower water levels. For example, emergent vegetation in marshes along the St. Lawrence River occupied 37% of the surface area under low water levels, 18% under current water levels and only 6% under high water conditions. Fluctuating water levels could favour the invasion of the wetland by opportunistic or exotic species. Thus the character of marshes could change from large marshlands at low water levels to open water at high water levels.

Conditions in northern Canada where precipitation exceeds evapotranspiration and mean annual temperatures are cold, result in peat accumulation. Organic matter accumulates as peat where soil oxygen needed for plant decomposition is limited (e.g., where the plant remains are saturated with water). Much of Canada's peatland area is underlain by permafrost ranging from sporadic to continuous. A warming of 5°C would result eventually in the melting of permafrost everywhere but in the far north. Climatic warming of even 2°C would shift most of the peatland region of Canada from a zone of discontinuous to sporadic permafrost. It may also renew peat accumulation in subarctic regions, although degradation of southern peatlands may be much faster than northward migration and the total area of Canada's peatlands likely will decrease.

Wetlands also are an important source of DOC for ponds, lakes and streams. The outflow of DOC is related to total annual precipitation and basin topography and will be affected by temperature and precipitation. Some climate change scenarios suggest a decrease in wetland discharge and DOC outflow. The ecosystem repercussions of these changes are not easily predictable because DOC affects lake and stream colour, and light and UVB penetration with subsequent implications for water temperatures and primary productivity.

There are still major gaps in our understanding of wetlands and their likely responses to climate change. Wetlands lag behind other ecosystems in being adequately modelled and are often excluded from global models studying climate change effects. Research is needed on the hydrogeochemical processes of wetlands and on interrelationships between water levels and wetland vegetation. Simulations of habitat changes associated with climate change are needed to understand the potential changes in wetland numbers and quality and the impact on waterfowl production and biodiversity. Work also needs to be done in establishing the area, depths and types of peatlands as well as their carbon storage capabilities and their responses to climate change especially of methane and carbon dioxide. Climate models should be used in conjunction with other models such as those for precipitation, runoff and groundwater to assist in estimating consequences of climate change for wetlands in Canada and the functions and values they provide.

INTRODUCTION

From the sloughs of the prairies, to the shores of the Great Lakes, the St. Lawrence, Fraser and Saint John Rivers, as well as to the wide expanses of the north, Canada is dotted with a variety of wetlands which cover 14% of its area (Figure 3.1). Most Canadians know wetlands better as marshes, sloughs, swamps, muskeg, peatlands and bogs and although many scientific definitions exist, all involve four elements: water, soil, nutrients and vegetation. Wetlands can be thought of as transitional zones, where the characteristics of aquatic and terrestrial environments come together. They often are found along the shores of lakes or river floodplains where periodic high water provides natural flooding. Other wetlands may be fed by water that is just below the surface or by run-off from rainfall or snowmelt. Wetlands are a critical resource that provide habitat for important plant and animal species. They are also significant in the cycling of carbon, nitrogen and sulphur. They buffer against pollution and help regulate stream flows and water storage.

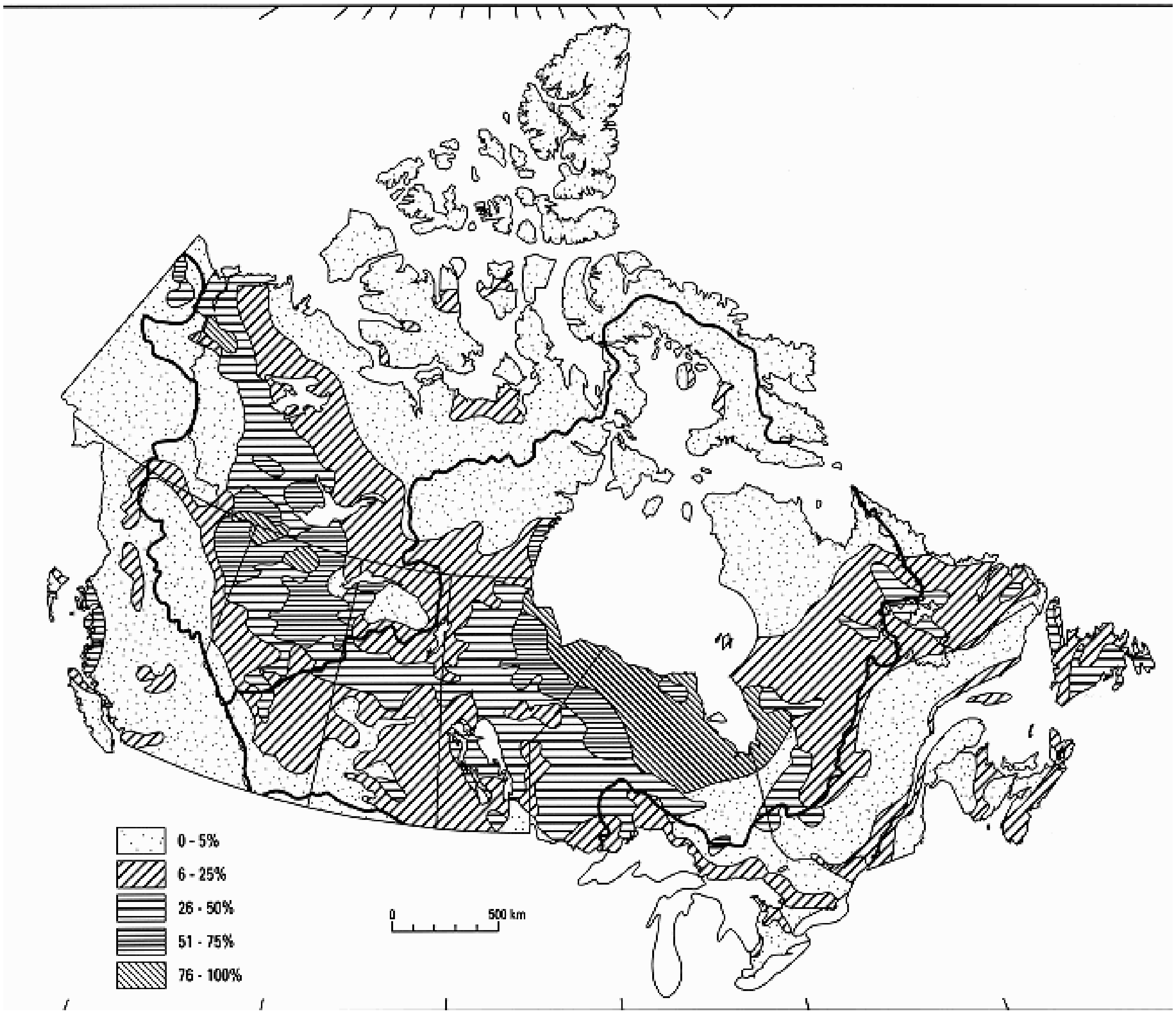
Wetlands may range in size from wet hollows of a few square metres to the vast peatlands of the Hudson Bay and James Bay lowlands. They occur in a great diversity of types with their own distinct flora and fauna. Among the showy or unusual plants of wetlands are diverse carnivorous plants (e.g., sundews, pitcher plants, Venus flytraps and bladderworts), numerous species of orchids and mosses.

One of the most important products of wetlands is dissolved organic matter (DOM). In aquatic systems, DOM is an important component of the food web and the acid-base balance of soft waters. It has a major role in the transport and toxicity of trace metals and other contaminants, affects light penetration and protects aquatic organisms from the effects of ultraviolet (UV) radiation. In addition, export of dissolved organic matter constitutes the main loss of nitrogen (N) from forested catchments (Schiff *et al*., in press).

Complex interactions occur among air, water, land, vegetation and wildlife components in wetland ecosystems and these interactions are often affected by activities occurring within the wetland or on adjacent land. The hydrology of wetlands, for example, is related to water inflow and outflow in their catchment area. Activities which affect the water balance in wetlands will affect their hydrology, vegetation and wildlife the wetland supports. These activities include climate change, agricultural practices, forestry, road construction and urbanization.

There is a complex relationship between the wetland and the surrounding upland landscape. Most migratory birds in the Great Plains require upland habitat. Others, such as waterfowl, require both upland and wetland habitat for the successful rearing of broods. Many of the benefits wetlands provide such as forage, recreational opportunities and wildlife habitat may be lost if the wetland margins are cleared of vegetation (Larson, 1994).

Figure 3.1: Wetlands in Canada



Wetland Characteristics

Wetlands can been defined as "land that has its water table at, near, or above the land surface or which is saturated for a long enough period to promote wetland or aquatic processes" (Woo *et al*., 1993). Wetlands in Canada can be subdivided into two broad categories: a) organic wetlands, commonly referred to as peatlands which contain a minimum accumulation of 40 cm of organic material, and b) mineral wetlands with less than 40 cm of organic material (NWWG 1988). This system is hierarchical, classifying wetlands on characteristics of the wetland landform, surface patterns, and vegetation composition. The system recognizes five major wetland classes: bog, fen, swamp, marsh, and shallow open water (Figure 3.2).

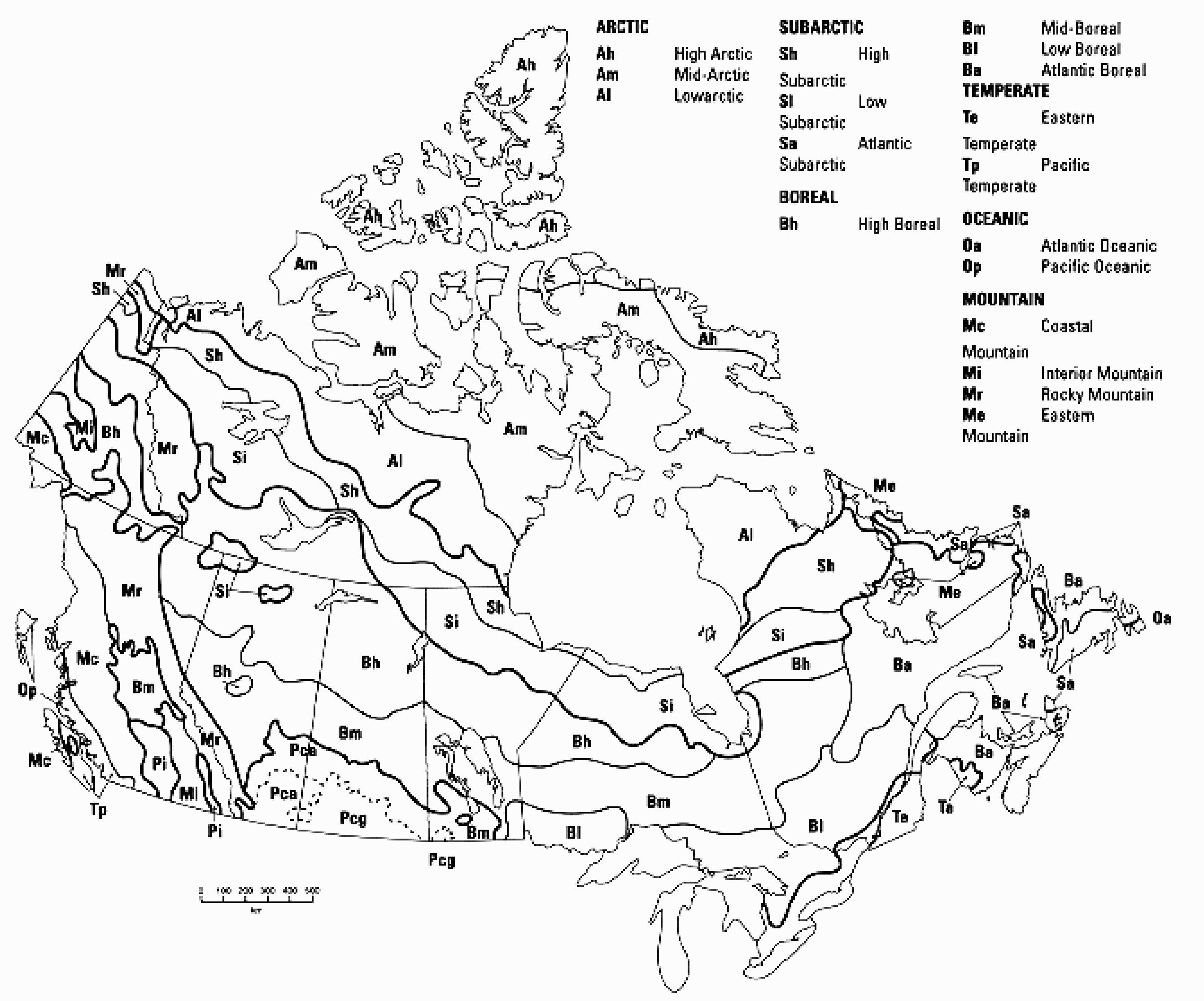
All bogs are peatlands. The bog surface and its groundwater table are often raised and usually, the surface vegetation is isolated from mineral-rich soil waters. Hence the surface waters of bogs are strongly acidic and the upper peat layers are extremely deficient in nutrients or ombrotrophic. Sphagnum mosses are common, along with heath shrubs. Trees may be absent; if present (usually black spruce and larch), they form open forests often with low stunted trees (NWWG, 1988; Warner and Rubec, 1997). These are most common in the Boreal ecozones of Canada, but are also often found elsewhere also.

Fens are most often peatlands characterized by a high water table and with some internal drainage. A slow moving water table is enriched by nutrients from upslope surface drainage or groundwater discharge; thus fens are minerotrophic as opposed to ombrotrophic bogs. The thickness of peat usually, but not necessarily, exceeds 40 cm. Fens can be subdivided into rich fens which are mineral-rich with abundant vegetation and poor fens, transitional between bog and fen, which have some influence by mineral-rich waters and contain less productive vegetation. (NWWG, 1988; Warner and Rubec, 1997). These are located throughout the country from the Boreal ecozone towards the south.

Swamps can be both peatlands and mineral wetlands. There is water movement in the subsurface through swamps with standing or gently flowing waters occurring seasonally or for longer periods on the surface. The water table may drop seasonally below the rooting zone, creating aerated conditions on the surface. Swamps are usually mineral-rich which supports luxuriant growth of trees and tall shrubs. The substrate consists of a mixture of mineral and organic material, often woody and well-decomposed (NWWG 1998, Warner and Rubec, 1997).

Marshes are largely mineral wetlands that are periodically or permanently inundated by standing or slowly moving water and hence are usually rich in nutrients. Marshes are mineral-soil areas but shallow well-decomposed organic sediments may be present. Marshes are subject to a high groundwater table, and water remains within the rooting zone of plants for most of the growing season. Marshes are characterized by an emergent vegetation of reeds, rushes and sedges. The surface water levels of marshes may fluctuate seasonally with declining levels exposing zones of matted vegetation, mud or salt flats (NWWG 1988; Warner and Rubec, 1997).

Figure 3.2: Wetland Classes in Canada



Distribution and Abundance

The extent of wetlands in Canada is not known with any great accuracy (NWWG, 1998), although mapping and classification is on-going (e.g. Halsey and Vitt, in press). Estimates of wetland abundance indicate that about 14% of Canada or 127.2 million hectares (ha), is covered by wetlands (Table 3.1, Figure 3.1). The peatland component of Canada's wetlands has been estimated at about 111.3 million ha, and the indicated volume of peat, based on average peat thickness, is 3 trillion m^3 for all of Canada.

The distribution of wetlands in Canada is determined chiefly by the regional and local hydrogeomorphic setting and climate which determine the amount of water received through precipitation and lost through evapotranspiration. The dependence of wetlands on climate and landform is illustrated by the distribution of wetlands in Canada (Figure 3.1). The greatest concentration of inland wetlands occurs in a belt across northern Ontario, central Manitoba and

Saskatchewan, northern Alberta and the Mackenzie valley. This is an area of cool climate withvery cold winters and cool summers with relatively low mean annual precipitation; conditions favourable for peatland development. Within this belt, the highest concentration of peatlands occurs in areas of low relief; such as in the Hudson Bay and James Bay lowlands and around Lake Winnipeg. The hummocky moraines of the Prairies contain innumerable depressions, many of which have developed into wetlands, possibly covering between 15 and 20% of the area (NWWG, 1988).

Table 3.1: Occurrence of peatlands and wetlands in the provinces and territories in Canada (from: NWWG, 1988)

Province or Territory	Peatland Area ha x 10^3	Peatland Area % of land area in province or territory	Total Wetland Area ha x 10^3	Total Wetland Area % of land area in province or territory
Alberta	12 673	20	13 704	21
British Columbia	1 289	1	3 120	3
Manitoba	20 664	38	22 470	41
New Brunswick	120	2	544	8
Newfoundland-Labrador	6 429	17	6 792	18
Northwest Territories	25 111	8	27 794	9
Nova Scotia	158	3	177	3
Ontario	22 555	25	29 241	33
Prince Edward Island	8	1	9	1
Quebec	11 713	9	12 151	9
Saskatchewan	9 309	16	9 687	17
Yukon Territory	1 298	3	1 510	3
Canada	111 327	12	127 199	14

Wetland Functions and Values

In the past, wetlands have been characterized as wastelands, areas that provided obstacles to development or were a nuisance to humans. Increasingly, we are learning that this is not the case. In their natural state, wetlands exhibit a variety of hydrological functions (NWWG, 1988) which produce benefits of value to society. These values may include flood control, nutrient uptake, contaminant reduction, recreation, opportunities for education and scientific study, and agriculture and forest production (Table 3.2). These functions and values are not static. Environmental and human-induced changes can enhance, degrade or eliminate functions, thus altering the value of a wetland. Climate change is one factor that could initiate significant change in wetland functions and values.

Table 3.2: Wetland functions and values (adapted from Cox 1993)

Function	Value
Life-Support	
Regulation/absorption of water	flow stabilization
climate regulation	groundwater recharge/discharge
toxics absorption/adsorption	storm damage reduction
stabilization of biosphere processes	erosion control
hydrological	contaminant reduction/waste assimilation
cleansing of nutrients	
Ecosystem Health	
nutrient cycling	environmental quality
food chain support, habitat	maintenance of ecosystem integrity
biomass storage	maintenance of rare, threatened and endangered species
genetic and biological diversity	
Social/Cultural	
Science/Information	
specimens for research, zoos, botanical gardens	greater understanding of nature
representative and unique ecosystems	locations for nature study, research and education/interpretation opportunities
Aesthetic/Recreational	
non-consumptive uses such as viewing, photography, bird-watching, hiking and swimming	personal enjoyment and relaxation tourism industry and benefits to local economy
Cultural/Psychological	
wetland uses may be part of traditions of communities, religious or cultural uses	social cohesion maintenance of culture
future opportunities	value to future generations
	symbolic values
Production	
Subsistence Production	food, fibre
natural production of birds, fish, plants	community self-reliance
	import substitution
	maintenance of traditions
Commercial Production	
Production of foods (fish, crops) fibre (wood, straw) and peat	products for sale, jobs, income, contribution to GNP

Marshes exhibit three main hydrological functions: flow stabilization, groundwater recharge and discharge, and erosion control. Wetlands also conserve water by retaining snow and replenishing soil moisture (Fuller, 1997). The drainage of wetlands can cause flooding and eutrophication of downstream waterbodies, and reduce the rate of groundwater recharge. Wetland vegetation also controls erosion by stabilizing shorelines, dissipating wave and current energy, and trapping sediments. Erosion control is especially significant on riverine marshes, shore marshes and large shallow wetlands (NWWG, 1988). Marshes also have value as filters, improving water quality by trapping and removing pollutants such as sediments, heavy metals, nutrients and pesticides (Mortsch, 1990).

Marshes play a significant role in supporting food due to their high primary productivity and microbial activity (NWWG, 1988). The net productivity of marshes and swamps is higher than that of lakes, streams or agricultural land (Mortsch, 1990) and wetlands are an important contributing factor to biodiversity on the Canadian prairies (Robarts and Waiser, 1998). Prairie wetlands constitute the single most important breeding area for waterfowl on the North American continent. The prairie region annually produces 50 to 80% of the continent's total duck production (Poiani and Johnson, 1991) including 20 of the 34 species that breed in North America (Covich *et al.*, in press). Water conditions in May play a critical role in waterfowl breeding success and the number of spring-time wetlands is related to the annual waterfowl production and breeding pair density (Sorenson and Root, in press). The quality of breeding habitat depends on the mix of permanence types found in a wetland complex (Larson, 1995, Poiani and Johnson, 1991) as persistence of wetlands through the waterfowl breeding season is important for brood survival. Temporary and seasonal wetlands provide abundant invertebrate and seed food resources and are heavily used by dabbling ducks in spring. Seasonally flooded wetlands also provide food, nesting habitat and brood-rearing sites for both dabbling and diving ducks, particularly in years of high water. As seasonal wetlands dry, renesting birds feed and rear broods in open-water areas of semi-permanent wetlands (Poiani and Johnson, 1991). Wetlands in the other areas of the continent also provide important habitats. For example, the Great Lakes coastal wetlands also provide migration and staging habitats for approximately three million waterfowl from the Atlantic and Mississippi flyways as well as breeding habitats for a wide range of species.

Many rare, endangered and threatened species of animals and plants survive in unique habitats found only in wetlands. Many furbearer species depend on wetland habitat, while other mammals use wetlands periodically for feeding, cover, breeding, resting and other purposes. They are essential to the maintenance of some fish stocks and a wide variety of fish use wetlands for spawning, rearing, feeding and cover. The greatest diversity and abundance of animal species occur when aquatic and emergent vegetation zones are interspersed with open water. The value of a wetland for wildlife habitat depends on the wetland type and size, the structure and diversity of vegetation communities, water chemistry, the presence of suitable food and cover and freedom from disturbance, and surrounding land uses. Each of these parameters will be influenced by changes in climate (Larson, 1994). These habitat functions provide recreational opportunities such as bird watching, hunting, hiking, canoeing, camping and photography as well as commercial enterprises such as fishing and trapping (Mortsch, 1990).

Peatlands present much less varied habitat than marshes and support a much simpler fauna. Few species of wildlife live in peatlands year round, but many use them on a seasonal or opportunistic basis for food and shelter. Waterfowl densities in peatlands also are low compared to that of marshes or open water wetlands, though the extensive area of peatlands still results in large bird numbers of birds being contributed to continental populations (NWWG, 1988).

Boreal peatlands are significant carbon sinks because the rate of addition of dead vegetation is greater than its decomposition (Brown, in press). They contain about 500 x 10^{15} g of organic carbon, most accumulated in the last 5000 years at an average rate of about 100 terragrams per year (Tg/yr) (Moore *et al*., in press). An average of 800 grams of carbon per meter^2 (gC/m^2)is stored within the surface vegetation and 1 x 10^5 g C/m^2 stored within the peat itself (Poschadel *et al*., in press). This is equivalent to about 100 years of current fossil-fuel combustion and represents a reduction in atmospheric CO_2 concentration of about 40 ppm (Roulet *et al*., 1997). Peatlands have been mined for horticultural use and for fuel. Fibrous *Sphagnum* peat, found in bogs, is preferred for horticultural use and there are several peat processing plants in the boreal wetland region of Canada. The use of peat for fuel is feasible, but present economics do not favour its use in Canada (NWWG, 1988).

Complex interactions occur among components of air, water, soil, vegetation and wildlife components in wetland ecosystems. These interactions can be affected by activities occurring within the wetland or on land adjacent to the wetland. The hydrology of wetlands, for example, is related to water inflow and outflow in the wetland catchment area. Human activities, which directly affect the water balance in wetlands will affect their hydrology and other components of the wetland, and may contribute to climate change. These can include agricultural practices, forestry, road construction and urbanization. In addition to the interrelationship between wetlands and hydrology, there is a complex relationship between the wetland and the surrounding upland landscape. The presence of wetlands in forested catchments greatly modifies the chemical export in surface streams. For example, Precambrian Shield wetlands increase the retention of sulfate and nitrate, thus mitigating the effects of acid deposition.

One of the most important products of wetlands is dissolved organic matter (DOM). In aquatic systems, DOM is an important component of the food web, has a major role in the transport and toxicity of trace metals and other contaminants, affects light penetration and protects aquatic organisms from the effects of ultraviolet (UV) radiation.

POTENTIAL IMPACTS OF CLIMATE CHANGE ON WETLANDS

Hydrology

Wetlands should respond quickly to changes in climate. A warmer, drier climate will affect inland wetland hydrology, geochemistry, ecological functions, and water quality, as well as groundwater recharge. Higher air temperatures and warmer water temperatures also will affect the energy balance of lakes and wetlands and may reduce winter ice cover in certain areas (Mortsch and Quinn, 1996). Water level changes in semi-permanent wetlands will induce changes in the ratio of emergent cover to open water. Semi-permanent wetlands may become choked with emergent vegetation during prolonged dry periods and maintain open water or more balanced conditions during wet or average years. The results of simulation models (Poiani *et al.*, 1995) suggested that the naturally occurring wet/dry cycles characteristic of semi-permanent wetlands could change dramatically with increased temperatures and changes in growing season precipitation. In these simulations, wetland hydrology and vegetation were highly sensitive to seasonally-varying changes in precipitation, and maximum water levels were dramatically lower under warming scenarios than under current climate conditions.

Poiani *et al.* (1995) tested a number of other scenarios related to climate change. These showed that an increase in spring precipitation and snow melt runoff amounting to 10% of the total growing season precipitation was the only condition that compensated for increased water loss from evapotranspiration due to a warmer climate. A comparable 10% decrease in spring precipitation produced the lowest water levels of any climate change scenario, emphasizing the importance of spring precipitation and runoff in prairie wetland water budgets. These simulations suggest that a semi-permanent wetland could change from an open-water dominated wetland to a basin completely closed with emergent vegetation even under the wide range of seasonal precipitation changes currently projected for the Great Plains region.

The ecological response to subtle changes in hydrology could be dramatic. The loss of even a small amount of water during dry years would allow for faster establishment of seedlings on exposed mudflats. This sensitivity to hydrologic change could have repercussions on wetland vegetation dynamics in the long-term and may speed up the loss of open water areas. One unexpected result from the Poiani *et al.* (1995) study was the dramatic loss of the meadow/shallow marsh zone with either increased or decreased spring precipitation.

Another major effect of simulated increases in temperature and decreases in precipitation was to increase salinity as a result of decreased inputs of surface runoff and direct precipitation for dilution; increased evapotranspiration; and reduced surface discharge (Covich *et al.*, in press). Changes in precipitation patterns would alter snowmelt runoff and groundwater outflow patterns under prairie pothole wetlands, affecting solute transport and water quality in the wetlands and wetland ecosystems. Because most prairie wetlands do not have surface streams flowing in and out, their salinity is strongly influenced by groundwater. Groundwater outflow is driven by infiltration of snowmelt water, which carries chloride leached from the surrounding farmland (Hayashi *et al.*, 1997).

Land management changes have a potential to affect wetland hydrology. Data indicate that prairie wetlands water levels decrease when cultivated fields are converted to grassland (Fuller 1997). Grassing the watershed seems to lead to a drying up of marshes over time, as compared with catchment areas that are in a crop-fallow rotation. Conversely, agricultural practices have increased flooding by enhancing run-off from bare fields (Hall *et al*., 1997, Su *et al*., 1997).

Changing climatic conditions also can be expected to affect the balance between photosynthesis and decomposition in wetland soils. Photosynthesis, decomposition and CH_4 emission all may be expected to increase directly with rising temperatures and longer growing seasons. Such effects are likely to be strongly overshadowed by those caused by hydrological changes, especially alterations in the level of the water table. These effects probably will include substantial water table drawdowns and peat oxidation in southerly regions owing to greater evapotranspiration, and, in more northerly locations where precipitation may increase, to melting of the permafrost. Rapid runoff of water from melting permafrost may exacerbate the fall in water tables to be expected from higher temperatures and increased evapotranspiration from larger standing crops of vegetation. Lower water tables favour the release of carbon dioxide (CO_2) by peat oxidation, however it also is likely to inhibit methane (CH_4) emissions. The degree of peat oxidation induced by falling water tables, and indirectly by climate warming, is likely to be important, but it also will be extremely difficult to forecast. The hydrology of large peatlands is complex and can be affected by the nature of the vegetation as well as by the pattern of peat deposition (Gorham, 1991).

Permafrost

Although permafrost is characteristic of very cold climates, distribution along its southern border is influenced by local relief, soil type, hydrology, vegetation and fire frequency. A warming of $5^{o}C$ would result eventually in melting the permafrost everywhere but in the far north (Gorham, 1995). Under a climate experienced during the Holocene warm period, about 6,000 years ago, when the mean annual temperature was about $5^{o}C$ warmer than at present, the distribution of permafrost in peatlands shifted 300 to 500 km to the north compared to its distribution today (Zoltai, 1995). Climatic warming of even $2^{o}C$ would shift most of the peatland region of Canada, and most notably the vast Hudson Bay and James Bay lowlands, from a zone of discontinuous permafrost to a zone of sporadic permafrost with major consequences for their ecology and biogeochemistry. It also could shift the tree line into landscapes further north and renew peat accumulation in subarctic peatlands, where it has ceased due to climatic cooling and the development of continuous permafrost (Gorham, 1991).

Under the current climate change scenarios the area of Canada that is underlain by permafrost might be reduced from about 43 to 23% with the subarctic and boreal ecozones most affected as the permafrost area retreats northward (Kettles *et al*., 1997). These changes will affect the rate of peat decomposition, the flux of CO_2 and CH_4 and the export of dissolved organic carbon from peatland areas with subsequent impacts on water quality in peatland basins.

Over the longer term, permafrost melting is likely to have two opposing effects. On the one hand, it is likely to lower water tables in areas where runoff leads to thermokarst erosion and gully formation. This will lead to greatly increased emissions of CO_2 and the shutdown of CH_4 emissions. Also, where thaw lakes are formed, they may initially be sources rather than sinks for CO_2 though such lakes will eventually undergo plant succession and develop into fens and bogs that sequester CO_2. Nevertheless, the overall balance between landscape drainage and flooding as the permafrost melts currently cannot be assessed (Gorham, 1995).

Wetland Abundance and Distribution

An indication of the potential impact that climate change may have on prairie pothole wetlands can be obtained through an assessment of the impact of the droughts during the 1980s (since there was more than one significant drought during this decade) on wetland projects managed by

Ducks Unlimited. This assessment showed that 5 to 23% of Ducks Unlimited's projects in the Prairies were dry and only 58 to 75% provided adequate brood habitat compared with pre-drought conditions (Table 3.3). Wetlands that did not have a guaranteed water supply were most affected (Coley, 1997). Future wetland conditions may be assessed from current and past estimates of snowfall, which can then be used to predict spring wetland inundation. However, soil moisture in the fall and topography may strongly influence this relationship (Woo *et al.*, 1993).

Table 3.3: Model projections for increased temperature and precipitation (Larson 1995)

	Mean % wet basins/year (% change in parentheses)						
Model Area	Observed 1974-87	+3^{o}C	+6^{o}C	+10% precip.	+3^{o}C +10% precip.	-10% precip.	+3^{o}C and -10% precip.
Parkland	51.5	22.4 (-56)	4.5 (-91)	57.2 (+13)	31.2 (-38)	36.3 (-28)	13.4 (-74)
Canadian grassland	49.2	42.0 (-15)	35.1 (-29)	55.0 (+12)	50.0 (+2)	38.9 (-21)	34.1 (-31)
United States grassland	51.4	36.4 (-28)	22.8 (-56)	57.8 (+12)	45.3 (-12)	38.2 (-26)	22.8 (-56)

Larson (1995) developed models to relate the number of wetland basins to climate variables in the Prairie Pothole Region and to explore the potential effects of temperature and precipitation changes on the number of basins holding water. Temperature had the greatest effect in the parkland region where an increase of 3^{0}C resulted in a 56% decline in the average number of wet basins (Table 3.3). The Canadian grassland region was less affected by a similar change, showing a 15% decline in wet basins. A 10% increase in precipitation alone resulted in a 11 to 12% increase in the percentage of wet basins throughout the regions studied. A 10% increase in precipitation also compensated for some of the effect of increased temperature, but results varied by region. In the Canadian grassland, a 10% increase in precipitation nearly balanced a 3^{0}C increase in temperature, while Parkland wet basins still declined by 39%. Decreasing precipitation alone by 10% resulted in roughly similar declines in wet basins among these regions. When decreased precipitation was examined with a 3^{0}C temperature increase, the models again revealed the sensitivity of wetlands to temperature in the parkland compared with the grasslands: parkland wet basins declined by 74% compared with 31% decline in the Canadian grassland wet basins (Larson, 1995). Johnson (1997) also reported that under a scenario of an increase in temperature of 3^{o}C and a decrease in precipitation of 20%, 15 to 20% of the wetlands in the Southern Plains would be lost. Temperature was the most important factor and a 20% increase in precipitation was required to offset a 3^{o}C temperature increase.

Reasons for the sensitivity of parkland wetlands to temperature and precipitation changes include a greater evapotranspiration component in parkland due to more developed vegetation layers and biomass. The greater vulnerability of parkland basins has important implications for waterfowl that rely on these wetlands for breeding habitat. Basin density in the parkland is two to three times as high as that in the grassland regions, representing a significant reservoir of breeding habitat. Studies suggest that many duck species enter the breeding grounds from the south, stopping at the first available habitat (Sorensen *et al.* in press). Birds not finding suitable habitat in the grasslands move northward into parkland habitat. Other species, such as canvasbacks, use parkland as their primary breeding area, dispersing further north or northwest if wetland conditions in the parkland are not suitable for nesting. One important consequence of the geographical difference in wetland response to temperature is the decreased probability of finding better conditions as waterfowl migrate farther north. Therefore, it is important to conserve wetlands in grassland areas that may be less affected by climate changes (Larson, 1995).

Climate change is likely to cause substantial alterations in the distribution of Canada’s peatlands. With rising temperature the major zones of peat accumulation are likely to migrate northward as discussed earlier. It seems probable, however, that a greatly increased frequency of severe summer drought, despite overall increasing precipitation, will cause degradation of southern peatlands much faster than northward migration into polar regions, particularly if they become subject to much more frequent droughts and fires. Therefore, it is likely that the total area of peatlands is likely to decline (Gorham, 1994; 1995).

Wetland Ecosystems

Waterfowl

Duck abundance between 1955 and 1974 in the prairie-parklands of Canada was related significantly to variations in climate and wetland conditions. Northern pintail, mallard, northern shoveler, blue-winged teal, and redhead populations, in particular, tracked changes in wetland conditions (Bethke and Nudds, 1995). Simulation models (Larson, 1995, Poiani and Johnson, 1991) suggest that anticipated climate changes may result in both fewer and lower-quality wetlands for waterfowl production although neither study addressed the potential loss of temporary wetlands, which provide important habitat to migrating waterfowl and shorebirds (Larson, 1995). In general, a warmer, drier climate could lower waterfowl production by increasing the frequency of dry basins and less favourable cover-water ratios (i.e., heavy emergent cover with few or no open-water areas). An increase in emergent cover could have a negative effect on waterfowl production, especially if waterfowl dependency increases (Poiani and Johnson, 1991).

The possibility of diminished waterfowl production under climate change comes at a time when waterfowl numbers have declined sharply for other reasons such as diseases, losses of habitat and overhunting and, in combination with existing stresses from agriculture, may further increase the loss of wetland value and function (Coley, 1997; Covich *et al.*, in press). Drier conditions in the shallow, temporary and seasonal wetlands may increase their vulnerability. A changing climate will certainly exacerbate the current problem of waterfowl decline. Should this occur, efforts outlined in the North American Waterfowl Management Plan to reduce the current waterfowl decline may need to be redoubled (Poiani and Johnson, 1991).

Ducks Unlimited has over 2,000 wetland projects and over 2,600 upland projects involving more than 1,100,000 ha in the prairie and parkland areas of Manitoba, Saskatchewan and Alberta. These projects may be impacted if climate change results in decreases in both water depth and the number of ponds, especially seasonal and temporary ponds, holding water in the spring and summer. Many of Ducks Unlimited's wetland projects are expected to be dry under a drier climate, although wetlands with a water supply in partnership with irrigation systems will not be as threatened unless overall water supply becomes an issue (Coley, 1997).

In the Great Lakes Basin, Ducks Unlimited has developed 63 marsh projects involving 6,300 ha. Most of these are self-contained and have a limited catchment basin supply. They are replenished and operated by pumping systems from the Great Lakes. Lower lake levels in the Great Lakes would mean an adjustment in pumping capacity to supply marsh units. Water allocation by permit may be a significant problem under altered climates as a result of anticipated increased competition for water. Ducks Unlimited can adjust its programs to try to minimize the impacts, continue to develop arrangements with irrigation districts to guarantee water for wetlands, and secure and reserve wetland and upland areas in the forest-parkland fringe (Coley, 1997). However, managed systems are but a small fraction of the wetland base in Canada.

Biodiversity

One of the most important effects of climatic change is the alteration that takes place in plant communities (Gorham, 1995). Wetlands have evolved in response to climate and the historical long-term water level regime. Each wetland community has a distinct position along the water depth gradient and shoreline slope relative to other communities. Their distribution expands or contracts with fluctuating water levels. For example, seasonal and annual flooding and drying maintain Great Lakes coastal wetlands at productive stages of development (Mortsch, 1990). Large rivers typically have a broad continuum of wetlands from seasonally, to constantly submerged, aquatic systems (Hudon, in press). Moreover, flood levels, minimum water levels, seasonal timing of flood and low water, average annual water level and the short-term and long-term variability in water levels contribute to species diversity by providing a wide range of conditions for opportunistic species.

With a changing climate, wetlands would have to adjust to a new pattern of water level fluctuations (Mortsch, 1990, Mortsch and Quinn, 1996). Wetland response to lower annual water levels would depend on the type of wetland, its geomorphology and bathymetry. Although landward edges of marshes would dry, their dominant vegetation (i.e., sedges, grasses, reeds and aquatic plants) could colonize suitable exposed sites if water depths permit. In open shoreline wetlands, vegetation migration is not physically constrained and could colonize newly available habitat. However, Precambrian Shield wetlands located in areas of irregular slope and rocky substrate, would likely have fewer sites for successful recolonization (Mortsch, 1990).

Studies conducted at Delta Marsh, Manitoba, indicated the complexity of plant responses to different water levels and changes in water levels (Seabloom *et al.*, 1997). Plant species respond to both biotic and abiotic conditions and to present as well as past events. Plant abundance is affected by water depth, vegetative spread, germination conditions, survival rates under flooding and drought conditions, and dispersal mechanisms, among other factors. The greatest changes in species distribution occur immediately after rapid changes in factors such as water depth.

Hudon (in press) studied the impact of water level fluctuations on marshes along a 165 km long section of the St. Lawrence River. Water level appeared to exert a determining influence on the distribution of emergent and submergent plant biomass with the depth of maximum biomass well-defined for most species. Although the 1995 minimum water levels resulted in drying up of between 0 and 77% of the surface area previously colonized by submerged vegetation, the distribution and abundance of emergent vegetation were not affected by the dry spell. Emergent marshes occupied 37% of the total area under low water levels, 18% under prevailing water levels and only 6% under high water levels. Thus the inherent character of Lake Saint-Pierre changed from a large marshland at low water levels to an open water body at high water levels (Hudon, in press).

The well-developed below-ground systems of emergent vegetation make it resistant to changes in water levels, while submerged plants with little below-ground rizomes could not survive dry periods. Falling water levels, which cause the death of existing vegetation at the upper marsh edge and availability of new space in the lower fringe, could favour invasion by opportunistic or exotic species. Unfortunately, many exotic species provide wildlife with sub-optimal cover or reduced foraging potential, in comparison with native plant species. Changes in plant species composition may matter as much as, if not more than vegetation biomass for inhabitants of shoreline marshes. Species diversity, exotic species invasion and mono-specific dominance may be strongly influenced by the seasonal and year-to-year variability in water levels and the high unpredictability of discharge patterns and flow reduction under dry periods (Hudon, in press).

Alterations in climate also will have a profound effect on peatland vegetation succession, and consequently, on their biogeochemistry. Where water tables are drawn down severely, vegetation may have great difficulty in re-establishing itself in situations where nutrients are extremely limiting (Gorham, 1995).

Greenhouse gases also directly influence the response of biotic systems to climate change. The CO_2 fertilization effect could increase wetland ecosystem productivity, change the composition of upland vegetative communities and influence availability and suitability of upland habitat for various species of waterfowl. Effects of CO_2 on plant growth varies among species and thus can change competitive interactions.

Biogeochemistry

Greenhouse Gases

Peatlands are particularly important as carbon reservoirs as they store more soil carbon than other terrestrial ecosystems. Their response to changing climate, rising atmospheric CO_2 concentrations and other factors such as land use change, remains uncertain and an area of active research. Some modeling studies suggest climate change will result in an increase in net ecosystem productivity and hence enhance current terrestrial carbon sinks while others imply that limits in nutrient supply are important constraints on net increase in ecosystem carbon content (Environment Canada, 1997).

An important part of carbon cycling within wetland environments is the aerobic and anaerobic decomposition of peat, which results in the loss of CH_4 and CO_2 to the atmosphere. Oxidization of only 1% of the carbon stored in peatlands would release an amount of CO_2 equivalent to anthropogenic releases (Roulet *et al.*, 1997). Development of anaerobic conditions within the peat stimulates production of CH_4 and the post-glacial development of northern peatlands may have lead to an increase in global CH_4 emissions of 10 to 30 x 10^{12} g/yr and the increase in atmospheric concentration of CH_4 from 0.60 to 0.75 parts per billion volume (ppbv) that occurred between 6000 and 200 years ago (Moore *et al.*, in press). Natural wetlands remain a major source of atmospheric CH_4 emitting 15 to 20% of the global methane budget. Canadian wetlands produce about 3.5 Tg/yr of methane (Moore *et al.*, in press), 66% from peatlands in the mid-boreal region. However, major deficiencies exist in aerial estimations of carbon flux as well as the depth and density of peat.

Methane is produced throughout the peat profile, but most methane produced in the peat soils is oxidized to carbon dioxide before it can reach the atmosphere. Methane produced in the deep soils will slowly diffuse into the upper layers and once there is subject to oxidation. However, considerable methane is accumulated within the deep peat as a reservoir of gas and could be released as methane if there were rapid degradation of the peat under drying conditions (Brown, in press).

Waddington *et al*. (in press) noted that, although several studies suggest that northern wetlands may become a source of atmospheric carbon in a warmer drier climate, results from their study indicate that because of changes in groundwater holding capacities, total “wet” wetlands may increase thus increasing net wetland carbon sink functions. It is important to consider the effect of water table position within the wetland on net ecosystem production and respiration.

The most important controls on the wetland carbon budget are plant community, temperature, hydrology, especially water table position, and the chemistry or quality of plant tissues and peat. Older, more recalcitrant peat has been shown to produce less CH_4 and CO_2 than shallow, newer peat. Accumulation and decomposition rates of peat can differ spatially within a wetland and lead to variations in substrate quality (Poschadel *et al.*, in press). Peatlands are very stable under some conditions and unstable under others (Roulet *et al.*, 1997) as site-to-site variability is likely controlled by differences in substrate quality between sites. Gas production rates from surface peat often are higher than production rates from deep peat and are likely due to the presence of labile (i.e., biodegradable) carbon sources from newly deposited organic matter, which can be easily mineralized (Poschadel *et al.*, in press).

Other studies suggest warmer springs and wetter summers may lead to an increased uptake of CO_2 because peatland plants may have higher productivity (Brown, in press) although Gorham (1991) suggests that increasing temperature is likely to increase plant respiration to a much greater degree than photosynthesis. It also is likely to increase microbial and fungal respiration, thus increasing CO_2 release to the atmosphere. Once ombrotrophic bogs become dry there will be a loss of peat and the carbon sequestered within the bog will be vulnerable to being discharged into the atmosphere. If much of the northern temperate wetlands were lost due to a lowering of the water table, this would have a considerable effect on the composition of the atmosphere (Brown, in press), as more carbon incorporated in wetland soils will be mineralized to CO_2.

Methane production tends to be more variable than CO_2 production, both temporally and spatially (Moore *et al*., in press). Increased temperatures in the peat profile are likely to lead to increased CH_4 emissions. The large summer pulse of CH_4 emissions also suggests that rising temperature could increase CH_4 emissions substantially. Net production of CH_4 is also very sensitive to water table levels (Roulet *et al*., 1997). Northern wetlands show a great deal of spatial variability in vegetation and water table, so that there will be differential responses of CH_4 emission to climatic change. The largest change in CH_4 flux is likely to be found in the high boreal and low subarctic zones, where there is discontinuous permafrost. Melting of the permafrost will create collapse bogs and fens with much higher CH_4 emissions than at present (Moore *et al*., in press). Emission rates also appear to be broadly related to vegetation type; however emissions from ponds can be 3 to 30 times that of adjacent vegetated areas. This suggests that vegetation classification through remote sensing could serve as a proxy for estimates of total emissions over large areas.

Reservoirs created by flooding of natural wetland areas often emit CH_4 and CO_2 at significantly higher rates compared to natural wetlands (Moore et al, in press). Flooding appears to increase CH_4 production rates and increase the ratio of CH_4 to CO_2 produced. The total greenhouse gas production in the flooded peatland consisted of approximately 40% CH_4 and 60% CO_2 . Artificial reservoirs could potentially act as sources of CH_4 and CO_2 to the atmosphere for a very long time (Poschadel *et al*., in press). Flooding resulted in the formation of peat islands, allowing warm pond water to circulate beneath the floating peat mats, increasing the temperature in the deep peat layer. The floating nature of the peat islands would also alter the peat properties and hydrochemical regime of the peat and may allow additional nutrients to reach the peat microbial population, as well as allowing diffusion of gases and waste products of metabolism out of the peat islands. The temperature increase in the floating islands to 20 to 25°C from 4°C caused production rates of CH_4 to quadruple (Poschadel *et al*., in press).

Kelly *et al*. (1997) reported that wetland ponds flux both CO_2 and CH_4 all day, even when photosynthesis was occurring. Carbon flux was greater from ponds than from the surrounding peatlands where net carbon fixation may be occurring. If future climate change reduces the pond/vegetation ratio or lowers water tables, related methane emissions will decrease significantly. However, local CO_2 emissions would increase, perhaps by enough to more than offset the climatic effects of reductions in methane emissions. Succession models are needed for assessing such climate change-wetlands feedback, because emissions appear to be strongly influenced by disturbances and succession changes (Environment Canada, 1997). The peat to water ratios have different implications in different types of wetland/pond systems.

Freshwater Chemistry

Modification of freshwater habitats in peatland areas under climate warming and the role they play in transport of DOM might be of considerable importance for biota that use these areas

(Gorham, 1991). Many studies have been carried out to determine how much carbon is stored in various components of the biosphere and how it is transferred from one compartment to another. Large northern peatlands often are dotted with shallow pools, ponds and lakes and the function of these freshwater habitats in transferring carbon from peat to aquatic food chains has been demonstrated (Gorham, 1991).

The dissolved organic carbon portion of DOM lost from peatlands and exported by streams and rivers ranges from 5 to 40 $g/m^2/yr$. Export rates per unit area are greater in temperate ecosystems than in boreal ecosystems, although boreal ecosystems export more DOC because they are larger in total area. Hydrology controls both the position of the water table and the velocity of water movements along flow paths and therefore affects the export of DOC from wetlands. Clair and Ehrman (1996) noted that in Atlantic Canada the main variables controlling C and N exports were total annual precipitation and basin topography, so that the flatter and wetter the basins, the more DOC and dissolved organic nitrogen (DON) would be generated and exported. Molot and Dillon (1996) also found that DOC output from peatlands was very dependent on the catchment area for carbon input and was affected primarily by flushing and the proportion of the catchment occupied by peatlands.

Temperature and precipitation affect the export of DOC and DON by controlling a number of processes, especially runoff, but also organic matter mineralization and plant growth. Production of dissolved carbon is generally highest in surface peat due to a higher input of fresh litter and labile organic matter. However, the maximum DOC porewater concentration occurs significantly below the surface because the groundwater flow is slower allowing accumulation of DOC. Under low soil moisture conditions, outflow is low but may have high DOC concentration. Rising water levels permit flows in shallow organic rich soil horizons allowing transport of near surface DOC at lower concentrations. Hence DOC concentration decreases with increasing discharge.

The results of work by Clair and Ehrman (in press) predict a very complex seasonal pattern of changes to hydrology and geochemical fluxes with changes in climate. Overall, however, it is expected that there will be higher carbon exports under General Circulation Model scenarios than is occurring now. The model developed by Clair and Ehrman (1996) suggests that modification in precipitation will lead to changes in run-off that will affect the rate of organic matter transport from soils in a linear fashion.

DOM is an important source of nitrogen (Moore *et al*., in press) and phosphorous (P) (Molot and Dillon, 1996). Both annual stream total phosphorus concentration and export are a linear function of runoff so that less runoff may lead to a decrease in P loading to lakes. As a complicating factor, acidification of the catchment will affect peatlands and reduce the amount of P available for export (Molot and Dillon, 1996).

DOM is also an important control on light penetration and consequently the heat budget and stratification regime especially for lakes on the Precambrian Shield and in Atlantic Canada. Drier conditions will decrease terrestrial DOM export and increase lake residence time suggesting that under a drier climate, lakes on the Precambrian Shield may be clearer (Moore *et* *al*., in press). UVB radiation penetration may thus increase and thermoclines deepen, reducing cold water fish habitat. Catchments with a significant wetland component may experience less fluctuations in stream DOC concentrations with changes in hydrologic flux.

Prairie aquatic systems may be vulnerable to increasing UVB radiation because of their shallow depth, and because their DOM types have different photochemical characteristics (Vaughan *et al*., 1997). DOM is subject to photolysis which plays an important role in carbon cycle in wetlands (Robarts and Waiser 1998). Like peatlands, the source and amount of DOC input to these wetlands depends on inflow (Vaughan, 1997), with the winter snowfall and subsequent spring runoff conditions having the greatest impact on inputs (Clair and Ehrman, in press). Thus the amount and chemical nature of DOC input to prairie wetlands will be affected by climate change and changes in wetland hydrology.

Climatic Impact on wetland values

Tourism

Wetlands and other waterbodies support a range of recreational and tourism activities which contributes to both wetland conservation and destruction. The impact that climate change will have on wetland-related tourism will depend on the nature of the activity. Climate change will influence the length of the tourism season, how people will participate in a tourism activity and the quality of their experience. Because much tourism takes place on or near the shoreline of rivers, lakes and wetlands, effects of climate change on these areas has significant economic implications.

The impact of climate change on tourism depends on the individual wetland and the shape of the littoral zone. If water levels decline, there likely would be increased competition between the hydrologic function of wetlands and their recreational use. There has been a long history of adjustments to low or changing water levels at various locations across the country, though the problem and the necessary adjustments vary with location and use. Individuals tend to be fairly adaptive to change and able to substitute alternative uses and tourism experiences in response to change. Businesses, however, are less adaptable to change because of larger capital investment (Wall, in press).

Water management

The International Joint Commission is considering climate change in developing new water management and operational plans for the St. Lawrence River. Lake Ontario provides the base flow for the St. Lawrence River and discharge from the Great Lakes may decrease under climate change scenarios. These scenarios and the interests of all users and affected parties need to be considered in developing management plans (Hudon, in press**)**. One of the important potential downstream impacts involves managed wetlands in the St. Lawrence River.

Barabe *et al*. (1997) show that wetlands in Lac St. Pierre near Trois Rivières, Québec have considerable economic importance to the region because of their importance as waterfowl staging and breeding areas. They also have economic importance for fisheries, nature watching, hunting, and trapping. Agriculture and wetlands conflicts have existed in the area but have been worked out over the past few years. With changes in river flow regimes, wildlife and anthropogenic uses which have evolved in the past will have to be renegotiated under more stressful conditions.

WETLAND POLICY IN CANADA

In June 1987, the Federal-Provincial Committee on Land Use produced a report entitled *A Framework for Wetland Policy in Canada*. Also in 1987, the Federal Interdepartmental Committee on Land identified the need to develop a wetland policy statement to supplement "wise land use" provisions of the *Federal Policy on Land Use*. The *Federal Water Policy*, adopted in 1987, also identified wetland conservation as a significant water resource issue (Rubec, 1994).

The *Federal Policy on Wetland Conservation* (Government of Canada, 1991) focuses on the sustainable wise use of wetlands in Canada and applies to all federal agencies, programs and policies. The stated objective of the Government with respect to wetland conservation is:

> "to promote the conservation of Canada's wetlands to sustain their ecological and socio-economic functions, now and in the future."

In support of this objective, the Government of Canada, in cooperation with the governments of its ten provinces and two territories as well as the Canadian public, have committed to achieve the following goals:

a) maintenance of the functions and values derived from wetlands throughout Canada;
b) no net loss of wetland functions on federal lands and waters;
c) enhancement and rehabilitation of wetlands in areas where the continuing loss or degradation of wetlands or their functions have reached critical levels;
d) recognition of wetland functions in resource planning, management and economic decision-making with regard to all federal programs, policies and activities;
e) securement of wetlands of significance to Canadians;
f) recognition of sound, sustainable management practices in sectors such as forestry and agriculture that make a positive contribution to wetland conservation while also achieving wise use of wetland resources; and
g) utilization of wetlands in a manner that enhances prospects for their sustained and productive use by future generations.

The wetland conservation policy focuses on areas of federal jurisdiction and management of wetlands under direct federal authority. It outlines seven strategies aimed at building on past achievements and working in concert with ongoing initiatives for wetland conservation. The policy promotes a non-regulatory, cooperative approach. The seven strategies focus on:

a) developing public awareness
b) managing wetlands on federal lands and waters and in other federal programs
c) promoting wetland conservation in federal protected areas
d) enhancing cooperation with federal, provincial, territorial and non-government partners
e) conserving wetlands of significance to Canadians
f) ensuring a sound scientific basis for policy, and
g) promoting international actions.

If governmental policy decisions regarding the future of wetlands are to be made on a sound basis, some consideration must be given to potential changing climatic conditions.

KNOWLEDGE GAPS

A 1991 workshop on wetland hydrogeochemistry and habitat research needs identified what basic research was needed to widen our understanding of the hydrogeochemical processes of wetlands (Wedeles *et al*., 1992). These included:

a) effects of water table fluctuations on wetland function and integrity;
b) interaction of temperature and moisture in the unsaturated zone of wetlands;
c) effects of changes in the quantity of water in, or flowing through, a wetland on wetland water quality;
d) effects of permafrost melting;
e) influence of atmospheric CO_2, temperature and moisture on plant growth;
f) response of wetlands to changes in fire frequency and intensity; and
g) adaptiveness of wetlands to climatic change

These research needs still exist.

In most regions of Canada, wetlands have received less attention than other ecosystems. For example, in the Great Lakes an assessment of wetland areal and vegetation change in response to water level changes and many of the water level – wetland relationships still must be verified and the interrelationships of wetland vegetation, birds, mammals, fish and water quality, as well as their individual and combined sensitivity to water level fluctuations should be quantified (Mortsch, 1990, Vaughan *et al.* 1997).

A long-term, integrated approach to identify the major aspects of wetland ecological structure and functions is needed and as well as broad-scale comparisons of matched watersheds of similar size and regional location but with different land uses (Covich *et al*., in press). Before it is possible to make detailed predictions about the consequences of climate change in the northern

Great Plains, we must understand the basic mechanisms of interactions among biotic systems, climate and greenhouse gases in the region (Larson, 1994). It also is necessary to determine the direct effects that a changing environment may have on the physical well-being of birds with emphasis on responses to a range of environmental stresses (Larson, 1994).

The probable loss of waterfowl habitat due to increasing cover: water ratios in semi-permanent wetlands and the loss of temporary and seasonal ponds may be significant under climate change. Quantitative estimates of new water conditions and the resulting change in number of ponds and cover: water ratios can be a first step in determining the potential effects of climate change on waterfowl populations. Further simulations of habitat changes associated with global warming are needed to learn more about climate, hydrology and ecological interrelationships. One improvement in wetland modelling would be to simulate changes in an entire wetland complex, including ponds of all sizes and types of water permanence, because these other classes, as well as semi-permanent wetlands, are critical to overall waterfowl success (Poiani and Johnson, 1991).

The water table is often the single most important variable governing the function and distribution of wetlands. The degree of contact with the water table determines the wetland type, the wetland's control on downstream basin hydrology and its effect on water quality (Wedeles *et al.*, 1992). Wetland models would benefit from a better understanding of soil and groundwater interactions with surface water as well as the implications of climate change for local and regional water tables (Larson, 1994).

Wetlands lag far behind other ecosystems in being modeled adequately and, as a consequence, are often excluded from any global models of studying climatic change effects on ecosystem functioning and carbon budgets (Moore *et al.*, in press). Climate models should be used in conjunction with other models such as those for precipitation, runoff and groundwater models to assist in estimating the changes in wetland functions and values in the future (Fuller, 1997).

Effects of climate change on aquatic plant communities are complex and difficult to predict. The amount of water in a wetland basin has a direct effect on the extent of aquatic vegetation, but wetland chemistry, growing season length, carbon dioxide fertilization and effects of UVB on plant growth form also influence wetland community composition and structure. Little is known about these effects and questions of basic biochemistry and physiology must be addressed before predictions can be made regarding species-specific responses and the extent to which wetland habitat will be altered (Larson, 1994).

Extensive shifts in vegetation resulting from climate-induced changes in fire and disturbance regimes may influence wetland dynamics in ways not anticipated by models dealing solely with climate. Other aspects of climate also need to be studied including the effects of UVB on prairie wetland habitat, photoenhanced toxicity of pesticides after UVB irradiation, the relative vulnerabilities of plants to increased UVB and the interactive effects of UVB with temperature, precipitation and carbon dioxide (Larson, 1994).

Much work remains to be done in establishing the area, depth and types of Canada's peatlands. Of particular interest concerning responses to past climate change is a better understanding of the timing of peatland initiation in different parts of the country and subsequent rates of soil formation (Gorham, 1994). Given the complexity of issues affecting peatlands, the possible influence of climate change on the carbon cycle in boreal and subarctic peatlands merits intensive research (Gorham, 1991). The deficiencies in knowledge with respect to the area, depth and density of peat need to be addressed. It will be especially important to measure changes in the area of boreal and subarctic peatlands, because climate change is likely to destroy them in some regions while stimulating their development in others.

Rates of release of CO_2 and CH_4 from drained peatlands require more study in relation to regional temperature and precipitation the impacts of lowered water tables. It will be of particular value to examine the balance between drawdown due to potential local permafrost melting and the formation of thaw lakes (Gorham, 1991). Comparisons of open-water areas with adjacent wet sedge fens and drier *Sphagnum* bogs should be made and the relationship of CH_4 emissions to the depth of the water table deserves particular attention (Gorham, 1991).

More research is also needed to understand the interactions between groundwater and surface water and their effects on plant communities, element cycles, trace-gas emissions and CO_2 and CH_4 emissions. The balance between productivity and decomposition in drained bogs also are of much interest as well as improved understanding of how the storage and export of DOC and DON to outflow streams will be affected by alterations in hydrology.

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CHAPTER FOUR

IMPLICATIONS OF GLOBAL CLIMATIC CHANGE FOR CANADIAN AGRICULTURE: A REVIEW AND APPRAISAL OF RESEARCH FROM 1984 TO 1997

VOLUME 1: SYNTHESIS AND RESEARCH NEEDS

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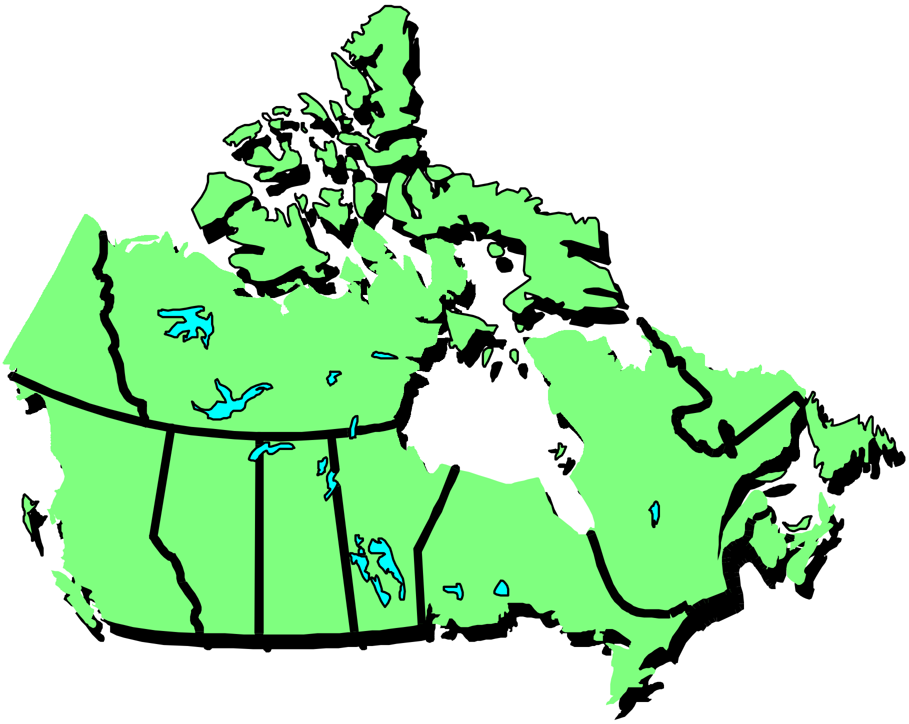

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PREFACE

This report on *Implications of Global Climatic Change for Canadian Agriculture: A Review and Appraisal of Research from 1984 to 1997 (Volume 1)* was completed under contract (Contract No. KM170-7-6194) to the Atmospheric Environment Service, Environmental Adaptation Research Group, Environment Canada. This report has also benefited from support provided by Agriculture and Agri-food Canada.

The report was completed as part of the Canada Country Study (CCS) co-ordinated by Environment Canada. CCS Phase I projects draw upon and review the existing knowledge base and are to identify research gaps and priorities. New research initiatives are planned under CCS Phase II.

This initiative was undertaken as part of CCS Phase I and completed as a joint project by researchers at Carleton University and the Université de Montréal. It reviews and appraises research on Canadian agriculture and global climatic change. It provides a state-of-the-art assessment of the research conducted between 1984 and 1997, and proposes research to enhance our collective understanding of the interactions between global climatic change and Canadian agriculture.

EXECUTIVE SUMMARY

CONTEXT AND PURPOSE

1. Substantial research over the last fifteen years has been undertaken into the potential impacts of global climatic change on human activities including agriculture. This research has undergone an important evolution in terms of:

    a) the focus of attention (starting off with a focus on potential impacts on agro-climatic properties, subsequently dealing more with potential impacts on crop productivity and more recently stressing the adaptation of agriculture to global climatic change and its socio-economic consequences); and

    b) the methodologies employed (with the models dealing with crop productivity impacts covering an increasingly wider range of variables and more recently, with methodologies on adaptation being integrated which use various types of farmer-based information).

2. In Canada, an important dimension to the relationship between climatic change and agriculture is the wide range of conditions for agricultural production between different regions. Much of the research has been undertaken in the context of specific regions. Unfortunately the use of different assumptions and models has hampered inter-regional comparisons of research findings.

3. In light of this dynamic and complex situation, the purpose of this report is to provide a state-of-the-art assessment of the results from research on Canadian agriculture and global climatic change from 1984 to 1997.

4. The report summarizes the main findings of this body of research, identifies its strengths and limitations and makes a set of recommendations concerning future research to enhance the understanding the impacts of global climatic change on Canadian agriculture.

REVIEW AND APPRAISAL

Global climatic change and agro-climatic properties for Canadian agriculture

The considerable body of research dealing with global climatic change scenarios suggest considerable warming for all Canadian regions. Longer frost free seasons more conducive for commercial agriculture than the existing thermal regimes are expected. Considerably less research has assessed the implications of climatic change for agricultural moisture regimes. Regional variations in potential agro-climatic impacts are large.

1. Estimates of increases in the frost free season under global climatic change range from a minimum of one week to a maximum of nine weeks. For the Prairies, Ontario and Québec, most estimates suggest an extension of three to five weeks. The extension is somewhat longer for Atlantic Canada (four to eight weeks) but only from three to four weeks near the current agricultural margin.

2. Estimated temperature increases for the frost free season in Ontario and Québec are mostly in the 1.5^0C to 5.0^0C range, and are generally much larger in the northern-most parts of these provinces. Estimated temperature increases for Atlantic Canada are smaller (3.5^0C to 4.5^0C range), but in the Prairies and Peace River regions, there is less consensus regarding the estimated temperature increases.

3. Results relating to agricultural moisture regimes show a broader range of estimates compared to the thermal regimes. For instance, in the Prairies and Peace River regions, estimated precipitation changes range from decreases of about 30% to increases in the 80% range.

4. Despite favourable potential impacts in terms of longer and warmer frost free seasons and of greater precipitation, most scenarios also imply important increases in potential evapotranspiration. Thus, larger seasonal moisture deficits are estimated in all regions, with the severest situations anticipated for Ontario.

5. Thus, assessments of the implications of global climatic change should take account of both negative and positive impacts on agro-climatic properties.

Global climatic change and crop development and yields in Canadian agriculture

Research on the impacts of global climatic change on crop development and yields has been extensive, yet not as thorough as the research dealing with the impacts on agro-climatic properties. Furthermore, grain crops have been researched more extensively than other major crop groups (e.g., oil seeds, forages and potatoes). The research has been more heavily focused on the Prairies, Ontario and Québec.

1. Much of the research in Ontario pre-dates the more recent generation of crop development and productivity models which take into account the potential benefits of increased CO_2 levels on crop yields. The available studies therefore probably overestimate the negative effects of climatic change on crop yields, but this is difficult to determine without undertaking the research with the current generation of crop development and productivity models.

2. The studies suggest that warmer frost free seasons under the full range of global climatic change scenarios will increase the rate of development of grain crops, reducing the time between seeding and harvesting (e.g., by about one-and-one-half to three weeks in most regions of Canada for spring-seeded cereals and coarse grains).

3. In northern regions, the estimated decrease in maturation time would reduce the risk of frost-induced crop injury, a decided benefit for these regions. In contrast, in the Prairies, Ontario and Québec, the net effect from the interactions between the several agro-climatic variables used would be to depress yields.

4. In the Peace River region, the positive and negative influences tend to counteract each other, reducing the magnitude of the positive impacts of climatic change on cereal yields.

5. In the Prairies, the effects of climatic change on grain yields are more pronounced and variable, with spring-seeded cereal yields in the western Prairies being reduced by as much as 35% and in the eastern Prairies, increasing by as much as 66%.
6. Similar results are suggested for Ontario and Québec, except for the more generally positive impacts on grain production, especially corn, in northern Ontario and Québec.

7. Research into the impacts on yields for other crops such as oilseeds, forages and potatoes has been less extensive and has been conducted under a narrower range of climatic change scenarios and for fewer regions in Canada. Results suggest a reduction in oilseed yields because of increased crop moisture stress. Some offsetting effects would be realized by a northern expansion of the area capable of producing oilseeds.

Global climatic change and land and regional production potential in Canadian agriculture

Very little research has been conducted in Canada into the sensitivity of agricultural land and production potential to global climatic change, and what there is has focused mostly on the Peace River region and Ontario.

1. Studies suggest the Peace River region would see a considerable expansion of the land area suitable for commercial crop production. Similar conclusions have been reached for the northern agricultural regions in Québec and Ontario.

2. Impacts on agricultural land potential North of 60° are generally considered not to be very substantial.

3. Global climatic change is expected to enhance the potential for specialty crops in southern Ontario and Québec. For instance, the physical potential for fruit and vegetable production would expand beyond lakeside locations.

Global climatic change and agricultural economics

The few studies undertaken on the economic impact of climatic change on agriculture in Canada have focused on the Prairies and Ontario. They include limited regional and farm level investigations and only in relation to a subset of the climatic change scenarios.

1. For the Prairies, the economic impact of climatic change is estimated as relatively minor. However, this conclusion masks substantial variation at the subprovincial or subregional level.

2. The Ontario studies suggest similar results. One Ontario study dealt with a "typical" cash-grain farm in south-west Ontario; the estimated increase in profits depended upon a re-allocation of resources at the farm level. This study also underlined the potential for greater variability in annual farm profits.

3. The existing research on this theme does not provide an adequate basis for generalization of economic assessments to other regions nor to a wide range of crops.

Global climatic change and adaptation in Canadian agriculture

Agricultural impacts from climatic change represent potential choices among desirable and undesirable results for farmers. Although some of the economic studies implicitly tackled the notion of choice by investigating the potential re-distribution of on-farm resources, the field of climatic change and agricultural adaptation represents a relatively new sub-field of research, in which methodologies are evolving rapidly. These methodologies include investigations of the effects of incorporating irrigation possibilities into modelling exercises as well as farm-level surveys and focus groups with farmers.

1. The initial focus of this research and reflection has been the identification of options regarding adaptation. Many of the options identified in the literature involve preventing or delaying the onset and rate of global climatic change, e.g., the reduction of greenhouse gas emissions through altering crop mixes and cropping practices.

2. Other options identified deal with adaptation strategies that involve coping with and adapting to climatic changes. These include spreading risks, reducing the potential occurrence and/or magnitude of negative impacts, capitalizing on new "opportunities" arising from climatic change and developing appropriate research and education programs.

3. The second focus, more recent and still in its infancy, involves the assessment of agricultural adaptation strategies to environmental change. These studies have focused on Ontario, on the Prairies and on regions near the current climatic boundary for Canadian agriculture. There is an absence of studies dealing with Atlantic Canada and British Columbia.

4. Within this body of research: the effects of switching to longer season spring-seeded cereal cultivars varies across the Prairies, but in some locations partially offset yield reductions from climatic change; winter wheat enhances yields in the southern Prairies, but at the current climatic boundary would do little to favour the production of winter cereals; irrigation strategies reduces the negative effects of climatic change and enhances crop yields; and climatic change may permit the growing of high value field crops such as corn and soybeans in some northern regions of Ontario and Québec.

5. However, these studies have not generally addressed the economic feasibility of such adaptations nor the ability or willingness of the farm community to undertake them.

Global climatic change and Canadian agriculture in an international context

Despite all of the research reported on above and Canada's position as a major world exporter of agricultural products, very little research has attempted to assess explicitly the implications of global climatic change for Canada's agriculture compared to agriculture in other world regions. What has been undertaken has produced contradictory results.

1. Several global climatic change scenarios estimate relatively large temperature increases for much of Canada, northern Europe and the former U.S.S.R. and much smaller increases for the temperate regions. Little consensus exists on precipitation changes except for a drying trend in the interiors of northern continents. Evidence regarding the net impact of such changes on Canada's comparative position in agriculture relative to other nations is lacking.

2. The inconclusive nature of the studies is underscored by their contradictory results regarding wheat, Canada's main agricultural export crop. Conclusions range from the generation of new export opportunities for Canadian wheat to a downturn in world wheat prices, thereby reducing Canada's comparative advantage in cereal markets.

3. In view of the preoccupation with globalization of the world economy over the last decade or so, the lack of research which fully integrates issues on climatic change with international economies represents a serious knowledge gap.

RECOMMENDATIONS

There has been considerable research into the relationships between global climatic change and Canadian agriculture since the early to mid-1980s. However, the research has been: more extensive in terms of impacts on agro-climatic properties especially thermal regimes than in terms of crop productivity; more concentrated in Ontario, the Prairies and to a lesser extent in Québec, with much of the earlier research in Ontario not having been followed up using the more recent generation of crop productivity models; very limited in relation to the economic consequences of climatic change for agriculture; and more recently concerned with the phenomenon of farm and agricultural adaptation, without for the moment having developed a generally accepted approach to assessing adaptation strategies.

In light of this assessment of this body of research, it is recommended that:

1. Attention be given to supporting research that would utilize a common set of climatic and crop productivity models for all regions of the country to generate more easily comparable results in terms of impacts of climatic change on yields.

2. Research is needed to develop an assessment of the economic impacts of climatic change that takes into account scenarios based on different adaptation strategies. The research should develop linkages between:
    a) various scales (e.g., farm, regional, national), and
    b) crop and livestock operations and enterprises.

3. Research should be encouraged to address the implications for Canadian agriculture of global climatic change in the context of changing levels of comparative advantage and changing world agricultural commodity markets. Linkages between specialists analysing the climatic change implications for agriculture and those focusing on international economy and trade need to be improved in order to ensure that the most recent and reliable appraisals are employed in a credible manner.

4. It is clear that a greater understanding of farm and agricultural adaptation is required. This is arguably the most important domain for further research since upon it rests the credibility of the assessments of the socio-economic implications of climatic change for agriculture, including the economic impacts, both regionally, nationally and in the context of the international market place. Further research in the domain of adaptation must also address ways of effectively integrating those agro-climatic indicators which farmers identify as important in their decision-making into the climatic change scenarios, e.g., greater information on the variability of estimated changes in key agro-climatic variables.

5. The final recommendation is for a national research program designed to:
    a) better integrate biophysical and socio-economic dimensions of climatic change and Canadian agriculture, and
    b) identify root causes of differential vulnerabilities.

   This research would identify which types of agriculture and which regions are most sensitive to global climatic change. This would provide a more coherent and systematic basis for developing targeted policies and programs to alleviate potential stresses on those agricultural systems most vulnerable to global climatic change.

INTRODUCTION

Climatic Change and Agricultural Research Frameworks

Research into the potential impacts of global climatic change on human activities has flourished over the past fifteen years, with considerable research on the interface between climatic change and agriculture. Many of the investigations into global climatic change and Canadian agriculture have been founded upon established agricultural research practices for investigating relationships among food production, weather and climate.

The usual starting point for investigating the potential impacts of global climatic change on agriculture involves specifying scenarios for global climatic change. Several approaches have been employed to generate these scenarios, including:

- the application of general circulation models (GCMs) to elevated CO_2 levels for the Earth's atmosphere,
- historical and spatial analogues, and
- incremental changes to the observed weather record.

The next step in impact assessment usually involves a reduction from global to regional scales, and the conversion of standard climatic properties (e.g., temperature profiles) to agro-climatic properties (e.g., frost free season length). When combined with crop productivity models and other impact assessment methods, these regional scenarios for long-term agro-climatic change then become the foundation for estimating:

- crop yield sensitivities to climatic change,
- impacts on agricultural land and production potential, and
- changes in farm and regional agricultural economies.

This "comparative static approach" to impacts research has been instrumental in estimating the sensitivity of selected attributes of Canadian agriculture (e.g., crop yields, agricultural land suitability) to various climatic change scenarios.

More recently, this research framework has been expanded and restructured to address explicitly concerns relating to the capacity of Canadian agricultural systems to recognize and if necessary adapt to global climatic change. These revised frameworks are not as well developed as the conventional impacts frameworks summarized above, but they are characterized by:

- identification and evaluation of alternative adaptive strategies,
- assessments of farmer perceptions of change (in climate and/or other conditions),
- evaluations of the importance of climatic change vis-à-vis other influences including other environmental, economic, political and socio-cultural factors in agricultural decision-making,
- investigations of differential vulnerabilities across the agricultural sector to the changing conditions.

Purpose of the Report

This report reviews and appraises research on Canadian agriculture and global climatic change. It provides a state-of-the-art assessment of the research conducted between 1984 and 1997, and:

a) summarizes the main findings of this research,
b) identifies strengths and limitations of current research, and
c) proposes research to enhance understanding of global climatic change on Canadian agriculture.

Report Structure

The report is presented in two volumes.

Volume 1 is the main report and presents in summary form a synthesis of the extant literature on global climatic change impacts on Canadian agriculture. It highlights major research findings, and compares and contrasts current understanding across attributes and sectors of the Canadian agricultural system and across regions of Canada. Overall, this summary and synthesis provides a foundation for developing recommendations for future research thrusts.

Volume 1 is based on the structure of research frameworks employed to assess relationships between climatic change and Canadian agriculture. After a brief description of the project's, a summary of research focusing on biophysical dimensions of Canadian agriculture is presented. It includes subsections on the impacts of global climatic change on:

- agro-climatic properties,
- crop development and yields, and
- land and regional production potential.

Socio-economic perspectives are reviewed in Section 4, with subsections on global climatic change and:

- agricultural economics,
- adaptation, and
- Canadian agriculture in an international context.

Volume 1 concludes with a set of recommendations to guide the next generation of research into the relationships between global climatic change and Canadian agriculture.

Volume 2 is an appendix which contains supporting material for Volume 1. It summarizes more than 70 studies which address issues relating to global climatic change and Canadian agriculture. Volume 2 is divided into six appendices, one for each of the subsections employed in Volume 1.

DEVELOPMENT OF A GLOBAL CLIMATIC CHANGE CANADIAN AGRICULTURE DATABASE

Overview of Literature Searches

Research which explicitly investigates relationships between global climatic change and Canadian agriculture dates back to the mid-1980s and covers a wide range of related topics and themes. For example, this research base includes reports on:

- frameworks and methods for assessing agricultural impacts of global climatic change,
- greenhouse gas emissions from and carbon sequestering potential of Canadian agriculture,
- the sensitivity of Canada's agricultural resources to climatic change, and

- case studies focusing on specific agricultural subsectors and/or Canadian regions.

Given this breadth, it should not be surprising that research into global climatic change and Canadian agriculture has been documented in several locations (e.g., government documents, scientific journals and conference proceedings) and reported on in diverse arenas (e.g., publications focusing on physical and life sciences, rural sociology, environmental change and agricultural economy).

Table 2.1 presents the 10 databases that were consulted and the key words used in these searches. Overall, these database searches were designed to detect research which focused on the sensitivity of Canada's agricultural resources to climatic change, and case studies into specific agricultural subsectors and/or Canadian regions. Publications which did not pertain directly to this project were culled, and the synthesis and summaries presented in Volumes 1 and 2 are derived from the remaining 70+ publications (see Reference List).

Research Report Summaries

Summaries of the publications considered in this project are presented in Volume 2. Volume 2 is divided into six appendices (agro-climatic properties, crop yields, land and regional production potential, agricultural economics, adaptation, and Canadian agriculture in an international context). To assist with interpretations, each appendix is subdivided into the following Canadian agricultural regions: British Columbia-Lower Mainland, Peace River and the Agricultural Margin, Prairies, Ontario, Québec and Atlantic Canada.

Each publication entry in Volume 2 includes a citation for the publication(s), and a summary of spatial coverage, base climate, climatic change scenario, research methods, major assumptions, and major results and findings associated with each publication. In those instances where two or more publications are reporting on related or similar studies, the entry in Volume 2 identifies the "family" of publications and these publications are presented as a single entry in Volume 2.

Interpretation Guidelines and Assumptions

Research into relationships between global climatic change and Canadian agriculture has evolved considerably since the mid-1980s. New generations of general circulation models have been developed and these modelling enhancements have resulted in revised scenarios for global climatic change.

Many different impact assessment methods have been employed to gauge the sensitivity of various aspects of Canadian agriculture to global climatic change. Some of these methods have included resource rating schemes, crop productivity models, farm-level economic models and regional models for agricultural production. These methods have continued to evolve. For example, some crop productivity models from the mid-1980s considered only climate and soil factors, and routinely employed a seasonal time step based on the length of the frost-free season. The current generation of crop models are more sophisticated. These models estimate crop yield as a function of thermal and moisture regimes, atmospheric CO_2 concentrations and an array of management inputs, and operate on a daily rather than seasonal time step.

Table 4.1: Overview of Literature Searches

(a) Databases Searched

Database Name	Years
Current Contents (CC)	1988-present
Carleton University Bibliographic Enquiry (CUBE)	1988-present
Science Citation Index (SCI)	1994-1996
GeoBase (covers Geographic Abstracts: Human and Physical, Ecological Abstracts, Mineralogical Abstracts, International Development Abstracts, Geological Abstracts, Oceanographic Literature Review)	1990-present 1985-present
Commonwealth Agricultural Bureau International (CAB)	1990-present
Agricultural Sciences Database (AGRICOLA)	1985-present
Environmental Periodical Index (EPI)	1988-present
Canadian Periodical Index (CPI)	1993-present
Swets and Zeitlinger Inc. Electronic Table of Contents (SWETSCAN)	1990-present
Internet Resources: Numerous government and university sites	

(b) Keywords Searched[1]

Theme	Related Terms
Climate	agroclimate, agroclimatic, climate, climate change, climatic, climatic change, climate variability, climatic variability, environmental change, global change, temperature, warming, weather
Agriculture	adaptation, agriculture, agricultural, corn, crop, farm, farming, forage, frost-free season, grain, growth models, harvest, impact, socioeconomic, wheat, yield
Location	Alberta, Atlantic, British Columbia, Canada, Central Canada, Eastern Canada, Lower Mainland, Manitoba, Maritimes, New Brunswick, Newfoundland, north, North America, Northern Canada, Northwest Territories, Nova Scotia, Ontario, Prairies, Prince Edward Island, Québec, Saskatchewan, Yukon

[1] Searches were performed with various combinations of climate, agriculture or location-related terms using connectors "and", "or" and "with". To ensure all word forms were included, the "*" function was employed where possible (eg. "climat*" captures all terms beginning with "climat").

The absence of standardized methods and the continual evolution of assessment methods has created an uneven spatial and temporal research foundation. In order to minimize the extent to which these differences might influence interpretations and generalizations of previous research, this project will place greater emphasis and weight upon the most recent research. When the best available information is several years old, attempts will be made to re-interpret findings in light of results generated by the most recent studies.

BIOPHYSICAL PERSPECTIVES ON GLOBAL CLIMATIC HANGE AND CANADIAN AGRICULTURE

Impacts on Agro-Climatic Properties

There has been considerable research into the possible implications of several global climatic change scenarios for agro-climatic conditions in all regions of Canada except southern British Columbia (Table 4.2). These studies have considered several climatic change scenarios and have examined the implications of altered climates for wide range agro-climatic properties, including the growing and frost free seasons (G/FSL), and seasonal values for temperature (T), growing degree days (GDDs), corn heat units (CHUs), precipitation (P) and moisture deficits (MD). The implications for thermal regimes have been investigated more thoroughly than the implications for moisture regimes.

All of the global climatic change scenarios and studies suggest considerable warming for all Canadian regions. Under these warmer conditions, frost free seasons would be expected to be longer and warmer, and more conducive for commercial agriculture than the existing thermal regimes which are characterized by relatively short and cool frost free seasons in many regions of Canada. Estimates of extensions to the frost free season are not uniform across Canada, and range from a minimum of one week to a maximum of nine weeks. For the main agricultural regions in the Prairies, Ontario and Québec, most estimates suggest the frost free season will be extended by three to five weeks. The estimated lengthening of frost free seasons for Atlantic Canada is somewhat longer, with several studies suggesting a four to eight week extension. This is contrasted by studies focusing on the Peace River region and other regions near the current agricultural margin where estimated extensions for the frost free season are limited to about three to four weeks.

Table 4.2: Estimated Impacts of Climatic Change Scenarios on Selected Agro-climatic Properties

PROP	Climatic Change Scenario	BC- Lower Mainland	Peace River Agricultural Margin	Prairies	Ontario	Québec	Atlantic Canada
G/FSL	T↑1 to ↑3°C	↑14 (↑10)	↑14 (↑14)	↑12 (↑12)	↑10 (↑ 7)		↑11 (↑ 7)
		↑42 (↑31)	↑37 (↑38)	↑32 (↑31)	↑39 (↑33)		↑47 (↑38)
days	CCC		↑13 (↑10)			↑33 (↑20)	
			↑18 (↑14)			↑42 (↑38)	
(%)	GFDL		↑29 (↑22)		↑35 (↑23)	↑24 (↑22)	↑64 (↑43)
					↑45 (↑31)	↑34 (↑28)	↑85 (↑68)
	GISS		↑25 (↑25)	↑48	↑49 (↑36)	↑42 (↑38)	↑41 (↑31)
			↑32 (↑40)		↑68 (↑49)	↑46 (↑43)	↑61 (↑49)
	OSU						↑34 (↑25)
							↑46 (↑37)
	EXP. OP.			(↑20)	↑40		↑41
				(↑30)	↑60		↑61
T °C	CCC		↑1.0	↑2.6	↑5.1	↑2.3	
			↑4.1	↑8.3		↑2.8	
	GFDL		↑4.0	↑2.0	↑1.5	↑1.4	↑4.6
			↑6.0	↑5.5	↑5.1	↑3.3	↑5.5
	GISS		↑0.8	↑2.5	↑1.5	↑3.1	↑3.3
			↑1.6	↑4.6	↑3.6	↑4.5	↑4.1
	UKMO			↑5.0			
				↑9.5			
	OSU						↑3.0
							↑3.2
	EXP. OP.		↑7.0	↑3.0	↑1.5		↑3.3
				↑8.0	↑1.9		
GDDs	T↑1 to ↑3°C						↑180 (↑13)
							↑680 (↑57)
units	CCC		↑600 (↑63)			↑ 762 (↑51)	
			↑635 (↑79)			↑1103 (↑70)	
(%)	GFDL		↑800 (↑85)			↑443 (↑38)	↑1095 (↑ 73)
						↑582 (↑43)	↑1215 (↑102)
	GISS		↑420 (↑42)		↑1075 (↑38)	↑660 (↑58)	↑742 (↑50)
			↑486 (↑79)			↑819 (↑67)	↑811 (↑75)
	OSU						↑595 (↑43)
							↑691 (↑55)
	EXP.OP.						↑750
							↑800

NOTES:

1. Table values were derived from: Arthur 88a, Arthur 88b, Arthur and Abizadeh 88, Bootsma *et al.,* 84, Brklacich *et al.,* 89, Brklacich and Tarnocai 91, Brklacich *et al.,* 92, Brklacich and Stewart 93, Brklacich and Curran 94, Brklacich *et al.,* 94, Brklacich and Stewart 95, Brklacich *et al.,* 96, Brklacich *et al.,* 97a, Delcourt and van Kooten 95, DPA Group 89, Hall and Burkholder 93, Land Evaluation Group 85, Land Evaluation Group 86, Lilley and Webb 90, Maybank *et al.,* 95, Mills 92, Mills 94, Parker and Cowan 93, Parry and Carter 89, Roots 93, Schweger and Hooey 91, Singh *et al.,* 87, Singh and Stewart 91, Singh *et al.,* 96, Singh *et al.,* 97, Smit 87, Smit *et al.,* 89, Stewart *et al.,* 88a, Stewart *et al.,* 88b, Stewart 89, Stewart 90, Stewart and Muma 90, Stewart 91, Toure *et al.,* 95, Viau and Mitic 92, Wheaton *et al.,* 92, Wheaton 94, Williams *et al.,* 88.

Table 4.2 (con't)

PROP	Climatic Change Scenario	BC-Lower Mainland	Peace River Agricultural Margin	Prairies	Ontario	Québec	Atlantic Canada
CHU	T↑1 to ↑3OC	↑ 377 (↑15) ↑1171 (↑46)	↑335 (↑21) ↑987 (↑62)	↑310 (↑17) ↑915 (↑49)	↑ 289 (↑24) ↑1125 (↑52)		↑ 307 (↑12) ↑1173 (↑55)
units	CCC					↑1217 (↑43) ↑1631 (↑66)	
(%)	GFDL				↑ 900 (↑36) ↑1200 (↑45)	↑671 (↑34) ↑867 (↑40)	↑1796 (↑66) ↑1863 (↑75)
	GISS			(↑48) (↑75)	↑1300 (↑48) ↑1610 (↑65)	↑1057 (↑53) ↑1240 (↑63)	↑1147 (↑45) ↑1333 (↑73)
	OSU						↑ 974 (↑38) ↑1063 (↑53)
	EXP. OP.				↑1300 ↑1600		↑1100 ↑1300
P	T↑1 to ↑3OC						(↑ 3) (↑39)
mm	CCC		(↓ 25) (↑ 25)	(↓ 30) (↑ 70)	(↓ 35) (↓ 6)	(↑ 20) (↑ 36)	
(%)	GFDL		(↓ 25) (↑100)	(↓ 20) (↑ 82)	(↓ 52) (↑ 40)	(↑ 4) (↑ 34)	↑249 (↑63) ↑367 (↑90)
	GISS		↑63 (↑ 40) ↑81 (↑131)	(0) (↑ 30)	(↓ 34) (↑ 42)	(↑ 28) (↑ 48)	↑138 (↑33) ↑255 (↑62)
	UKMO			(↓ 20) (↑ 58)			
	OSU						↑128 (↑33) ↑176 (↑43)
	EXP. OP.		Increase	(↓ 30) (↑ 80)	↑100 ↑150		(↑38) (↑62)
MD	CCC		↑40 (↑17) ↑57 (↑33)			↓84 (↓50) ↑48 (↑72)	
mm	GFDL		↑ 5 (↑ 2)		↑ 92 (↑122) ↑146 (↑230)		
(%)	GISS		↑75 (↑29) ↑80 (↑44)	(↑40) (↑60)	↑ 95 (↑112) ↑170 (↑235)		
	OSU						
	EXP. OP.			Increase		↑125	

NOTES:

2. Estimates of T (Temperature), GDD (Growing Degree Days), CHU (Corn Heat Units), P (Precipitation) and MD (Moisture Deficts) apply to the G/FSL (Growing/Frost-Free Season).
3. Values represent the estimated range under the identified climatic change regime and region, with estimated changes to absolute values followed by estimated per cent change in brackets.

Estimates of possible changes in mean temperatures during the frost free season vary considerably across regions and global climatic change scenarios. For example, the most extreme temperature increases are estimated for the Prairie region under the UKMO. The lower limit for temperature increases under this scenario for this region is about 5.0°C, which exceeds the upper limit for temperature increases under most other scenarios for this and other regions in Canada. Overall, this suggests investigations which have employed climate scenarios derived from the UKMO GCM should be treated cautiously, recognized as atypical and based on temperature increases which are not in line with other climatic change scenarios.

Estimated temperature increases for the frost free season in Ontario and Québec tend to be in the 1.5°C to 5.0°C range, with the largest increases associated with the more northerly areas in these provinces. For Atlantic Canada, differences among the estimated temperature increases are smaller and tend to converge around 3.5°C to 4.5°C. This is in sharp contrast with the Prairie and Peace River regions, where there is less consensus regarding estimated temperature increases. Similar trends are evident for other thermal regime properties, including growing degree days and corn heat units.

The estimated implications of global climatic change for agricultural moisture regimes are characterized by a broader range of possible outcomes than the estimated impacts on thermal regimes. For the Prairies and Peace River regions, estimated changes in precipitation typically range from decreases of about 30% to increases in the 80% range. The GFDL estimates for the Prairies region encompass this full range, with a precipitation decrease estimated for the western portion of the Prairies region and an increase in the eastern areas. For Ontario, precipitation increases and decreases are estimated but relative to the Prairies, the estimated decreases tend to be more extreme and increases are typically in the 40% range. The consensus for Québec and Atlantic Canada is an increase in seasonal precipitation levels, with the largest increases anticipated in Atlantic Canada.

While the prospect of longer and warmer frost free seasons and in many cases increases in precipitation during the cropping season suggest a more favourable climate for commercial agricultural production in many regions across Canada, most scenarios for global climatic change also imply substantial increases in potential evapotranspiration. These increases are expected to more than offset the estimated precipitation increase in most regions, and thereby reduce the inherent moisture supply for crop production. Larger seasonal moisture deficits are estimated for all regions, with the most severe changes anticipated in Ontario.

In summary, there is a strong consensus that global climatic change will result in longer and warmer frost free periods across Canada and thereby generally enhance thermal regimes for commercial agriculture. These changes in agro-climatic conditions are not expected to impact regions on an equal basis, with the longest extensions of the frost-free season expected in Atlantic Canada. The extent to which these longer and warmer frost free seasons might benefit Canada however will in all likelihood be diminished by increases in seasonal moisture deficits in all regions and under all climatic change scenarios. Hence, it is crucial that all assessments of the implications of global climatic change for Canadian agriculture take account of the possibility of both negative and positive impacts on agroclimatic properties.

Impacts on Crop Development and Yields

While there has been considerable research into the impacts of global climatic change on crop development and yields, coverage of these aspects of agricultural systems have not been as thorough as agro-climatic assessments. Grain crops, including grain corn, spring and winter wheat, oats and barley (Table 4.3), have been investigated more thoroughly than other major crop groups such as oilseeds, forages and potato (Table 4.4), and for all crop groups, the assessments have tended to focus on the Prairies, Ontario and Québec.

Many of the Ontario-based studies were completed prior to the implementation of the current generation of crop development and productivity models. These studies provide insight into the effects of alternative climates on crop yields but they do not consider the potential benefits of elevated CO_2 levels on crop yields. Overall, the most recent studies for Ontario probably overestimate the potential for negative effects of climatic change in crop yields, especially for cereal grains, but the degree to which negative impacts might be overestimated is difficult to determine. The potential benefits of higher CO_2 concentrations are sensitive to many factors including crop type and degree of crop moisture stress, making it inappropriate to apply simple adjustment factors to this earlier research.

All of the investigations suggest that warmer frost free seasons associated with the full range of global climatic change scenarios will accelerate the rate of development for grain crops and thereby reduce the time between seeding and harvest (Table 3.2a). Estimates based upon a range of climatic change scenarios and the continued use of current crop cultivars indicate that the maturity time for spring-seeded cereals and coarse grains will be reduced by about one-and-one half to three weeks in most regions of Canada. For winter-seeded cereals, the earlier onset of frost free days and warmer spring temperatures would hasten ripening and advance the harvest date by as much as four weeks.

Near the current northern boundary for Canadian agriculture, fall frosts can occur before a crop reaches maturity, and under these conditions, a decrease in crop maturation time can reduce the risk of frost-induced crop injury. This potential benefit for more northerly regions is in sharp contrast with the conclusions reached in several studies which have focused on climatic regimes associated with the Prairies, Ontario and Québec. In these regions, the evidence suggests that shorter maturation times also imply a reduction in the length of the grain filling phase of crop development, which in turn would tend to suppress crop yields. Interactions between climatic change and crop development will be complex, and involve both positive and negative influences. The net effects of this complex set of interactions on crop yields will in likelihood be sensitive to many factors such as the severity of the estimated change in climate, geographic location and crop type.

Current climate restricts commercial agriculture in the Mackenzie Basin to the Peace River Region and other localized areas within the southern portion of the Basin. Short, cool frost free seasons elsewhere in the Basin virtually prohibit commercial agriculture.

Table 4.3: Estimated Impacts of Global Climatic Change on Grain Crops[1]

a) Grain Crop Development[2]

ATMOS CHANGE	CROP MODEL	BC / LOWER MAINLAND	PEACE R./ AGRIC. MARGIN	PRAIRIES	ONTARIO	QUÉBEC	ATLANTIC CANADA
T↑,P↓↑[3]	FAO						SG: 0.5-2.5
CCC	FAO					SG: O.5-3.0 CG: 1.0-3.5	
	CERES		SG: 1.5-3.5				
	Y-W REG			SG: Decrease			
GFDL	FAO						SG: 0.5-2.5
	CERES		SG: 0.5-2.5	SG: 1.5-4.0	WW: 0.5-3.0		
	VSMB			SG: Decrease			
	Y-W REG			SG: Decrease			
GISS	FAO			SG: 0.5-2.0			SG: 0.5-3.5
	CERES			SG: 1.5-3.0	WW: 3.5-4.5		
	VSMB			SG: Decrease			
UKMO	CERES			SG: 3.0-4.5			

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[1] Derived from: Arthur 88b, Arthur and Abizadeh 88, Bootsma *et al.*, 84, Brklacich *et al.*, 89, Brklacich 90, Brklacich *et al.*, 92, Brklacich and Stewart 93, Brklacich *et al.*, 94, Brklacich and Stewart 95, Brklacich *et al.*, 96, Brklacich *et al.*, 97a, Delcourt and van Kooten 95, DPA Group 89, El Mayaar *et al.*, 97, Land Evaluation Group 85, Lilley and Webb 90, Mooney and Arthur 90, Parry and Carter 89, Savdie 89, Singh *et al.*, 87, Singh and Stewart 91, Singh *et al.*, 96, Singh *et al.*, 97, Smit *et al.*, 89, Stewart *et al.*, 88a, Stewart *et al.*, 88b, Stewart 89, Stewart 90, Stewart and Muma 90, Stewart 91, Toure *et al.*, 95, Tubiello *et al.*, 95, Viau and Mitic 92, Wheaton *et al.*, 92, Wheaton 94, Williams 85, Williams *et al.*, 88.

[2] For small grains (SG) and coarse grains (CG), estimates represent decreases (in weeks) for crop maturation times. For winter wheat (WW), estimated impacts represent decreases (in weeks) in harvest date.

[3] Derived from studies employing T↑ of 1°C and 2°C and P↓↑ of 80% and 120%.

b) Grain Yields (% change from current)

ATMOS CHANGE	CROP MODEL	BC/LOWER MAINLAND	PEACE R./ AGRIC. MARGIN	PRAIRIES	ONTARIO	QUÉBEC	ATLANTIC CANADA
T↑,P↓↑[3]	FAO	SG: ↓45-0 CG: ↓73-↑10	SG: ↓46-↑18	SG: ↓48-↑18	SG: ↓28-↑11 CG: ↓31-↑4		SG: ↓17-0
$CCC+CO_2$↑	FAO					SG: ↓15-↑40 CG: ↓7-↑45	
	CERES		SG: ↓24-↑4	SG: ↑15			
	VSMB				CG: ↓14		
	Y-W REG		SG: ↑7-↑14				
GFDL	FAO				SG[4]: ↓23-↑25 CG[4]: ↓15-↑66	SG: ↓43-↑9 CG[4]: O-↑859	
	VSMB			SG: ↑4-↑28	CG: ↓12		
	Y-W REG			SG: Decrease			
$GFDL+CO_2$↑	CERES		SG: ↓12-↑12	SG: ↓35-↑66	WW: ↓19-↓2		
GISS	FAO			SG: ↓18 CG: ↓9-↓5	SG: ↓31-↑17 CG[4]:↓14-↑53	SG: ↓75-↑73 CG[4]: 0-↑1200	
	VSMB			SG: Increase	CG: ↓6		
$GISS+CO_2$↑	FAO			SG: ↓14-↓6			
	CERES			SG: ↓2-↑50	WW: ↓18-↓2		
$UKMO+CO_2$↑	CERES			SG: ↓40-↓20			

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[4] Reported yield changes are for regions in Ontario and Quebec where grains are currently produced. In northern Ontario and Quebec, wheat and grain corn production does not occur under current climatic conditions, but it has been estimated that biophysical conditions under the specified climatic change would be suitable for the production of these grains.

Table 4.4: Estimated Impacts of Global Climatic Change on Oilseed, Forage and Potato Yields

(% change from current)

a) Oilseeds[5]

ATMOS CHANGE	CROP MODEL	BC-LOWER MAINLAND	PEACE R./ AGRIC. MARGIN	PRAIRIES	ONTARIO	QUÉBEC	ATLANTIC CANADA
T↑,P↓↑[6]	FAO	↓59-0	↓39-↑13	↓50-↑25	↓31-↑11		↓24-0
CCC+CO$_2$↑	FAO					↓21-↑49	
GFDL	FAO			↓40-↓4	↓41-↑33[7]	↓40-↑21[3]	
GISS	FAO				↓32-↑30[3]	↓43-↑89[3]	

b) Forages[8]

ATMOS CHANGE	CROP MODEL	BRITISH COL/ LOWER MAINLAND	PEACE R./ AGRIC. MARGIN	PRAIRIES	ONTARIO	QUÉBEC	ATLANTIC CANADA
T↑,P↓↑	FAO	↓43-↑3	↓39-↑2	↓43-↑19	↓13-↑3		↓8-↓4
GFDL	FAO				↓20-↑7		
GISS	FAO				↓15-↑24		

c) Potato[9]

ATMOS CHANGE	CROP MODEL	BRITISH COL/ LOWER MAINLAND	PEACE R./ AGRIC. MARGIN	PRAIRIES	ONTARIO	QUÉBEC	ATLANTIC CANADA
T↑,P↓↑	FAO	↓50-0	↓25-↑23	↓45-↑24	↓29-↑25		↓15-↓5
GFDL	FAO				↓27-↑360	↓27-↑178	
GISS	FAO			↓21-↑9	↓23-↑344	↓42-↑31	

Net positive and negative impacts have been estimated for grain yields (Table 3.2b). The combined effects of elevated CO$_2$ levels and climatic change on cereal grain yields for the Peace River region is expected to be relatively minor. Cereal yields are expected to increase by no more than 14%, with declines of up to 24% estimated for some sites. Warmer temperatures and higher CO$_2$ levels provide a more favourable set of conditions, but it has been estimated that these potential benefits

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[5] Derived from: Bootsma *et al.*, 84, Brklacich *et al.*, 89, Brklacich 90, El Mayaar *et al.*, 97, Land Evaluation Group 85, Mooney and Arthur 90, Singh *et al.*, 87, Singh and Stewart 91, Singh *et al.*, 96, Singh *et al.*, 97, Smit *et al.*, 89, Smit and Brklacich 92, Stewart 90, Wheaton 94, Williams *et al.*, 88.

[6] Derived from studies employing T↑ of 1°C and 2°C and P↓↑ of 80% and 120%.

[7] Reported yield changes are for regions in Ontario and Quebec where oilseeds are currently produced. In northern Ontario and Quebec, oilseeds production does not occur under current climatic conditions, but it has been estimated that biophysical conditions under the specified climatic change would be suitable for oilseed production.

[8] Derived from: Bootsma *et al.*, 84, Brklacich *et al.*, 89, Land Evaluation Group 85, Lilley and Webb 90, Mooney and Arthur 90, Smit *et al.*, 89, Stewart 90.

[9] Derived from: Bootsma *et al.*, 84, El Mayaar *et al.*, 97, Land Evaluation Group 85, Mooney and Arthur 90, Singh *et al.*, 87, Singh and Stewart 91, Singh *et al.*, 96, Singh *et al.*, 97, Stewart 90.

will be offset by increases in crop moisture stress and accelerated crop maturation. In aggregate, positive and negative influences tend to counteract each other and thereby reduce the magnitude of positive impacts of climatic change on cereal yields in this region.

In the Prairies, the estimated effects of climatic change on grain yields tend to be more pronounced and variable. This is especially evident under the GFDL scenario. In the western portion of this region, the combined effects of estimated declines in precipitation with concomitant increases in crop moisture stress and accelerated crop maturation times would more than offset the benefits of warmer temperatures and elevated CO_2 levels, and it has been estimated these conditions would reduce spring seeded cereal yields by as much as 35%. In the eastern portion of the Prairies under the GFDL scenario, expected increases in precipitation would reverse this trend and cereal yields could increase by as much as 66%.

For Ontario and Québec, trends in grain yield responses to climatic change would be similar to the trends described for the Prairie region, with one substantial difference. The severe limitations imposed by the current climate on grain production in the clay belts in northern Ontario and Québec would be relaxed considerably under several of the climatic change scenarios, and new opportunities for grain production, especially for corn, could be expected.

Relative to assessments of the sensitivity of grain yields to climatic change, the effects of climatic change on yields for other crops such as oilseeds, forages and potato have been not been examined as carefully (Table 4.4). There are considerably fewer assessments, and these assessments have been conducted under a relatively narrow range of climatic change scenarios and for fewer regions within Canada.

Preliminary evidence for oilseeds indicates that increases in crop moisture stress will suppress yields in many regions where oilseeds are currently being produced. Under most of the climatic change scenarios considered so far, it has also been estimated this negative impact would be offset somewhat by a northward expansion of the area which has the inherent biophysical potential to support oilseed production. For forages and potatoes, the few studies conducted to date make it difficult if not impossible to develop firm conclusions, but the preliminary evidence suggest yield trends would be similar to the trends described for oilseeds. For potatoes, estimated yield increase in northern regions of Québec and Ontario are attributable to more favourable conditions at harvest rather than a longer and warmer frost free season.

Impacts on Agricultural Land and Production Potential

Estimates of agricultural land and production potential are derived from the integration of agro-climatic and yield data with estimates of the spatial extent of the agricultural land base. Several schemes for gauging land suitability for agriculture have been developed. These methods are usually based upon assigning and summing of factor scores for climatic, soil and topographic conditions. More sophisticated approaches employ mathematical programming models to integrate these data and to determine optimal patterns for resource use.

There have been relatively few Canadian studies into the sensitivity of agricultural land and production potential to global climatic change (Table 4.5). The available studies focus mainly on

Ontario and the Peace River Region, with fewer studies conducted for the Prairies and Québec. The extent to which global climatic change might alter agricultural land and production potential in the British Columbia - Lower Mainland region and in Atlantic Canada has not been investigated to date.

Recent research suggests the benefits of longer and warmer frost free seasons would be most pronounced in the Peace River Region, where a considerable expansion in the land area suitable for commercial crop production has been forecast. Studies focusing on the northern agricultural regions in Québec and Ontario have reached similar conclusions, and identified new opportunities for field crop production in these regions.

Table 4.5: Estimated Impacts of Global Climatic Change on Land and Production Potential[10]

CLIM CHAN	METH	PEACE R./AGRIC. MARGIN	PRAIRIES	ONTARIO	QUÉBEC
T↑	FAO			Each ↑1°C expands corn limit by 60-100km north	
CCC	CLIM CLASS	Ag. land base ↑2x10^{6}ha(↑1%) Ave land suit ↑ from class 5.2 to 3.5			
	LAND SUIT	Mack Basin: Suit ag land ↑31%			
GFDL	LAND SUIT	Mack Basin: Suit ag land ↑41%			
	ECON SUIT			Land suit for corn ↑14%, wheat ↓17%, oilseeds ↓5%.	
GISS	CLIM CLASS	Lower Mack R: No change Cent & Upper Mack R: PE↑ offset T↑	Suit ag land ↑28%	New pot. in N. Ont. for sweet corn & apples. Fruit & veg potential ↑ beyond lakeside locations.	New pot. in Montreal sud for apples. New pot. for field crops in Abitibi-Tem.
	FAO			Land with severe moisture deficits for: corn ↑29%, oilseeds ↑55%, no change for small grains & hay	
	ECON SUIT			Land suit for corn ↑21%, wheat ↓16%, oilseeds ↓6%. New opportunities in north offset by losses in south.	
	PROD POT		↑ cereals in n. prairie & ↑ oilseeds in s. Man.	Prov. prod. pot. ↓4%	

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[10] Derived from: Arthur 88a, Arthur 88b, Bootsma *et al.*, 84, Brklacich *et al.*, 89, Brklacich and Tarnocai 91, Brklacich and Smit 92, Brklacich and Curran 94, Brklacich *et al.*, 96, Brklacich *et al.*, 97a, Goos 89, Land Evaluation Group 85, Land Evaluation Group 86, Mills 92, Mills 94, Mooney and Arthur 90, Parker and Cowan 93, Parry and Carter 89, Roots 93, Singh and Stewart 91, Smit *et al.*, 89, Smit and Brklacich 92, Stewart 90.

Impacts on agricultural land potential North of 60° (i.e., in the Mackenzie River Valley) however are not expected to be as pronounced. Under most climatic change scenarios, the greatest amount of warming is expected during the winter months, and therefore anticipated extensions of the frost free season and summer temperature increases in the most northerly areas are often not as significant as one might initially expect. It has also been estimated that the benefits of a more favourable thermal regime would be offset somewhat by declines in summer precipitation with concomitant increases in moisture deficits. For regions beyond the current northern boundary for agriculture, it appears unlikely that climatic change will result in a substantial expansion of the area of land suitable for agriculture

Global climatic change would be expected to enhance the potential for specialty crops in southern Ontario and Québec. For southern Ontario, areas with a physical potential for fruit and vegetable production would be expected to expand beyond lakeside locations, and new opportunities for apples have been suggested for the area south of Montreal.

SOCIO-ECONOMIC PERSPECTIVES ON GLOBAL CLIMATIC CHANGE AND CANADIAN AGRICULTURE

Impacts on the Agricultural Economy

While there has been considerable speculation about the economic implications of climatic change on Canada's agricultural sector, the few economic studies conducted so far have focused exclusively on the Prairies and Ontario (Table 4.6). These studies have included a limited number of regional and farm level examinations, and only the implications of the GFDL and GISS climatic change scenarios and "dry" years have been considered. This modest information base does not provide a foundation for firm conclusions or generalizations, but it does provide insight into the sorts of economic assessments that might be pursued.

At the regional scale, the overall economic consequences of climatic change for the Prairies is estimated to be relatively minor. For example, the estimated effects of climatic change on total cash receipts from farming in Alberta are in the -7% to +5% range, and similar results have been estimated for Saskatchewan and Manitoba. These tentative conclusions are however based upon several adjustments at the subprovincial level including an intensification of agricultural production in central Alberta to offset production declines elsewhere in the province, and increases in the production of high value crops. This comparison of impacts at provincial and subprovincial scales emphasizes the need to gauge the economic effects of climatic change at multiple scales. The preliminary evidence generated by these case studies demonstrates that seemingly minor effects at one scale could mask relatively major changes at other levels. These changes may be positive for some regions and agricultural subsectors but nevertheless the full range of possible outcomes needs to be evaluated.

Results from the Ontario studies exhibit similar trends to those estimated for Alberta. The potential increases in profits for a "typical" cash grain farm in southwestern Ontario estimated under a climatic change scenario hinged upon the re-allocation of resources at the farm level. This study also concluded that increases in year-to-year variability in farm profits could be expected under the GISS climatic change scenario, thereby accentuating economic risks. The extent to which this study might apply to other farm types, other climatic change scenarios and other locations is unknown, but it does illustrate the importance of linking economic assessments with climatic change.

Table 4.6: Estimated Impacts of Global Climatic Change on the Agricultural Economy[11]

CLIMATIC CHANGE	APPROACH	PRAIRIES	ONTARIO
GFDL	PROV CROP VALUE		Total value all crops ↓12%
	REGIONAL I/O	Total crop receipts: Alta ↓7%, Sask ↑3%, Man↑2%	
	FARM ECON MODEL	Sask farm income ↓7%, prov ag employment ↓1%	
GISS	PROV CROP VALUE		Total value all crops ↓7%
	REGIONAL ECON OPT	Man ag gross margins ↑53% with ↑ hi value crop prod, greatest land value ↑ in NW Man	
	REGIONAL I/O	Total crop receipts: Alta ↑5%, Sask ↑7%, Man 0%	
	FARM ECON MODEL		SW Ont cash grain farm ave profits ↑24%. In wet yrs profits ↑44% & ↓68 in dry yrs

Climatic Change and Agricultural Adaptation

The summaries of the estimated impacts of global climatic change on agro-climatic properties, crop yields, production potential and agricultural economies presented in the previous sections illustrated that changing climates will in all likelihood result in both negative and positive impacts for Canadian agriculture. In this context, the agricultural impacts arising from a climatic change can be viewed as representing potential choices among desirable and undesirable results. The economic studies indirectly embraced this notion of choice by employing analytical methods which considered potential re-distributions of farm level resources.

In addition to recognizing that global climatic changes will in all likelihood result in both positive and negative impacts on Canadian agriculture, more general arguments have been made recently to re-structure and expand the research context of climate impacts research and develop methods which explicitly consider human behaviour and the cumulative influences of changes in climatic and non-climatic conditions. These factors have sparked considerable interest in examining the

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[11] Derived from: Arthur 88a, Arthur 88b, Arthur and Abizadeh 88, Arthur and van Kooten 91, Arthur and van Kooten 92, Brklacich *et al.,* 89, Goos 89, Land Evaluation Group 85, Land Evaluation Group 86, Lilley and Webb 90, Mooney and Arthur 90, Parry and Carter 89, Stewart *et al.,* 88a, Stewart *et al.,* 88b, Stewart 89, Wheaton *et al.,* 92, Wheaton 94, Williams *et al.,* 88.

capacity of Canadian agriculture to adapt to multiple environmental and socio-economic changes generally, and climatic change specifically.

Climate change and agricultural adaptation represents a relatively new subfield of research. It is not as well developed as research focusing on the interface between climatic change and the biophysical dimensions of agriculture. So far, much of the research into climate change and agricultural adaptation in Canada has focused on two themes:

1. identifying agricultural adaptation options (Table 4.7a), and
2. feasibility assessments of potential options (Table 4.7b).

Given this a relatively new field of inquiry, it should not be surprising that much of the research to date has focused on identifying options, and less attention has been directed towards a systematic evaluation of strengths and limitations associated with these adaptation strategies.

Many of the identified options are directed towards preventing, or at least delaying the onset and rate, of global climatic change (Table 4.7a). Adaptation options for Canadian agriculture that would contribute to this broad objective include measures which would reduce greenhouse gas emissions from the agricultural sector and alternative farming practices which would sequester carbon in agricultural soils or crops.

The remaining options identified in Table 4.7a are based upon responding to an altered climatic regime, and therefore are intrinsically different from approaches aimed at preventing or delaying its onset. These include adaptation strategies which would:

- reduce the potential losses to individuals by spreading risk over larger regions or populations,
- reduce the potential occurrence and/or magnitude of negative impacts,
- facilitate the capturing of new opportunities stemming from climatic change, and
- develop research and education programs which explicitly consider climatic change and its impacts
- on Canadian agriculture.

Most of the preliminary assessments of alternative strategies for agricultural adaptation to climatic change have focused on the Prairies and regions near or beyond the current climatic boundary for Canadian agriculture (Table 4.2b). No studies have explicitly investigated adaptation prospects in Atlantic Canada or British Columbia - Lower Mainland. The studies completed to date present preliminary technical assessments of the extent to which selected adaptation measures might offset potential negative impacts arising from a global climatic change. The selected adaptation strategies include approaches aimed at reducing the potential occurrence and/or magnitude of negative impacts as well as capturing new opportunities. Among the preliminary findings from these technical assessments of selected adaptation strategies for Canadian agriculture to climatic change, the following points are noted:

Table 4.7: Adaptation of Canadian Agriculture to Global Climatic Change[1]

a) Identified Options 2

Modify the Events (i.e., prevent or delay onset of global climatic change)	• Improve agricultural efficiency – improve on-farm fuel efficiency for tractors, heating, etc. – improve livestock feeds to reduce CH4 production • Resource Conservation – return marginal agricultural land to grasslands or forests – greater use of soil conservation measures – greater use of shelter belts, agro-forestry – reduce pesticide and herbicide use – enhance use of renewable energy sources • Food Pricing – food prices restructured to reflect production plus environmental conservation and if necessary restoration costs
Share Losses (i.e., spread risk over larger regions or populations)	• Public and/or private compensation offsetting losses stemming from: – reduced water resources for agriculture – increased production risks
Prevent/Avoid Impacts (i.e., reduce potential occurrence of negative impacts)	• Adjust/shift current agricultural practices – expand forage and grain northward – greater emphasis on high value agricultural products • Introduce longer season cultivars or new crops – exploit longer FFS with cultivars currently used in warmer regions and/or new crops – greater use or introduction of winter cereals • Water-related strategies – increase use of crop irrigation – develop on-farm water reservoirs – enhanced trapping of snow and better control of spring melt – adjust water runoff management
New "Opportunities" (i.e., reposition farm practices within the context of changing production parameters)	• Niche marketing • Conversion to longer season cultivars and/or new crops • Relocation of farming activities
Research and Education (i.e., RandD to facilitate change in agricultural practices)	• Re-establish North of 60° agricultural research station • Develop heat and drought resistant cultivars • Develop comprehensive regional databases for water supply and use • Improve technology transfer to farms

1. Derived from: Arthur 88b, Arthu and Abizadeh 88, Arthur and van Kooten 91, Arthur and van Kooten 92, Brklacich 90, Brklacich and Tarnocai 91, Brklacich and Stewart 93, Brklacich *et al.*, 94, Brklacich and Stewart 95, Brklacich *et al.*, 97a, Brklacich *et al.*, 97b, Bryant *et al.*, 97, Crosson 89, Delcourt and van Kooten 95, DPA Group 89, Major *et al.*, 91, Maybank *et al.*, 95, Mooney and Arthur 90, Ont. Round Table 92, Parry *et al.*, 88, Parry and Carter 89, Roots 93, Savdie *et al.*, 91, Schweger and Hooey 91, Singh *et al.*, 96, Singh *et al.*, 97, Smit 93, Smit *et al.*, 96, Stewart *et al.*, 88a, Stewart *et al.*, 88b, Stewart 89, Stewart 91, Tubiello *et al.*, 95, Viau and Mitic 92, Wheaton *et al.*, 92, Wheaton 94, Williams *et al.*, 88.

2. Identified Options refers to potential agricultural adaptation strategies which have been identified but have not been explicitly assessed in the context of global climatic change

b) Potential Options[12]

CLIM CHAN	ADAPT STRAT	PEACE R./ AGRIC. MARGIN	PRAIRIES	ONTARIO	QUÉBEC
T↑P↓	WINTER CEREAL		Econ losses ↓16%		
CCC	IRRIG	CMS↓, wheat yields↑		↑ Jun & Aug irrig	
	ALT CULT	Neg. yield impacts ↓ but persist			Corn: neg impacts offset Soybeans: yield ↑ in south, new opport in north
	WINTER CEREAL	Lower Mack. Basin: winter kill persists			
GFDL	IRRIG	CMS↓, wheat yields↑	CMS↓, wheat yields↑	↑ Jun & Jul irrig	
	ALT CULT	Minor yield ↓			
	WINTER CEREAL	Lower Mack. Basin: winter kill persists	N Alta: winter kill persists		
	EARLY SEEDING		Most effect in driest areas		
GISS	IRRIG	Lower Mack R: No change Upper Mack R: CMS↓	CMS ↓ wheat yields ↑	↑ Aug irrig, effective for corn but not beans & wheat	
	DROUGHT/ HEAT TOLERANT CULT		Partial recovery of Man ag econ		
	WINTER CEREAL		Winter kill ↓, winter cereals feasible		
	EARLY SEEDING		Effective in east, Alta variable		
UKMO	IRRIG		CMS ↓ wheat yields ↑		
	WINTER CEREAL		North: winter kill persists		
	EARLY SEEDING		Neg. yield impacts ↓ but persist		

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[12] Adaptation strategies included in this category have been subject to a preliminary assessment of their feasibility to offset potential negative impacts stemming from global climatic change.

- the yield effects of switching to longer season spring seeded cereal cultivars will vary across the Prairie region; in some locations, this strategy is estimated to reduce but not fully offset yield reductions,
- winter wheat may provide a means to enhance grain yields in the southern Prairies; but near and beyond the current climatic boundary for Canadian agriculture, climatic change may not result in winter conditions which would be conducive to the production of winter cereals,
- many of the climatic change scenarios imply increases in crop moisture stress; therefore adaptation measures which augment spring and summer moisture regimes, including artificial irrigation, would reduce the negative effects of climatic change and enhance crop yields, and
- under climatic change, it may be feasible to introduce high value field crops such as corn and soybeans in northern regions of Québec and Ontario.

It must be emphasized that these preliminary assessments have been conducted relative to biophysical conditions only. The economic feasibility and the extent to which the farming community might wish or have the capacity to undertake any of these options has not been addressed. In some of the most recent research into the potential for agricultural adaptation to climatic change, it has been stressed there is an urgent need to involve the farm community to a greater degree in the research process. This would assist with determining the appropriateness of agro-climatic indicators employed by researchers for farm level assessments and gauging the differential vulnerabilities of various farm types to global climatic change.

4.3 Implications of Climatic Change for Canadian Agriculture: An International Perspective

The studies reviewed in the previous sections have examined the implications of global climatic change for Canadian agriculture at the subnational scale and have not attempted to place Canada's agricultural sector in a broader international context. Canada is a major producer and consumer of agricultural products on an international scale, and therefore changes occurring abroad may have as significant an influence on Canadian agriculture as changes in domestic production prospects. Major changes, whether these be positive or negative, in Canada's agricultural production capacity will be bound to have consequences within and beyond its national borders.

Several scenarios for global climatic change estimate relatively large temperature increases over much of Canada, with similar temperature increases anticipated for northern Europe and the former U.S.S.R.. Estimated temperature changes for the temperate regions tend to be significantly less than expected changes for Canada. There is considerably less consensus regarding changes in long term precipitation patterns, but a drying trend is anticipated for most of the interior regions of the northern continents. Overall it is difficult to determine whether changes in agro-climatic properties would favour Canada's position relative to other nations.

Studies into the extent to which Canada's comparative position as a producer of agricultural products might be influenced by climatic change have been inconclusive. Wheat is Canada's main export crop and clearly needs to be included in international assessments of agricultural production and trade. However these studies present conflicting conclusions ranging from new export opportunities for Canadian grown wheat products to declines in international wheat prices which in turn would reduce Canada's comparative advantage in cereal markets. The reasons for these opposing results are difficult to isolate, but are probably caused by several factors such as variations in input data and analytical methods.

Globalization of agricultural economies has become a major factor which influences food production and trade. Current evidence suggests that globalization will continue to shape agricultural production at all scales for the foreseeable future. Clearly there is an urgent need to develop research standards and protocols that will facilitate the orderly transmission of data and information between assessments of the implications of climatic change on national agricultural economies and procedures for evaluating agricultural markets at international scales.

RECOMMENDATIONS

There has been considerable research into the relationships between global climatic change and Canadian agriculture since the early to mid-1980s. However, the research has been:

- more extensive in terms of impacts on agro-climatic properties, especially thermal regimes, than in terms of crop productivity;
- more concentrated in Ontario, the Prairies and to a lesser extent in Québec, with much of the earlier research in Ontario not having been followed up using the more recent generation of crop productivity models;
- very limited in relation to the economic consequences of climatic change for agriculture; and
- more recently concerned with the phenomenon of farm and agricultural adaptation, without for the moment having developed a generally accepted approach to assessing adaptation strategies.

In light of this assessment of this body of research, it is recommended that:

1. Attention be given to supporting research that would utilize a common set of climatic and crop productivity models for all regions of the country to generate more easily comparable results in terms of impacts of climatic change on yields.

2. Research is needed to develop an assessment of the economic impacts of climatic change that takes into account scenarios based on different adaptation strategies. The research should develop linkages between:
   a) various scales (e.g., farm, regional, national), and
   b) crop and livestock operations and enterprises.

3. Research should be encouraged to address the implications for Canadian agriculture of global climatic change in the context of changing levels of comparative advantage and changing world agricultural commodity markets. Linkages between specialists analysing the climatic change implications for agriculture and those focusing on international economy and trade need to be improved in order to ensure that the most recent and reliable appraisals are employed in a credible manner.

4. It is clear that a greater understanding of farm and agricultural adaptation is required. This is arguably the most important domain for further research since upon it rests the credibility

of the assessments of the socio-economic implications of climatic change for agriculture, including the economic impacts, both regionally, nationally and in the context of the international market place. Further research in the domain of adaptation must also address ways of effectively integrating those agro-climatic indicators which farmers identify as important in their decision-making into the climatic change scenarios, e.g., greater information on the variability of estimated changes in key agro-climatic variables.

5. The final recommendation is for a national research program designed to:
   a) better integrate biophysical and socio-economic dimensions of climatic change and Canadian agriculture, and
   b) identify root causes of differential vulnerabilities.

   This research would identify which types of agriculture and which regions are most sensitive to global climatic change. This would provide a more coherent and systematic basis for developing targeted policies and programs to alleviate potential stresses on those agricultural systems most vulnerable to global climatic change.

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APPENDIX 4A GLOSSARY OF TERMS USED IN THE CHAPTER

ac	acres
AES	Atmospheric Environment Service
amt.	amount
AP	Average Precipitation
avg	average
AWC	Available Water-holding Capacity
AY	Attainable Yields
bu	bushels
C	central, Celsius
CanSIS	Canada Soil Information System
CC	Climatic Change
CCC	Canada Climate Centre General Circulation Model
CCS	Climate Classification System
CFY	Constraint-Free Yields
CHUC	No. of days with Corn Heat Units >2300
CHUs	Corn Heat Units
CMS	Crop Moisture Stress
COMP	Composite scenario (Environment Canada)
CULT	Cultivar
CV	Current Value
d	days
E	east
EGDD	GDD modified by diurnal T range and photoperiod
ESM	Empirical-Statistical Model
est.	estimate
EXP. OP.	Expert opinion
F	Summerfallow, fallow, Fair climatic potential
FAO	World Food and Agriculture Organization Model
FAY	Farm-Attainable Yields
F.Corn	Fodder Corn
FFS	Frost-Free Season
G	Good climatic potential
GCM	General Circulation Model
G.Corn	Grain Corn
GDDs	Growing Degree Days (above 5?C)
GDP	Gross Domestic Product
GFDL	Geophysical Fluids Dynamics Laboratory Gen. Circ. Model
GHGs	Greenhouse Gases
GISS	Goddard Institute for Space Studies General Circ. Model
GS	Growing Season
GSE	Growing Season End
GSL	Growing Season Length
GSS	Growing Season Start
ha	hectares
HD	Harvest Date
HP	High Precipitation
hrs.	hours
HT	Heliothermic
I/O	Input-Output model
IRRIG	Irrigation
IS	Required Irrigation Supplement
kg	kilograms
km	kilometres
LP	Low Precipitation, Linear Programming model
LSRS	Land Suitability Rating System for Spring-Seeded Small Grains
max	Maximum
MD	Moisture Deficits
MDT	Mean Daytime Temperature
min	Minimum
mm	Millimetres
N	north
N/R	Not Researched
OSU	Oregon State University Gen. Circ. Model
P	Precipitation, Poor climatic potential
PDI	Palmer Drought Index
PE	Potential Evapotranspiration
ppm	parts per million
ProdPot	Production Potential
S	south
s	stubble
SD	Seeding Date
Spr.	Spring
std.	standard
STD	Standard Deviation
Summ.	Summer
T	Temperature
t	tonnes
Tot.	Total
UKMO	United Kingdom Meteorological Office Gen. Circ. Model
Var.	Variability
Veg.	Vegetables
VG	Very Good climatic potential
W	west
WUE	Water Use Efficiency
w/	with
yr.	year
Y-W REG	Yield - Weather Regression Model
⮝	change
↑	increase
↓	decrease

CHAPTER FIVE

CANADA COUNTRY STUDY: CLIMATE IMPACTS AND ADAPTATION: FISHERY SECTOR

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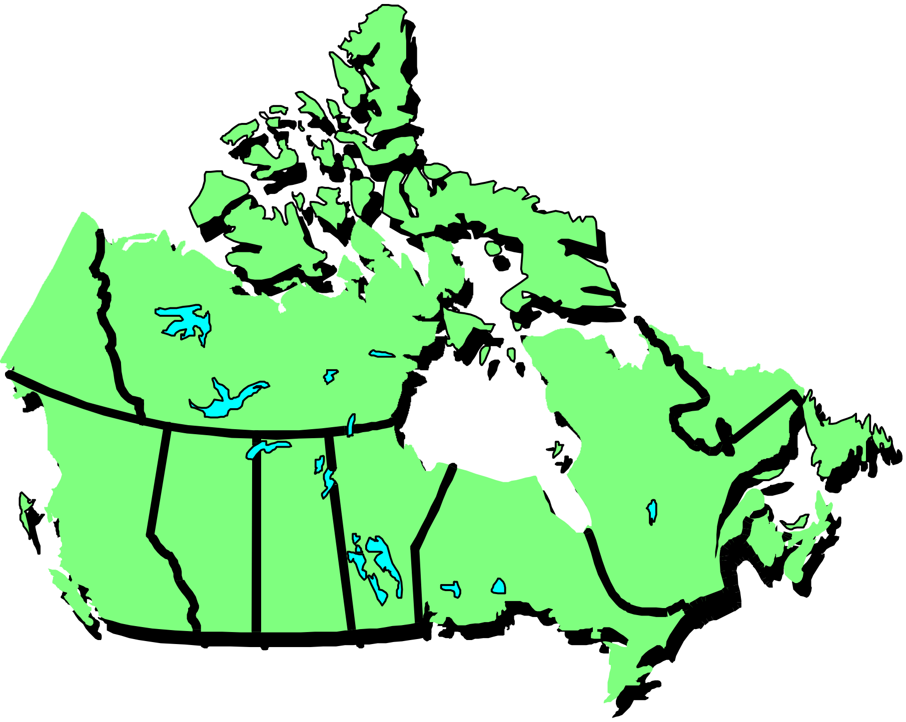

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EXECUTIVE SUMMARY

Sector Characteristics

Canadian aquatic ecosystems supporting fish and fisheries occupy an area of 5.38 million km^2, equivalent to 58% of the country's dry land area. Fisheries are important sources of food, sport and employment. There are three broad categories: commercial, recreational and subsistence. In 1994, the total commercial catch was 1,070 kilotonnes (k-tonnes), primarily from the oceans, with a landed value of $1.78 billion. Aquaculture is a rapidly growing sector in competition with commercial fisheries. In 1994, production reached 54 k-tonnes of fish, mainly salmon, valued at $300 million. One in five Canadians is an angler. The recreational fishery is predominantly freshwater and harvested 70 k-tonnes in 1990, generating expenditures and investments of $5.9 billion. Subsistence fisheries occur throughout the country but are particularly important in the north. In the mid-1980's, there were approximately 300,000 subsistence fishers in Canada and they consumed 15 k-tonnes. These catch and dollar figures reflect only the obvious aspects of the value of fishing activities to the fishers. In many parts of the country, social structures are founded on fishing as a primary activity of the adult populace. The "value" of these ways of life to the people who follow them defies effective quantification. Similarly, the impact of fishing activities on the natural ecosystems that sustain them is difficult to quantify, although scientific methods for doing so are the objective of current research.

Impacts of Climate Change on Fishes and Fisheries

Fish are poikilotherms - animals with a body temperature essentially equal to the temperature of the water they live in. The daily activities that sustain the life of individuals (e.g., feeding, predator avoidance, body maintenance and growth) and the seasonal activities that maintain the existence of populations (e.g., gonad development, reproduction, parental care) are all strongly affected by the annual pattern of water temperatures that fish experience. For fish, the temperature tolerance zones for survival, growth and reproduction are species-specific characteristics. Each species exhibits a characteristic preferred temperature - the temperature which individuals will choose to live in, when given a choice. Rates of survival and growth are maximal at temperatures close to the preferred temperature, and decline as temperatures move away from it. Preferred temperatures range from values well below 10°C to values above 25°C. Given the importance of temperature in shaping the vital activities of fish, wild fish populations should respond strongly to natural variations in climate that involve systematic changes in water temperatures. Such responses have been documented for many freshwater and marine populations. These responses fall into two broad categories:

1. Changes in fish production in a particular locale:

    - Shifts in the overall productivity of entire fish communities,
    - Changes in the relative productivity of individual populations within a community.

2. Changes in fish spatial distributions:

    - Shifts in the zoogeographic centres and boundaries of individual species and species groups, as defined on large geographic scales,

    - Shifts in the local distributions of individual population members, as defined on small geographic scales.

These categories capture most projections of the impacts on fish populations of climate change arising from greenhouse gas accumulation in the atmosphere. Such impacts will have two primary effects on fisheries:

The overall sustainable harvest of fish will rise and fall with shifts in overall aquatic productivity. Sustainable harvests from a specific population in a specific location may increase substantially or fall to zero depending on how new climate conditions and species-specific thermal characteristics interact to determine each population's share of available production.

Under the assumption that greenhouse gas accumulation will lead to a warmer, drier climate in most regions of Canada, possible impacts on regional fisheries include:

Pacific marine fisheries: lower and more variable sustainable harvests for southern salmon populations; higher, more consistent sustainable harvests for northern salmon populations - sockeye salmon most affected.

Atlantic marine fisheries: decrease in overall sustainable harvests for coastal and estuarine populations due to decreases in freshwater discharge and consequent declines in ecosystem productivity; widespread changes in sustainable harvests, locations of fishing grounds and gear efficiencies for many populations due to complex and likely unpredictable changes in the ocean current systems that shape offshore marine habitats.

Arctic marine fisheries: increases in sustainable harvests for most fish populations due to increased ecosystem productivity, as shrinkage of ice cover permits greater nutrient recycling; negative impacts on some populations of seals and polar bears, that are adapted to current seasonal and geographical patterns of ice cover.

Southern freshwater fisheries: decreases in sustainable harvests for many populations due to declining water levels in lakes, declining flow rates in streams, and reductions in nutrient loading and recycling for many lakes and streams on the Canadian shield; decline in the proportion of overall sustainable harvest obtained from coldwater fish species, and a reciprocal increase in the proportion of overall harvest obtained from cool and warmwater fish species.

Northern freshwater fisheries: increases in sustainable harvests for most fish species, due to longer warmer growing seasons and relatively small changes in water levels; potential increase in the diversity of fish species that can be harvested sustainably due to increases in the diversity of thermal habitats available to support new species, expanding their ranges from the south; possible range contractions of Arctic-adapted fish species (e.g. Arctic charr).

In all these systems, the primary climatic factors of sunlight, rain and wind interact with water currents to define fish habitats that are dynamic in both space and time. The character and location of these habitats define both the levels of sustainable harvest and the locations where that harvest can be most efficiently taken. Today, climate-driven variation in habitat operates on a variety of time scales, from annual to millennial. Changes from state to state can be rapid and the persistence of new states can be prolonged. This pattern of variation is not explicitly considered in most methods for estimating sustainable harvest. Current science is not able to forecast the impact of climate warming on these patterns of variation. However, such impacts will be of great importance to the fisheries involved.

Adaptation Options

The options available to a fishery for adapting to climate change are not unique. Many approaches have been proposed, and some have been implemented, in response to other kinds of environmental change. All approaches have their own limitations. Current concepts of sectoral adaptation to climate change assume orderly change, although increased unpredictability seems more likely for fisheries. Assessment of adaptation options for a particular fishery should explicitly consider the overall kinds and levels of sustainable use that are planned for the specific ecosystem involved. The scale of assessment in human and spatial terms affects the range of net gains and losses. On smaller scales, there are winners and losers, while on larger scales, pooling and averaging hide the inequities. Development of adaptation strategies should emphasize:

Minimizing negative impacts at the local level;

- Robust management regimes that are less dependent on short-term prediction of fish stocks;

- An ecosystem-centred “no regrets” approach wherein all stresses are reduced.

Research Gaps

A shift in emphasis from future climate prediction toward assessment of ecosystem responses and potential impacts is required. In the fisheries sector, several areas of research are receiving insufficient attention or are declining as a result of pervasive downsizing efforts. Three types of research initiative are necessary:

Knowledge Initiatives:

Sentinel Programs (Keeping watch for surprise): Establish/maintain long-term programs to monitor biological responses and ecological climate indicators in representative aquatic ecosystems with significant fisheries. Results will document responses to current climate variation and hence help define likely responses to future climate change.

Comparative Studies: Undertake comparative studies of ecosystems and populations across latitudinal and altitudinal gradients. Results will help define likely responses of such systems to climate change.

*Spatial Distributions of Populations and Species***:** Undertake studies designed to identify the factors that set the boundaries for current zoogeographic distributions of economically significant aquatic species. Results from such studies will enhance efforts to forecast effects of climate change on species invasions and disappearances.

Salmonids: Salmonid stocks in marine and fresh waters are highly prized and especially vulnerable to climate change. Increased life-history knowledge and coordinated international monitoring are required to develop reliable impact forecasts.

Interactive Effects of Other Environmental Stresses: Climate change will exacerbate many existing stresses on ecosystems. Increased understanding of these interactions will be needed if healthy ecosystems are to be maintained.

Ecosystem Design and Exotics: In species-poor areas, new opportunities to create and enhance fisheries through species introductions will require improved guidelines to avoid past mistakes. New legislation and regulations are currently needed to curb undesirable exotics.

Ecosystem Initiatives:

Marine: Develop increased understanding of existing low frequency-high magnitude variations in marine production and the role of climate in generating those fluctuations.

Freshwater: In lakes, develop greater understanding of the relative roles of nutrient, light, thermal and mixing regimes in determining fish production. In rivers and streams, conduct more extensive assessments of total fish production and the factors that determine it.

Arctic: Basic knowledge of life histories and production levels for marine and freshwater biota is inadequate in these regions where relatively large climatic changes are forecast.

Estuarine: Falling river discharges and rising sea levels will act synergistically to move salt-fresh water boundary areas inland. Thus, estuaries may provide some of the most sensitive indicators of ecosystem response to climate change and monitoring programs should be developed to take advantage of this.

Institutional Initiatives:

New Management Practices: New, more robust regulatory systems are needed to cope with variation in both the dynamics of exploited fish populations and in the response of such populations to exploitation and to other anthropogenic stressors. Such systems should be less dependent on accurate short-term forecasting.

Valuing Fisheries: Improved measures and valuations of subsistence and native fisheries are needed along with intercomparable valuation systems for all fisheries.

Upper Bounds for Sustainable Fisheries: Estimates of ecosystem and fishery carrying capacities are needed to place current or expected harvest levels into a wider context of sustainable ecosystem use.

INTRODUCTION

Fishes are important to Canadians, both as resources providing food, recreation, and concomitant economic and employment benefits, and as symbols of the health of our aquatic ecosystems. Fishes and the waters they inhabit are a central element in our sense, and others' perceptions, of Canada. Fisheries are one of the founding industries in Canada alongside forestry, agriculture, mineral extraction, and manufacture. As Canada has grown, the relative economic impact of fisheries has declined but their significance to Canadians has not diminished.

Canada is among the largest countries in the world, with a dry land area of 9.22 million km^2. Canadian aquatic ecosystems supporting fish and fisheries occupy an area of 5.38 million km^2, equivalent to 58 percent of the country's land base. The aquatic areas include those parts of three oceans lying within 200 miles of Canadian shorelines (Canada's extended economic zone - EEZ) and the large population of lakes spread throughout the country (Figure 5.1). Significant climate change will inevitably bring substantial changes to these vast aquatic ecosystems and to the fisheries on which many Canadians depend for their food and/or livelihood. In this review, we focus our attention on likely responses of these systems to the climate changes expected from greenhouse gas (e.g. carbon dioxide, methane, nitrous oxide, various fluorocarbons) accumulation in the atmosphere. For simplicity, we will refer to this phenomenon as CO_2-based climate warming.

Fish are poikilotherms - animals with a body temperature essentially equal to the temperature of the water they live in. The daily activities that sustain the life of individuals (e.g., feeding, predator avoidance, body maintenance and growth) and the seasonal activities that maintain the existence of populations (e.g., gonad development, reproduction, parental care) are all strongly affected by the annual pattern of water temperatures that fish experience. Typically, each species exhibits a characteristic preferred temperature - the temperature which individuals will choose to live in when given a choice. Rates of active metabolism and growth rise slowly as the preferred temperature is approached from below and drop rapidly after it is exceeded. Temperature tolerance zones for various vital processes are also species-specific characteristics. All tolerance zones include the preferred temperature but they vary greatly in breadth, with zones for "complex" (i.e., those associate with individual growth and reproduction) processes typically narrower than zones for "simple" (i.e., those associated with basic survival) processes (Regier *et al.*, 1996. Wood and MacDonald, 1997).

Given the importance of temperature in shaping the vital activities of individual fish, fish populations should respond strongly to natural variations in climate that involve systematic changes in water temperatures. Such responses to temperature changes and to other environmental changes (e.g. changes in sea level, changes in ocean current and upwelling patterns) have been documented for many freshwater and marine populations (Shuter and Meisner, 1992, Beamish, 1995). These responses fall into two broad categories:

A) Changes in Fish Production in a Particular Locale
  i) shifts in the overall productivity of entire fish communities;
  ii) changes in the relative productivity of individual populations within a community.

B) Changes in Fish Spatial Distributions
  i) shifts in the zoogeographic centres and boundaries of individual species and species groups, as defined on large geographic scales;
  ii) shifts in the local distributions of individual population members on small geographic scales.

Most projections of the biological effects of CO_2-based climate change on fish populations fall into these two categories and we will use them to organise our review of this material.

Such biological changes will probably cause several impacts on fisheries (Table 5.1). Those impacts will mainly operate in two ways:

1. the overall sustainable harvest of fish will rise and fall with shifts in overall aquatic productivity;

2. sustainable harvests from a specific population in a specific location may increase substantially or fall to zero depending on how new climate conditions and species-specific thermal characteristics interact to determine what the population's share of available production will be.

Table 5.1 Probable impacts of climate-induced changes in fish ecology on fisheries.

Change in fish ecology	Impact on fishery
a) Change in overall fish production in particular aquatic ecosystems	a) Change in sustainable harvests for all fish populations in the ecosystem
b) Change in relative productivity of individual fish populations in particular aquatic ecosystems	b) Change in the relative levels of exploitation that can be sustainably directed against the fish populations of affected ecosystems
c) Large scale shifts in geographic distribution of species	c) Change in the mix of species that can be sustainably harvested within specific geographic areas; change in location of profitable fishing grounds
d) .Small scale shifts in the spatial distribution of members of specific populations	d) Change in sustainable harvest for affected populations; change in efficiency of fishing gear, leading to changes in sustainable levels of fishing effort for affected populations; change in locations of profitable fishing grounds

Given such impacts, effective human adaptation to the effects of climate change on fisheries would involve reallocation of harvest from those populations that are adversely affected by climate changes to those populations that benefit from such changes. However, there are strong inertial forces in both ecological systems and harvest systems that complicate this simple picture. In ecological systems, concurrent shifts in basic productivity and thermal conditions will cause significant restructuring of the fish community. This period of restructuring can be prolonged and will be characterised by great uncertainty in the sustainable harvests that can be assigned to any community member. In any harvest system, there are consumer preferences for particular species that are difficult to change and will tend to prolong exploitation of populations that should be protected. The risk associated with these internal lags is that unsustainable exploitation levels will be maintained on adversely affected populations, leading eventually to both population and fishery collapse. Such risks will increase as the rate of climate change increases.

For many marine and freshwater systems, current ecological knowledge is sufficient to provide a rough classification of fisheries according to whether they are likely to be positively or negatively affected by specific climatic changes. Tools that promise more quantitative assessments of impacts and better management regimes have yet to be developed.

SECTORAL CHARACTERISTIC

We begin by providing some economic measures of the relative size and importance of various types of fisheries to social life in Canada. Such comparisons are difficult to interpret because each type of fishery is valued differently (Anderson, 1994). For example, valuation of commercial fisheries is based on the landed catch, whereas valuation of recreational fisheries is based on angler expenditures per fishing day. While interesting, such simple dollar figures can only reflect the most obvious aspects of the value of fishing activities to the people who engage in them. In many parts of the country, entire social structures are founded on the fact of fishing as a primary activity of the adult populace, where the purpose of the activity may include both food and income acquisition, as well as recreation. The “value” of these ways of life to the people who follow them is difficult to effectively quantify.

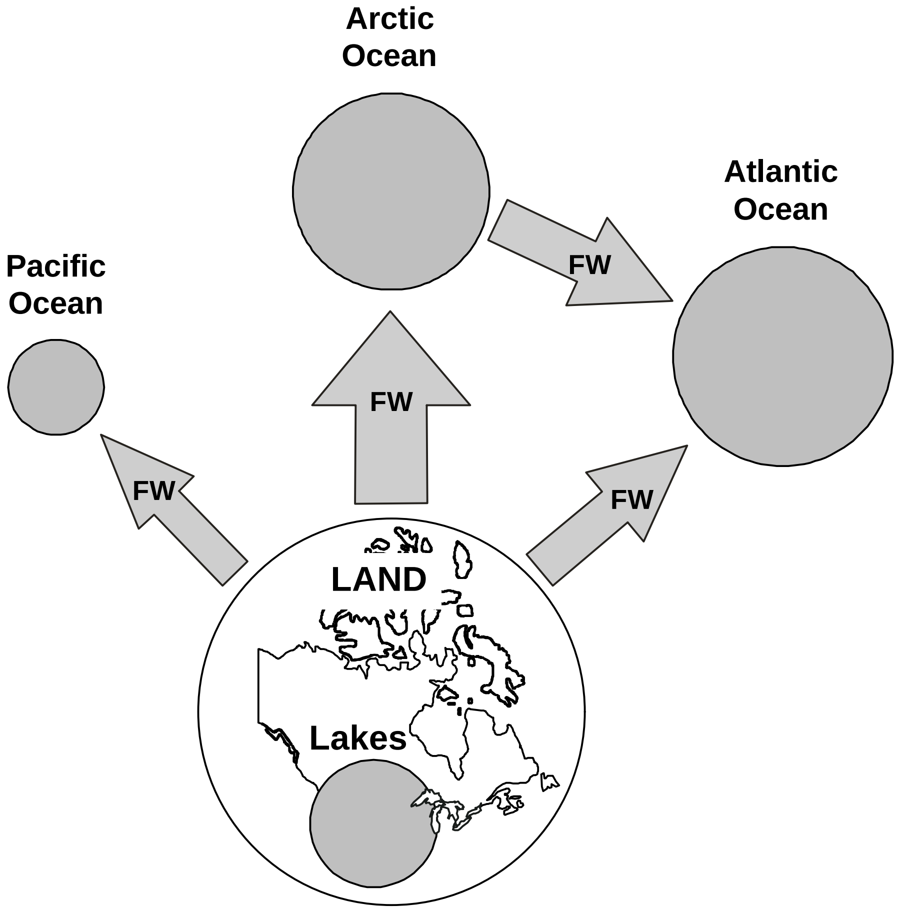
Similarly, such dollar figures have little bearing on the equivalent economic value of the “ecosystem services” (Costanza *et al.*, 1997) provided by aquatic ecosystems and their exploitable renewable resources or on the size of the “ecological footprint” (Wackernagel and Rees, 1996, Pauly and Christensen, 1995) that extractive uses like fishing impose on those ecosystems. We close this section by briefly addressing these issues.

Global Perspective

The FAO recently reported (FAO, 1997) that global fish harvest, including aquaculture, reached 109.6 million tonnes (MT) in 1994, increasing another 7.6 MT from 1993. Of the total, 34.7 MT were used for non-food purposes such as fishmeal and oil. Increases in marine exploitation and freshwater aquaculture accounted for 4.9 and 1.7 MT of the increase from 1993 to 1994. Most major fisheries, including those in Canada, are being exploited at rates that meet or exceed sustainable levels (FAO, 1992, Brown and Kane, 1994). World fish harvest appears to be at (or beyond) sustainable levels, with aquaculture set to replace harvest from wild populations in the future, rather than augmenting it (ibid). This replacement process is likely to be self-limiting, because fishmeal is itself a primary food source for aquaculture.

Figure 5.1. Relative amounts of land and water in Canada.

Areas of circles are proportional to the areas of the water bodies and land mass identified. Oceans are represented by the area lying between shore and the 200 mile limit. The area of Hudson Bay has been included with the Arctic Ocean. Areas of arrows are proportional to annual freshwater runoff from the land to the oceans. The arrow from Arctic to Atlantic represents the freshwater runoff from Hudson Bay, whose influence on salinity of Newfoundland Shelf waters has been empirically demonstrated (Myers *et al.*, 1990).



Canadian fisheries, with the addition of sport fishing, produce about 1% of the global total and show parallels with the wider trends and patterns. Canada has extensive areas of both freshwater and marine habitats supporting fisheries. Commercial and sport fishing have comparable importance to the Canadian people and the economy of the country. Management attention has been primarily directed to the commercial sector in marine ecosystems whereas the emphasis in freshwater has progressively shifted from commercial to sport use. The emerging aquaculture industry will tend to replace rather than augment the extractive commercial industry and is itself dependent on exploitation of natural aquatic production for fish food. The fisheries, like other renewable resources, produce a small portion of the country’s Gross Domestic Product (GDP) but have an important role as a source of food, employment, and recreation for Canadians.

Canadian Aquatic Habitats Supporting Fisheries

Canada's marine and freshwater ecosystem resources, the basis for our fisheries, are extensive. Canada is responsible for an area of 4.62 million km^2 in three oceans within the 200 nautical mile EEZ boundaries (Jake Kean, personal communication, Canadian Hydrographic Service, Ottawa, February 1997). In the Atlantic, Arctic (including Hudson Bay), and Pacific Oceans, the marine areas are 2.33, 1.87, and 0.42 million km^2 respectively. Canada has a long coastline, 243,792 km, with two thirds of that length in the Northwest Territories. For wide-ranging fishes like the salmonids, Canada's interest extends much further out into the Atlantic and Pacific Oceans.

In freshwater ecosystems, Canadian territory generates 7.1% of the world's runoff, includes 43% of significant Ramsar wetlands (i.e., wetlands identified in the Convention on Wetlands of International Importance, Ramsar, Iran, 1971) and contains close a large portion of the world's lake and river surface area (Minns and Moore, 1995). Freshwater flows to marine coastal systems are large and vary widely between oceans (Figure 5.1).

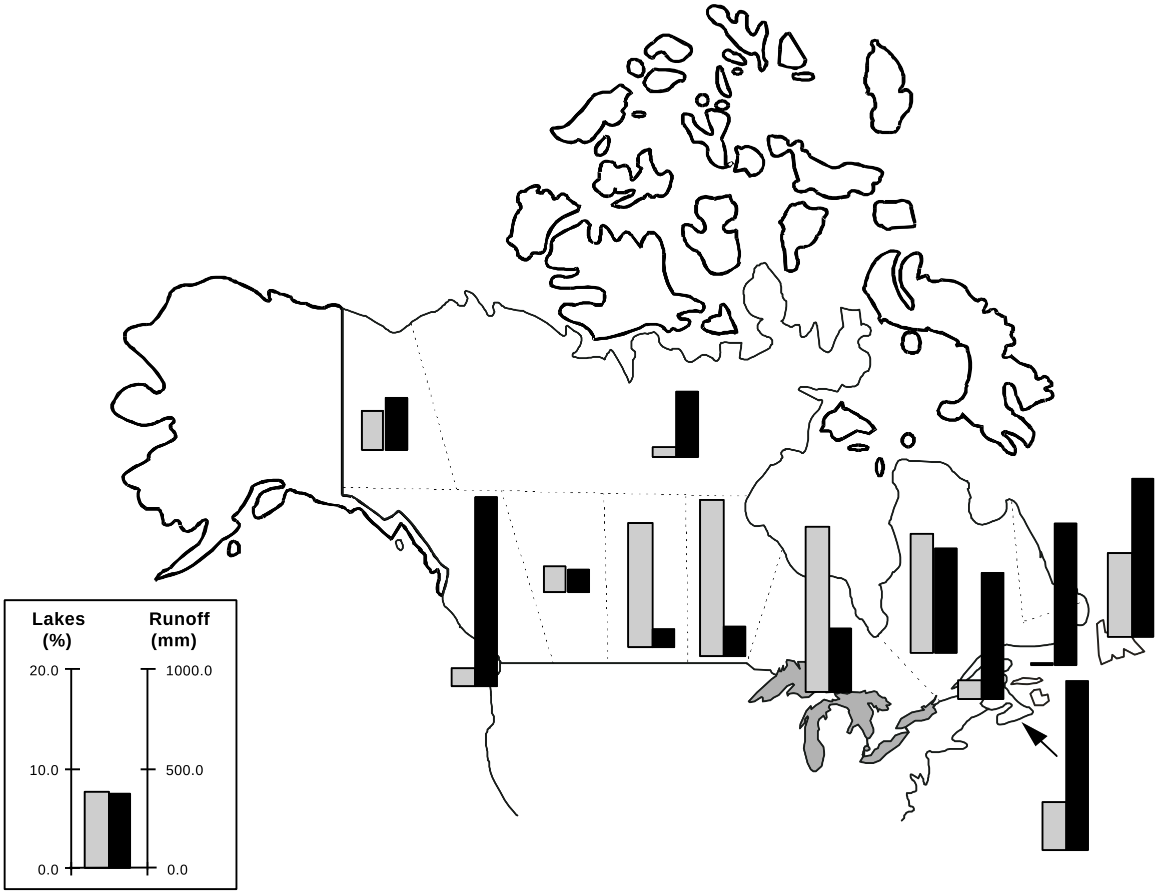
Lakes and runoff are unevenly distributed across Canada. The central provinces, from Québec to Saskatchewan, have the largest fraction of their surface areas taken up by lakes (Figure 5.2). Unit runoff levels are greatest in the Pacific and Atlantic coastal watersheds and lowest in the central Prairies and high Arctic watersheds (Figure 5.2). These differences in lake coverage and runoff are consistent with regional differences in the relative importance of lake and river fisheries. They even seem to be reflected in some aspects of the biology of individual species. For example, the number of lakes in Newfoundland is large, relative to other Atlantic provinces, and Atlantic salmon are known to make greater use of lakes in Newfoundland for smolt rearing than in the other Atlantic provinces.

Commercial Fisheries

On a national scale, the commercial fishing industry is small. In 1986, fishing and fish processing only accounted for $1.78 billion or 1.1 % of the GDP of commodity producing industries in Canada and, in 1985, employed 111,000 people or 3.2 % of the commodity industry work-force (Parsons, 1993). However, the fisheries are a major element on the Atlantic coast. Parsons (1993) wrote: "Of the 600,000 people in the Atlantic who live in fishing communities, about 200,000 live in communities where fishing activity is the principal, if not the only, employer".

Canadian commercial fishery catches declined significantly between 1990 and 1994 while the landed value of the catch rose (Table 5.2) (Statistics Canada, 1997). The Atlantic fishery was more than twice the size of the Pacific fishery and the commercial freshwater fishery was very small in comparison to either. In the Atlantic fishery, the main decline has been due to the collapse of groundfish stocks, especially cod. Groundfish were a major component of the catch in 1990 but in 1994 shellfish, lobster and shrimp, were dominant. In the Pacific fishery, pelagic species, especially salmon and herring, were the dominant components although the salmon catch declined between 1990 and 1994.

Figure 5.2 Percentage of the area of each province that is covered by lakes - annual runoff by province. (all values from Laycock, 1987)



Much of the commercial freshwater catch is sold by the Freshwater Fish Marketing Corporation (FFMC, 1996). The FFMC represents over 3,500 commercial fish producers in the Prairie provinces, northwest Ontario and the Northwest Territories. There are 14 freshwater species sold. In 1996, the FFMC sold 18.6 kilotonnes (k-tonnes) of fish including 6.3 k-tonnes of lake whitefish, 3.7 k-tonnes of mullet, 3.1 k-tonnes of walleye, and 2.4 k-tonnes of pike, for a total landed value of $47.1 million.

The landed value of the commercial fisheries does not reflect their full economic impact. Much of the fish is processed for consumption and the retail revenues will be much higher, including returns to the canning and processing industries, as well as transportation costs.

Table 5.2 An overview of Canadian commercial fisheries giving landed catch and landed value statistics for 1990 and 1994 (Statistics Canada 1997)

Fishery	1990		1994	
	Quantity k-tonnes	Value $million	Quantity k-tonnes	Value $million
Atlantic	1342	954	718	1123
Groundfish	646	386	144	124
Cod	395	243	22	30
Pelagic	423	85	251	74
Herring	260	38	207	28
Capelin	127	17	2	<1
Shellfish	230	474	291	912
Scallops	83	87	91	139
Lobster	48	232	41	354
Crab	26	49	60	270
Other	43	9	32	15
Pacific	304	480	281	473
Groundfish	139	85	147	101
Halibut	5	21	5	34
Hake	79	13	104	15
Pelagic	142	340	107	261
Herring	41	73	39	64
Salmon	96	263	65	195
Shellfish	21	46	26	94
Clams	7	16	4	37
Crab	2	9	6	24
Other	<1	8	<1	17
Freshwater	45	66	36	70
Total	1690	1500	1070	1776

Table 5.3. Production statistics for the Canadian aquaculture industry in 1994 (DFO, Policy Development and Analysis/Aquaculture, Ottawa, contact T. Davies)

Product	Quantity k-tonnes	Value $million
Salmonids	38	278
Salmon	32	244
Trout	6	33
Shellfish	15	18
Oysters	8	9
Mussels	7	8
Total	54	297

Aquaculture

Aquaculture is a rapidly growing sector of the Canadian fishing industry. According to DFO statistics (Department of Fisheries and Oceans Canada, Policy Development and Analysis/Aquaculture, Ottawa - Contact: T. Davies), the Canadian aquaculture industry produced 54 k-tonnes of fish and shellfish worth $297 million in 1994 (Table 5.3). British Columbia and New Brunswick are the largest producing provinces. In 1996, 26 k-tonnes of salmon were farmed in British Columbia, compared to a wild catch of 34 k-tonnes: “More than 42 percent of the world’s salmon is now raised in fish farms, a number that will increase to 50 percent by 2000 ...” (Cernetig, 1997). According to Contact Canada’s web-site, the Canadian aquaculture industry included 1,800 producers and 820 aquatechnology companies in 1996. The industry was estimated to provide 15-24 thousand jobs. Atlantic salmon, Arctic charr, and trout are the principal aquaculture products.

As with rapid growth in any renewable resource industry, there are attendant problems. Intensive aquaculture produces nutrient and organic waste, increases the incidence and transfer of disease leading to increased use of chemicals and drugs for control, increases accidental releases of exotics, and threatens the ecological and genetic integrity of wild stocks. In British Columbia, these concerns are currently being debated as the fish-farming sector strives to expand (Cernetig, 1997).

Recreational Fishing

One fifth of the Canadian population are regular sport fishers (DFO, 1994). Most of their effort is directed to freshwater fish and freshwater fish provide the majority of the catch. Trout, walleye, perch and northern pike are the major species, with catches distributed across Canada but concentrated in the interior regions. The 1990 retained catch of 70 k-tonnes is only 7 % of the 1994 commercial catch. However, the overall level of economic activity ($6 billion - Table 5.4) generated by recreational angling is comparable to that generated by commercial fishing.

Aboriginal and Subsistence Fisheries

There have been several broad surveys of fish resource use by subsistence fishers and native fishers (Table 5.5). All authors have explicitly recognised the large errors inherent in their estimates of overall use because of low survey effort and partial/incomplete sample design. Developing a logical rationale for assessing the economic value of a subsistence fishery is difficult and we were only able to find one author who attempted to do so. Clarke (1993) estimated that there were about 12,000 subsistence fishers in the Canadian Arctic in 1987 and that this fishery had a gross value of $15 million that year. These statistics can be used to derive an extremely rough estimate of the value of the entire Canadian subsistence fishery. From the above figures, the economic value of a single subsistence fisher is $1,250/year. From Table 5.5, there are roughly 300,000 subsistence fishers in Canada and therefore the value of the fishery is about $375 million/year.

Table 5.4 Profile of recreational fishing by residents and non-residents in Canada for 1990 (DFO 1994)

Category	Resident	Non-resident	Total
Anglers			
Number of anglers, millions	5.47	1.12	6.59
Percent of Canadian population	20.6	-	-
Effort, millions of angler days	60.19	6.96	67.15
Catch			
Total number caught, millions	245.66	57.84	303.50
Trout	63.83	2.63	66.46
Walleye	27.41	18.20	45.61
Perch	31.91	6.34	38.25
Northern pike	21.40	12.03	33.43
All salmon	7.00	1.59	8.59
Cod	3.90	0.01	3.91
Percent retained	56.1	32.7	51.7
Weight retained, k-tonnes	56.28	13.57	69.85
Economic activity			
Direct expenditures, C$ billions	2.18	0.65	2.83
Major investments, C$ billions	2.93	0.13	3.06

Alternate Measures of "Value"

Aggregate economic measures of Canadian fisheries tend to undervalue the role of this sector in Canadian society. The raw catches in metric tonnes are largely without context and their significance is hard to assess. Values derived from sport and commercial sources are not easy to compare. Two recent developments in ecological economics and resource assessment provide some remedy. Pauly and Christensen (1995) have developing a method for measuring the extent to which fisheries removals co-opt available primary production for human use via food web transfers. Costanza *et al*. (1997) have recently reported on a global project aimed at measuring the value of ecosystem services, services taken for granted by humans in most instances. These assessment approaches give added insight into the broader significance of fishes and fisheries to Canada and Canadians and an indication of how close we are to reaching and exceeding the ability of our aquatic ecosystems to sustain human uses.

Pauly and Christensen (1995) combined regional estimates of primary production and fisheries yields (and discards) to measure the proportion of primary production ending up via food chain transfers in harvested fisheries products. They showed that globally fisheries account for 8% of available aquatic primary production. In coastal, shelf and upwelling marine areas, the percentage ranged from 8.3% to 35.3% while the level in freshwaters was 23.6%. These results suggest that a significant proportion of the biological production in Canadian waters is being extracted through fisheries. High utilization levels make renewable resource use more vulnerable to additional stresses like those climate change might bring.

Table 5.5 Canadian subsistence and native fisheries: estimates of the number of fishers and the annual harvest for each fishery.

Type of Fishery and Region	Number of Fishers	Per Capita Consumption kg/yr	Total Annual Harvest k-tonnes	Year	Reference
Native Subsistence Fishery	30 459	53.5	1.60	1972-82	Berkes (1990)
Northern areas (parts of Labrador James Bay, N. Quebec, NWT)					
Central Ontario	4 967	62	0.30	1982	
Manitoba	35 000	50	1.70	1975	
Saskatchewan	71 047	26	1.85	1985	
British Columbia	43 000	53	2.27	1980	
Total Native Fishery				mid-1980's	Pearse 1988 (cf. Berkes 1990)
Yukon/NWT			1.50		
Maritimes + Labrador			0.10		
Ontario +			1.10		
Quebec			3.75		
Prairies			3.10		
British Columbia			9.55		
Canada			15.0		
Total Subsistence Fishery				mid-1980's	Berkes (1990)
Canada	300 000	50			

This assessment of resource use suggests that Canadian fisheries are harvesting at rates close to sustainable limits and contrasts strongly with the economic perspective that shows fisheries as a small component of a much larger whole. However the combination of these views still gives an incomplete picture of the overall ecosystemic importance of fishes, fisheries, and fish habitats to Canada. Costanza *et al*. (1997) have recently provided the first global estimates of the values of the many ecological services provided by ecosystems. Their dollar valuations were mainly derived by estimating the cost of replacing each service. Coastal marine waters and freshwaters have high unit service values of approximately $US 4000 and $US 8500 per hectare per year respectively. Most of the service value of marine areas is associated with nutrient recycling and of freshwaters with water supply and regulation. However, both are important sources of food, habitat refugia, and recreation. This total ecological services approach to ecosystems, and by inference to fisheries, along with the primary production co-option calculations clearly show that the landed values of commercial catches and the expenditures per angler-day in recreational fisheries undervalue the significance of fishes and fisheries to Canadians.

IMPACTS ON FISH

We now go on to review the existing literature on observed and predicted effects of climate on the biology and ecology of wild fish populations. We have organised the review according to the categories mentioned earlier, beginning with effects on productivity, at both ecosystem and population levels, and ending with effects on spatial distributions, at both the population and species levels.

Ecosystem Productivity and Fish Production

Empirical studies of links between various climatic factors and the biomass production of entire fish communities have produced findings that differ widely, depending on both the kind of aquatic system examined (e.g., lakes, oceans) and the spatial scale over which the data are accumulated. Comparing freshwater lakes from the arctic to the tropics, the overall production of fish is strongly correlated with mean annual air temperature - an index of nutrient availability explained only a relatively small, additional portion of observed variance (Schlesinger and Regier, 1982). Within smaller geographic regions, variation in fish community production is most closely associated with indices of nutrient availability and lake morphometry (Downing *et al.,* 1990, Leach *et al.,* 1987). In contrast, large decadal variation in overall fish production for the North Pacific, over the period 1925-1990, was strongly correlated with changes in strength of the wind patterns that drive rates of nutrient recirculation (Beamish and Bouillon, 1995; Polovina *et al.,* 1994). However, even here, individual pelagic ecosystems differed in their apparent response to the common climate forcing (Hayward, 1997).

Comparative, system level studies of this sort provide insights into the possible climatic dependencies of fish production systems. However, the empirical relations they produce are correlative in nature, do not necessarily demonstrate causality and hence may not be sufficient for reliable forecasts of the consequences of climate change. Because individual aquatic systems differ in their physical responses to climate variation and because these differences will likely produce quite different causal chains linking climate to fish production, we will focus our review initially on five different types of aquatic systems and examine the links between climate and those environmental changes most likely to affect ecosystem productivity in each system. The systems are: (i) marine offshore, (ii) marine arctic (iii) marine coastal and estuarine, (iv) freshwater lakes, and (v) freshwater rivers/streams. For each system, we will separate possible effects of changes in water supply (i.e. expected sea level rise in marine systems vs. water level declines expected for many freshwater systems) from possible effects of changes in water quality.

Marine Offshore

In marine systems generally, fish production varies with primary production (Nixon, 1988) and primary production is nutrient limited, with nitrogen the limiting nutrient (Mann and Lazier, 1996). The rate of production is driven by the upwelling of nutrients from deeper waters to the upper, mixed layer of the ocean, and by rates of nutrient recycling in the mixed layer itself (Denman *et al.,* 1996). Both of these processes are strongly and positively linked to the intensity of wind driven turbulence (Eppley and Peterson, 1979; Mann and Lazier, 1996). Thus, one would expect to find strong connections between variation in wind patterns and variation in offshore marine fish production. Recent work on historical variation in overall fish production in the North Pacific has revealed just such a close connection with variation in wind patterns on several time scales, running from the annual through the decadal (Mann and Lazier, 1996, Pearcy, 1997) to the centennial and even millennial (Pearcy, 1997). From the mid 1920's to the late 1980's, decadal scale shifts in the location and intensity of the Aleutian low pressure region have been accompanied by strong changes in annual productivity levels in several large, offshore marine ecosystems: changes in primary production, secondary production and overall fish production have been clearly demonstrated (Beamish, 1993, Beamish and Bouillon, 1993, 1995, Polovina *et al.,* 1994, Trenberth and Hurrell, 1994, Hayward, 1997, Pearcy, 1997), particularly for the large and rapid shift that occurred in the mid-1970's.

This connection between air pressure patterns and ecosystem productivity has a direct, causal interpretation. When the Aleutian low intensifies and moves east, the cyclonic winds in the Gulf of Alaska intensify, the northward flowing Alaska coastal current strengthens, transporting more warm water north, and with these changes come large increases in the intensity of nutrient regeneration and nutrient upwelling in the mixed layers of the Gulf of Alaska and adjoining waters. These increases in nutrient availability drive the observed increases in ecosystem productivity (Mann and Lazier, 1996, Pearcy, 1997) in waters dominated by the Alaska current system. Over the period 1920-1990, Hare and Francis (1995) and Francis and Hare (1994) were able to identify three distinct periods in both the weather records for the North East Pacific and the catches of Alaska pink and sockeye salmon: 1920-47 (high catches), 1948-76 (low catches), 1977-90 (high catches). The latter two periods match those identified by Beamish and Bouillon (1995) in their analyses of decadal-scale variation in catch records from other North Pacific fisheries. It is interesting to note that there appears to be a reciprocal relationship between productivity in these northern waters and productivity in the coastal waters south of British Columbia that are dominated by the southward flowing California current (Pearcy, 1997).

Smaller amplitude, annual variation in Gulf of Alaska circulation has been documented (Wooster and Hollowed, 1995) and associated with the synchronous appearance of strong year classes among many groundfish populations living in the region. Variation on this time scale appears to be related to climatic variation in the South Pacific, associated with El Niño-Southern Oscillation (ENSO) events: many, but not all, ENSO events have been followed by intensification of the Aleutian low (Mysak, 1986).

In the Northwest Atlantic, annual to decadal variation in fish production in the waters of Labrador and Newfoundland has been linked to variation in the air pressure difference between the Azores high pressure system and the Icelandic low pressure system (Drinkwater, 1994; Mann and Drinkwater, 1994). Historical analysis has shown that this pressure difference cycles on a decadal time scale. This North Atlantic Oscillation (NAO) is indexed by the pressure difference between the two systems. Variation in this index is associated with climate variation in the waters around Labrador and Newfoundland and in the waters south of the Gulf of Maine. Climatic conditions for the Gulf of Maine and the Scotian shelf are not associated with the NAO (Drinkwater, 1996; Krovnin, 1995). High values for the NAO index are associated with: cold winters on the Labrador shelf, strong northwest winds in winter and spring, extensive and prolonged ice cover through winter and, after ice melt in spring, cold, lower salinity surface waters extending throughout the summer. Opposite conditions are associated with negative values for the index.

Positive values for the NAO index have been associated with shorter growing seasons for both phytoplankton and zooplankton (Bochkov and Troyanovsky, 1996), reductions in the population biomass of almost all groundfish in the waters around Labrador and Newfoundland (Atkinson, 1993, cited in Mann and Drinkwater, 1994), reductions in the population biomass of some pelagic species (Colbourne *et al.*, 1994) and reductions in both individual growth (Krohn and Kerr, 1996, cited in Drinkwater, 1997) and population biomass (Mann and Drinkwater, 1994) of cod stocks in these areas. In an extensive study of temporal trends in phytoplankton and zooplankton species in Labrador and Newfoundland waters (Myers *et al.*, 1994), the great majority (80%) of data sets with statistically significant trends (about 20% of all data sets examined) exhibited declines that were coincident with the very strong increase in the NAO index over the period 1965-75.

It has been suggested (Mann and Drinkwater, 1994) that the conditions associated with high NAO values suppress ecosystem productivity via the following mechanism: prolonged and extensive ice cover and strong cold northwest winds delay initiation of phytoplankton and zooplankton growth in spring, while the cold low-salinity surface water present in summer creates a very stable thermocline that effectively prevents any nutrient input to the surface mixed layer from deeper water. In addition, low temperatures in the mixed layer itself insure low nutrient recycling rates. All these effects conspire to produce a short, cold growing season with low nutrient availability, severely limited primary production and consequent food shortages all the way up the food chain to fish, marine mammals and birds.

Low frequency variation in air pressure patterns over large geographic scales are among the least understood aspects of climate variability (Miller *et al.*, 1994), yet they appear to have profound and long term effects on the overall productivity of marine ecosystems, and on the sustainable harvests of fish that can be extracted from them. In order to detect and to forecast the impacts of CO_2-based climate change on such systems, it is essential to discriminate between low frequency “natural” cycles and “irreversible” trends imposed by climate change. The 1970's shift of the Aleutian low pressure system, and the productivity changes that accompanied it, appears to have been part of a “natural” cycle that is reversing, however concurrent declines in production observed off the coast of California continue (Hayward, 1997).

Current research is focused on trying to understand the likely effects of CO_2-based climate change on “natural” patterns of variation, operating at low and medium frequencies (e.g. El Niño events). A recent study suggests that El Niño frequencies are increasing and that this might be due to climate change (Trenberth and Hoar, 1996). Similarly, the frequency of the NAO appears to have increased after 1970 and it has been suggested that this change may be a product of CO_2-based climate change (Rodionov and Krovnin, 1992)

In addition to the uncertainty regarding impacts of CO_2-based climate change on natural cycles in nutrient upwelling and recycling rates in marine systems, there is some controversy regarding the likely impact on global average upwelling intensity itself. If climate change brings a decrease in the temperature difference between equator and poles, then an overall decline in the intensity of westerly winds will follow and this, in turn, will lead to reductions in nutrient upwelling and production in offshore marine ecosystems (Jilan and Miles, 1996; Beamish *et al.*, 1997). Under this scenario, one might expect to see the amplitude of the NAO decline, since it is part of the global system that generates westerly wind regimes. Alternatively, it has been suggested that climate change will bring an increase in the average temperature difference between oceans and land. An increase in along-shore wind stress will follow and this will, in turn, lead to increases in coastal upwelling and production in some coastal ecosystems (Bakun, 1990).

Marine Arctic

Basic knowledge exists of the distribution and abundance of diadromous fish (i.e., fish which migrate between the sea and freshwater) and marine mammals in the arctic, however knowledge of the basic biology of marine fish and invertebrates is incomplete and there is limited understanding of the functioning of arctic marine ecosystems (Clarke, 1993). This situation is made even more complex by variation in the seasonal and annual ice regimes, which act as important structuring agents for many marine ecosystems. The predictability of simple and complex effects of climate change on northern fish populations is generally quite low (Reist, 1994). In the limited literature available to us, likely effects of climate change on arctic marine productivity are associated with changes in the size and continuity of the arctic ice sheet and resultant positive effects on length of growing season and rates of nutrient re-circulation (Flittner, 1993):

- warming will lead to reduced ice cover; this will lead to higher light levels, greater mixing and higher nutrient levels, higher water temperatures and longer growing seasons in these new areas of open water; all of these changes will lead to increases in overall productivity;

- warming will lead to increases in the number and size of polynyas (the open water areas enclosed by ice fields); this will also lead to increases in overall productivity because of increases in light and nutrient levels within the polynyas;

- regions of high productivity are associated with ice edges; warming of the arctic should change the seasonal migration pattern of the ice edge, producing spatial shifts in productivity zones;

- productivity zones associated with polynyas will also shift in location.

Coastal Marine Ecosystems and Estuarine Ecosystems

There are many similarities in the potential effects of climate change on fish production in both estuaries and coastal marine waters (Table 5.6), hence they are treated together here.

There is extensive discussion in the literature (Ehler *et al.*, 1996) of the possible effects of water level rise on coastal marine ecosystems. Marine coastal wetlands are high productivity environments that house critical life stages of many fish species that spend much of their lives at sea. Slow rises in sea level may have a relatively small effect on overall wetland productivity if there are no physical impediments to inland migration of the wetlands. If inland migration is restricted by human development around existing wetlands then significant losses in productivity are inevitable.

A related effect is found in estuaries. The location of the boundary between salt and freshwater will move inland as sea level rises. There will rarely be serious impediments to this, but a consequence of this movement will be that freshwater ecosystems will be replaced by brackish or salt water ecosystems. If the upstream migration of the boundary is slow, this transformation may occur with relatively minor disruptions. However if it is rapid, large drops in production may occur as freshwater communities die out more rapidly than they can be replaced by saltwater communities. The rate of migration is a function of freshwater flow rate as well as sea level rise. A decline in flow rate will augment both the rate and extent of inland migration (Drinkwater and Frank, 1994).

Table 5.6 Potential Impacts of Climate Change on Ecosystem Productivity in both Estuaries and Coastal Marine Waters

Expected change in climate	**Ecosystem**	
	Estuary	**Coastal Marine**
Sea level rise	• Inland migration of salt-fresh water boundary • No effective barrier to movement • Rate of movement determines how disruptive the effect will be	• Migration of existing wetlands inland; status quo or even improvement if newly flooded lands can develop into replacement habitat • Migration subject to limitation by human flood control structures; such structures can insure existing habitat is flooded and made unusable, while no replacement habitat is created
Decrease in freshwater flows from river systems	• Augments inland migration of saline boundary already established by sea level rise • Reduction in nutrient mixing in estuary leads to broad decline in production throughout estuarine system (e.g., Therriault and Plourde, 1997)	• Reduction in nutrient regeneration that is driven by freshwater input; • Possible reduction in production and therefore sustainable harvest for individual populations (e.g., Gulf of St. Lawrence lobster and halibut - Sutcliffe *et al.,* 1977, various Atlantic cod stocks - Sutcliffe *et al.,* 1983)

Freshwater flow rates can influence levels of nutrient availability in estuaries and in coastal marine waters, by direct loading of new nutrients from the land, by intensification of nutrient upwelling to the euphotic zone from deeper waters (Drinkwater, 1986; Drinkwater and Frank, 1994) and by suppression of nutrient upwelling through intensification of density stratification (Sutcliffe *et al.*, 1983). The potential importance of links between freshwater runoff and marine primary production and fish production has been discussed in studies of both Pacific (McBean *et al.*, 1992; Pearsey, 1997) and Atlantic ecosystems (Sutcliffe, 1973, Drinkwater and Frank, 1994). Empirical demonstrations of correlations between measures of runoff and fish production also come from both coasts (Pacific: Beamish *et al.*, 1994; Atlantic: Sutcliffe, 1972, 1973, Sutcliffe *et al.*, 1977; 1983; Drinkwater, 1987; Gagne and Sinclair, 1991; Therriault and Plourde, 1997), however more attention seems to have been paid to the phenomenon in Atlantic waters, where the large freshwater discharges from the St. Lawrence River and Hudson Bay (Figure 5.1) play significant and well-recognised roles in determining seasonal variation in hydrological conditions in the Gulf of St. Lawrence, Scotian Shelf, Gulf of Maine (Sutcliffe *et al.,* 1976, Drinkwater, 1996; Krovnin, 1995) and Newfoundland Shelf (Myers *et al.,* 1990).

Freshwater Lakes

Most studies of the response of North American lakes to climate change have focused on the large number of lakes on the Canadian Shield and on the Great Lakes (e.g., Magnuson *et al.*, 1997) and have been directed by the kinds of climate change expected for this region: warmer air temperatures and a shift in the balance between evaporation and precipitation, leading to overall declines in both river flows and lake levels (Mortsch and Quinn, 1996; Magnuson *et al.,* 1997).

This set of climate changes will affect the physical character of lake systems in a variety of ways that will have both obvious and subtle impacts on ecosystem productivity in general, and fish production in particular.

The annual biological production of a lake can be defined as the product of the lake volume and the average level of production that each unit of that volume can support over one year (the annual average volume-specific productivity). The effect on annual production of a water level decline, and the volume reduction that accompanies it, is direct and clearly negative. The potential effects of climate change on volume-specific productivity are many and subtle.

Annual volume-specific productivity for most Canadian lakes is controlled by some combination of temperature, light (the portion of the year for which light is available = the ice-free period) and nutrients, with phosphorus the limiting nutrient in almost all situations. When nutrient availability is high, production rates for all organisms in the food chain from phytoplankton to fish vary with both the length and average water temperature of the ice-free period (Fee *et al.,* 1992; Hewett and Johnson, 1987; Plante and Downing, 1989; Shuter and Ing, 1997). When nutrient availability is low, overall production is set by the nutrient level and is relatively unaffected by changes in temperature (Dillon and Rigler, 1974; Downing *et al.,* 1990; Shuter and Ing, 1997; Martin *et al.*, submitted). The extent of nutrient limitation is a product of the annual net inflow (or loading) of new phosphorus to the lake from its watershed, the loss of existing phosphorus to lake sediments (Vollenweider, 1969; Dillon and Rigler, 1974; Dillon and Molot, 1996) and the rate of phosphorus recycling that occurs both within the water column and in the bottom sediments (Campbell, 1994; Fee, 1979; Fee *et al.,* 1994; Levine *et al.,* 1986; Nurnberg, 1984; Bostrom *et al.,* 1988). Net loading depends on both the amount of runoff, the length of the ice-period and the character of soils in the watershed (Richardson, 1985; Dillon and Molot, 1996; Dillon and Molot submitted). Phosphate recycling depends on the depth, temperature and degree of turbulence of the surface mixed layer of water during the ice free period: a deeper warmer mixed layer supports a greater phosphorus regeneration rate and hence makes more "recycled" production available to fish during the stratified period (Fee, 1979; Fee *et al.,* 1994; Reynolds, 1996; Tarapchak and Nalewajko, 1986). For lakes that stratify, the annual phosphorus regeneration rate will increase if hypolimnetic oxygen levels fall to low levels (Bostrom *et al.*, 1988; Magnuson *et al.,* 1997). The rate will decrease if the water column mixing associated with fall overturn is limited by failure of surface waters to cool below 4°C (McCormick, 1990).

Overall, the seasonal air temperature increase expected from increased atmospheric CO_2 should produce longer ice-free periods, longer periods of thermal stratification and higher epilimnetic water temperatures (Hondzo and Stefan, 1993; King *et al.,* 1997; McCormick, 1990; Meyer *et al.*, 1994; Schindler *et al.,* 1996; Shuter *et al.,* 1983). In the absence of nutrient limitation, these changes should result in longer growing seasons and greater production for both phytoplankton (Fee *et al.,* 1992) and zooplankton (Shuter and Ing, 1997): increases in lower trophic level production that should be reflected (Downing *et al.,* 1990; Leach *et al.,* 1987) in increased fish production. However these positive effects on potential production could be limited or even reversed by decreases in nutrient availability that could result from reductions in runoff and a general drying of watersheds. These changes will reduce lake loadings for both phosphorus and dissolved organic carbon (Magnuson *et al.,* 1997; Schindler *et al.,* 1996) and will increase lake water renewal times (Schindler *et al*., 1996). These changes could have positive or negative effects on volume-specific nutrient availability depending on such factors as lake size, lake morphometry, watershed soil composition (Fee *et al.,* 1996; Dillon and Molot, submitted; Richardson, 1985) and mixed layer depth. For small, oligotrophic lakes (lake area < 500 ha) mixed layer depths will likely increase with transparency as dissolved organic carbon (DOC) loading declines (Fee *et al.,* 1996). For larger lakes, mixed layer depth will likely decrease, as expected from both hydrodynamic studies (McCormick, 1990; Hondzo and Stefan, 1993; Meyer *et al.*, 1994) and historical analyses (King *et al.,* 1997).

In an historical study of the behaviour seven small, oligotrophic Canadian shield lakes over the period 1978-92, Dillon and Molot (submitted) showed that phosphorus loading from lake catchments declined with decreases in summer precipitation and that this effect appeared to dominate all other influences on lake phosphorus concentrations, leading to a general decline in phosphorus levels in these lakes over the period studied. These findings suggest that the warmer drier summers expected from CO_2-based climate warming will lead to increased nutrient limitation in oligotrophic shield lakes with large catchments.

Table 5.7 summarises the potential effects of climate change on lake productivity that have been identified in the literature. For small lakes, many effects lead to an increase in nutrient availability; hence some of these systems may be able to realise the increases in potential production provided by longer, warmer growing seasons (Porter *et al.,* 1996). However, empirical data from small, oligotrophic shield lakes (Dillon and Molot, submitted) suggest that effects leading to increased nutrient limitation will dominate in these systems. In larger lakes, many effects restrict nutrient availability; hence limitation, or even reversal, of increases in potential production seem likely for these systems.

Freshwater Rivers/Streams

We were unable to identify any studies that explicitly examined effects of climate change on overall fish production in rivers or streams. However, studies of expected abiotic changes in these systems can be used to infer possible effects on production, using results from lake studies as a guide.

Table 5.7. Potential effects of a warmer, drier climate on annual average volume-specific productivity of lake ecosystems in central Canada.

Physical/ chemical change in lake system	Change in potential production	Change in phosphorus (P) available to support potential production	
		Small lakes	**Large dimictic lakes**
Longer ice free period and, in dimictic lakes, longer stratification period	• ↑ Longer growing season;	• Increase in net nutrient loading from decline in runoff losses during ice cover period	• Increase in net nutrient loading from decline in runoff losses during ice cover period
Longer stratification period		• Reduced O_2 concentration in hypolimnetic sediments promotes increase in extent of P recycling	• Reduced O_2 concentration in hypolimnetic sediments promotes increase in extent of P recycling
Warmer surface water temperatures	• Higher temperatures promote increase in production rates among zooplankton and fish	• Warmer temperatures promote increase in rate of P recycling in surface waters	• Warmer temperatures promote increase in rate of P recycling in surface waters • Surface waters fail to cool below 4^{o}C, limiting degree of P recycling from bottom waters over the period from autumn through spring
Reduction in annual input of new P from watershed		• Decrease in P available to support new production	• Decrease in P available to support new production
For small dimictic lakes, reduction in annual input of DOC from watershed leads to greater transparency, increased heating of deeper waters and consequently, a deeper thermocline	• Increase in volume of productive mixed layer	• Increase in rate of P recycling in surfaces waters • Hypolimnetic volume decrease leads to lower O_2 levels in hypolimnetic sediments and thus increases P recycling	
For large, dimictic lakes, increase in spring/ summer air temperatures and decrease in wind strength leads to a shallower thermocline	• Decrease in volume of productive mixed layer		• Decrease in rate of P recycling in surface waters • Hypolimnetic volume increase leads to higher O_2 levels in hypolimnetic sediments and thus reduces P recycling

Under a climate change scenario of increased air temperature, coupled with reduced runoff and a general drying of watersheds, the following changes are expected: increases in headwater temperatures, resulting from increased groundwater temperatures (Meisner, 1990), increases in the duration of the ice-free period, earlier and less intense spring freshets, reduced flow from late spring through fall, and higher water temperatures from headwaters to stream mouth (Levy, 1992; Schindler *et al.*, 1996; Stefan and Sinokrot, 1993).

The overall reduction in water volume, coupled with the possibility that flow in smaller streams will become intermittent, should lead to reductions in overall aquatic production. However, this reduction could be mitigated by production increases among invertebrates (Morin and Bourassa, 1992) and other organisms as a result of longer, warmer growing seasons (Shuter and Ing, 1997).

Changes in Production Among Populations of a Single Species of Fish

Moving from climatic effects on ecosystem productivity to climatic effects on population production, we find an extensive empirical and theoretical literature for freshwater fish species and a largely empirical literature for marine fish species. We will focus our review around the conceptual models developed in the freshwater literature. Here, population-specific differences in production within a species are assumed to be strongly dependent on differences in the amount of thermally suitable habitat available to individual populations. The basis for defining thermally suitable habitat is outlined below.

When fish are studied in the laboratory, the temperature response of many of their critical physiological functions (e.g., respiration, food consumption, growth) is strong, consistent and replicable (Coutant, 1977, Wismer and Christie, 1987). These observations are consistent with the hypothesis that this temperature response "pattern" is "hard-wired" genetically at the species level and that there is little variation in the pattern among different populations of species, even if they reside in quite different habitats. The typical response pattern is characterized by a well defined peak, at a specific temperature characteristic of the species. Over the relatively narrow temperature range around the peak, physiological function is optimal. The optimal temperature ranges for many functions tend to overlap with each other and centre on the preferred temperature of the species (Brett, 1971; Hokanson, 1977; Regier *et al.*, 1996). This optimal temperature range has been labelled (Magnuson *et al*., 1979; Magnuson and DeStasio, 1997) the "fundamental thermal niche" and has been defined as ±2°C of the median preferred temperature of the species: the temperature range within which a fish in a preference tank in the laboratory will spend 2/3 of its time. The thermal niche "delineates temperatures at which a variety of optima occur in the life of fishes, such as maximum growth rate, maximum scope for activity and maximum swimming performance" (Magnuson *et al.*, 1990).

Many North American freshwater fish species fall into three broad groups (or guilds) with quite different thermal niches: coldwater fish, with niches centred around 15°C; coolwater fish, with niches centred around 24°C; and warmwater fish, with niches centred around 28°C (Hokanson, 1977). Reist (1994) has pointed out that fish adapted to life in the far north have preferred temperatures that are uniformly much lower than 15°C and hence could be grouped together as a fourth Arctic guild. The thermal guild scheme has provided a convenient framework for comparative studies of the temperature requirements of temperate fishes (e.g., Magnuson *et al.*, 1979; McCauley and Casselman, 1981; Magnuson and DeStasio, 1997), and has formed the basis for several comparative assessments of the potential effects of climate change on temperate freshwater fishes (Magnuson and De Stasio, 1997; De Stasio *et al.*, 1996; Magnuson *et al.*, 1990; Mandrak, 1989; Meisner *et al.*, 1987; Stefan *et al.*, 1996).

For any guild, the annual variation in surface water temperatures for most North American lakes (e.g. Shuter *et al.*, 1983) is much wider than the 4°C width of its thermal niche. Since optimal performance of the individual hinges on the availability of temperatures within its thermal niche, one would expect to see "large" responses of wild fish to "small" year-to-year variations in the cumulative time spent in, or near, this preferred temperature range. Considerable empirical evidence has now accumulated that population-specific differences in production do depend, to some extent, on differences in the amount of "thermally suitable" living space. Published studies fall into two categories:

(i) demonstrations of strong correlations between indices of population productivity and simple indices of environmental temperatures, that can be easily interpreted in terms of differences in amount of thermally suitable living space (e.g., length of stream over which temperatures never exceed upper thermal limit for a particular species, or guild - Rahel *et al.*, 1996.)

(ii)demonstrations of strong correlations between indices of population productivity and explicit estimates of the amount of thermally suitable living space, based on both the physiological characteristics of the species (i.e. range of temperatures required for near optimal growth, oxygen requirements, substrate requirements) and the topography and physical/chemical "climates" of the particular aquatic systems occupied by the individual populations studied (e.g., Christie and Regier, 1988).

Examples of both types of studies can be found in both freshwater and marine systems (Table 5.8).

Shuter and Meisner (1992) argued that the "thermally suitable habitat" paradigm provides a convenient and relatively objective means of forecasting effects of climate change on production at the population level, and at the level of thermal guilds. Several authors have used this forecasting approach for a variety of systems (Table 5.8). There are more freshwater studies than marine but the marine studies that have been carried out are sufficiently interesting to encourage further work in the area (Frank *et al.*, 1990, Reddin and Friedland, 1993).

Diadromous fish species support economically and socially important fisheries in most regions of the country. Such species could be quite sensitive to climate changes because they require at least two, and up to four, distinct aquatic habitats to complete their life cycles (Table 5.9). Each of the habitats utilised by a species will respond differently to climate change and thus each life stage of the species will experience different kinds of impacts (Levy, 1992). The overall response of a particular population to this complex set of environmental changes is likely also to be complex and quite unpredictable. In addition, effective utilisation of these multiple habitats is the result of some prior adaptation by each population to the seasonal sequence of changes in water temperature, stream discharge and ocean currents that is typical of its habitats. Climate change will tend to disrupt this sequence and could thus damage the ability of a population to make the most of its traditional set of habitats (Levy, 1992). In addition to the Pacific salmonids described in Table 5.9, other diadromous species supporting important fisheries include Atlantic salmon, American eel, sturgeon and Arctic charr.

Arctic charr populations tend to be anadromous (i.e. much of life cycle spent at sea, spawning carried out in freshwater) and more productive in warmer, lower latitude areas. In cooler, higher latitude areas, they are often non-anadromous (lacustrine life history) and less productive. Thus, climate warming may promote a shift from non-anadromy to anadromy, with concomitant increases in fishing opportunities due to the higher net production typical of anadromous populations (Reist, pers. comm., September, 1997)

Table 5.8. Summary of studies that either demonstrate a link between measures of population production and thermally suitable habitat or use such a link to forecast effects of climate change (acronyms: SFY = sustained fishery yield)

System	Empirical Demonstration	Forecast
Freshwater lakes	whitefish, walleye, northern pike: SFY increases to a peak and then declines with increases in mean annual air temperature; temperature at peak yield is species-specific (Schlesinger and Regier, 1983) lake trout, walleye, northern pike, lake whitefish: SFY increases with amount of thermally suitable habitat, defined as a time-weighted measure of the absolute amount of living space available annually with water temperatures in a 4°C range that contains the species specific optimal growth temperature (Christie and Regier, 1988)	whitefish, walleye, northern pike in Eastern Canada: climate warming moves region of maximum productivity ~600 km north (Minns and Moore, 1992) cold-, cool- and warmwater fish in Minnesota lakes: climate warming brings greatest loss of thermally suitable habitat to coldwater fish in eutrophic lakes; greatest gain to cool- and warmwater fish in oligotrophic lakes (Stefan *et al.,* 1996; Magnuson and DeStasio, 1997)
Freshwater streams	coldwater salmonids: biomass in Ontario streams varies with summer water temperature (Bowlby and Roff, 1986)	cold-, cool-, warmwater fish in United States: climate warming leads to a ~50% reduction in thermally suitable habitat for cold- and coolwater fish; for warmwater fish, habitat decreases for some species and increases for others (Eaton and Scheller, 1996) coldwater fish in Wyoming: climate warming brings 16-69% reduction in thermally suitable habitat (Rahel *et al.,* 1996)
Marine	Atlantic salmon: spring/summer abundance of Atlantic salmon varies with amount of thermally suitable winter refuge habitat in Labrador Sea (Friedland *et al.,* 1993, Reddin and Friedland, 1993) Atlantic cod: comparative study of 20 North Atlantic populations reveals positive association between population growth rate and average water temperature in population habitat (Myers *et al.,* 1997)	

Table 5.9. Habitat use over the life cycle of common Pacific salmonids (after Pearcy, 1992).

Each species exhibits great inter- and intra-population variation in the amount of time spent in each habitat type. The table provides rough bounds for the range of this variation and identifies larger inter-specific differences (e.g., the unique requirement of sockeye salmon for lake residency early in life).

Species	Habitat			
	Stream	**Lake**	**Estuary/Coastal Marine**	**Offshore Marine**
Sockeye salmon	days-months	days-months	days	up to 5 years
Coho salmon	1-2 years most common	-	days	up to 1.5 years
Chinook salmon	months up to 2 years	-	days to months	up to 6 years
Chum salmon	days-weeks	-	days	up to 4 years
Pink salmon	days-weeks	-	days	up to 1.5 years

Climate-induced changes in the spatial distributions of primary predators and prey can also exert a significant effect on the productivity of a population - an increase in the local density of its predators or a decrease in the local density of its prey can both lead to a decrease in overall population production. Marine populations are potentially more susceptible to such effects because the lack of physical barriers in the marine environment permits spatial distributions to respond rapidly to environmental changes. Examples of shifts in predation intensity, stemming from climate-induced changes in the spatial distribution of a predator, include increases in mackerel predation on Pacific salmonids and increases in hake predation on Pacific herring (Beamish, 1995).

Short Term Variation in the Distribution of Population Members

Individual fish actively select living areas based on suitable temperatures, oxygen concentrations and food availability. Fish will rapidly change their spatial distribution in response to changes in these and other factors. In a recent, comprehensive review of studies on freshwater fish in temperate lakes, Magnuson and DeStasio (1997) show that:

(i) fish maintain their thermal preferences year round, tending to choose the warmest temperatures available, providing the upper boundary of the thermal niche is not exceeded;

(ii) selection is not based solely on temperature but can be modified by abiotic factors such as oxygen concentration and pH (e.g. low levels are avoided) and biotic factors, such as prey abundance (attracted) and predator abundance (avoided);

(iii) in lake populations, three typical patterns of habitat use occur:
  - fishes occupy their thermal niche when those temperatures are abundant in the lake;
  - fishes occupy the most available temperatures, even if those temperatures are not within their thermal niche;
  - fishes often exhibit bimodal distributions, suggesting either age-related differences or forays outside their thermal niche to feed;

(iv) when the tendency to seek optimum thermal habitat is coupled with the presence of significant year-to-year and lake-to-lake variation in the availability of such habitat, populations of a single species will often be found living in different thermal environments in different lakes and in different years.

In streams, similar principles apply. Of particularly interest is the common observation (Meisner, 1990; Regier and Holmes, 1991; Rahel *et al.*, 1996) that cold water fish will actively avoid temperatures that exceed the upper boundary of their thermal niche, seeking refuge areas provided by sources of cooler water, such as: groundwater in seepage areas and headwater streams, higher elevation streams and glacier melt.

There are many examples of rapid shifts in the distribution of marine fish populations that suggest that similar principles are operative, at least for some species. These include the real time tracking of surface temperature isotherms by a variety of Pacific salmon species during the marine phase of their life cycle (Welch *et al.*, 1995), northward shift of hake abundance in response to warmer sea temperatures off the west coast of Vancouver Island (Ware and McFarlane, 1995), tracking of the 7°C isotherm by Atlantic mackerel during their spring migration (Loucks, 1981, as cited in Frank *et al.*, 1988), the southward shift and concentration of Atlantic cod in 1990-92 (Atkinson *et al.*, 1997) and the absence of migratory warm-water species (e.g. mackerel, squid, Atlantic saury) from the Northwest Atlantic during the cold periods of the 1990's (Montevecchi and Myers, 1995).

For marine systems, ocean currents as well as temperatures are important in causing shifts in distribution and, indirectly, the changes in mortality rates that can accompany such shifts (Frank *et al.*, 1990, Mann and Lazier, 1996). Shifts in local or regional current patterns can often be linked to changes in climate. For example, when the Aleutian low is strong, shifts in current and temperature patterns off Vancouver Island and off Sitka in northern British Columbia, lead to changes in the migration paths of sockeye salmon stocks returning to the Fraser (Xieh and Hsieh, 1989, Thomson *et al.*, 1992), Nass and Skeena (Hamilton and Mysak, 1986) rivers in British Columbia. Frank *et al.*, (1990) speculate that, in the Atlantic Region, climate warming will bring a decrease in the occurrence of the local, circular current anomalies known as “warm core rings”. These current patterns tend to drive larval fish offshore, into deeper water where they perish. Hence, a decrease in the frequency of occurrence of such current patterns would promote increased survival among larval life stages of many species of fish in the Atlantic region

Long Term Changes in the Distributional Boundaries of Species

Species-specific patterns of thermal tolerance and behaviour can interact with climate to establish boundaries to the zoogeographic distribution of a fish species. One set of mechanisms capable of setting the northern limit to the distribution of a species has been described in detail for both smallmouth bass and yellow perch by Shuter and Post (1990). The potential effects of climate warming on such boundaries can be categorised as follows:

(i) northern boundaries may extend and/or southern boundaries may retract;
(ii) a range may expand if greater warming in the north allows the northern boundary to extend over a distance greater than the distance over which the southern boundary retracts; a range expansion to the east or west may also occur if extension of the northern boundary releases a physical constraint on east-west expansion (e.g., the white perch invasion of the Great Lakes from the Hudson River - Johnson and Evans, 1990);
(iii) a range may shrink, or contract, if the northern boundary is fixed by some physical barrier (e.g., the Arctic coastline for lake trout and lake whitefish) and the southern boundary retracts;
(iv) a range may shift north if both boundaries are set by climatic conditions and both are significantly affected by warming.

A variety of empirical studies have demonstrated the importance of climate in setting the zoogeographic boundaries of some fish species (Mandrak, 1989; Mandrak, 1995; Radforth, 1944; Shuter and Post, 1990) and these findings, and others, have been used to forecast the effects of climate warming on those distributions (Table 5.10).

Table 5.10 Summary of observed/predicted/possible changes in zoogeographic boundaries of species

Distributional Change	Marine Pacific	Freshwater	Marine Atlantic
Extension, northern limit	• petrale sole (Beamish 1997)	• - perch, smallmouth bass: ~500 km extension of existing boundary across Canada with 4 C increase in mean annual air temperature (Shuter and Post 1990) • smallmouth bass, carp: ~500 km extension of existing boundary in Ontario with ~ 5 C increase in mean annual air temperature (Minns and Moore 1995) • minnows (8 species), sunfishes (7 species), suckers (3 species), topminnows (3 species): extension into Great Lakes basin possible with warming (Mandrak 1989)	• Atlantic mackerel: northern limit of spring migration moves with 7C isotherm (Frank et al. 1988); distribution moved north with the warming of the 1940's (Taylor et al. 1957 • - green crab: observed to move north with the warming of the 1940's (Taylor et al 1957)
Retraction, southern limit	• pink salmon (Beamish 1997) • pacific herring (Schweigert 1995) • rock sole (Beamish 1997) • pacific cod (Beamish 1997)	• whitefish, northern pike, walleye: suggested by the northward shift in sustainable yields predicted to result from climate change (Minns and Moore 1992) • lake trout: suggested for small shield lakes by predictions of smaller hypolimnetic refuges with lower O_2 levels (Stefan and Hondzo Schindler et al 1990, 1996)	• capelin: southern limit retracted north with warming through the 1970's (Frank et al. 1996) - this was preceded and followed by extensions southward during the cooling periods of the 1960's and 1990's (Frank et al. 1996, Drinkwater 1997)
Shift of entire range	• sockeye salmon, northward shift (Beamish 1997)		• Atlantic cod: range shrinks as both northern and southern boundaries shift over the period 1970-94 (Brown et al. 1996) • Arctic cod: range expands, mostly through large extension of southern limit over the period 1975-94 (Brown et al. 1996)
Barrier release, and range expansion		• white perch: invasion and spread through Great Lakes Basin when 1940's warming of Hudson River and Erie barge canal waters, effectively removed thermal barrier and permitted access (Johnson and Evans 1990)	• striped bass: warming may permit this species to invade the Great Lakes basin and thus expand its range eastward (Coutant 1990)

In examining potential effects of climate change on zoogeographic distributions, there is an important distinction between freshwater and marine systems that must be recognised. In freshwater systems, physical constraints (e.g., areas of land untraversed by water courses, drainage patterns, waterfalls in rivers, etc.) play a large role in determining the location of zoogeographic boundaries (Shuter and Post, 1990), and in the rate at which a species may respond to the release of a climate-determined boundary. For example, in the Great Plains of the United States and Canada, many rivers and streams are oriented in an east-west direction in areas where there is little physical relief. In such a situation, coldwater species will have little opportunity to avoid warming waters by retreating either northward or to higher elevations (Matthews and Zimmerman, 1990; Rahel *et al.*, 1996). Hence, coldwater populations resident in these areas may be much more sensitive to climate warming than those living in the high relief areas of British Columbia.

In Arctic systems, the distributions of some species will be strongly affected by changes in the seasonal distribution of ice. Migratory marine mammals will extend their summer ranges north and west as ice becomes thinner and its distribution more seasonal. Non-migratory mammals (e.g., ringed seals, polar bears) may exhibit decreased abundance on the southern fringes of their ranges (e.g., Hudson Bay) and may extend their ranges northward, toward the polar pack, as the areas of seasonal ice extend northward. In addition, general warming may lead to range contractions of Arctic-adapted fish species (e.g., Arctic charr).

In marine systems, physical constraints are less influential and therefore it is not surprising to see relatively rapid shifts of distributions in response to climate variation (Brown *et al.*, 1996) and one infers that many northern distributional boundaries are climatically determined (e.g.,: Greenland cod, Arctic and northern cod, mackerel on the Pacific coast and the impact of this shift on salmonid stocks, Pacific salmon - particularly their recent appearance in the Arctic coincident with the prolonged El Niñ of 1990-95 - see contribution by J.D. Reist).

In addition to its effect on the zoogeographic boundaries of a species, climate may be associated with systematic variation in life history characters exhibited by populations of a species across its range. For a variety of freshwater (walleye: Beverton, 1987; yellow perch and smallmouth bass: Shuter and Post, 1990; brown trout: Jonsson and L'Abee-Lund, 1993) and marine (soft-shell clams: Appeldoorn, 1995; Atlantic cod: Myers et al, 1996, Drinkwater, 1997) species, populations living in colder, higher latitude habitats tend to exhibit slower growth rates, lower

Arctic Sightings of Pacific Salmonids

by J.D. Reist

Occasional sightings of Pacific salmon in the western Canadian Arctic have been recorded infrequently as far east as Bathurst Inlet (Craig and Haldorson, 1986). These records include chinook salmon (O. tshawytscha), chum salmon (O. keta), pink salmon (O. gorbuscha), and sockeye salmon (O. nerka) (Craig and Haldorson, 1986). Coho salmon (O. kisutch) have previously been recorded as far east as Prudhoe Bay, Alaska (Craig and Haldorson, 1986). More recent records include the following: 1) Chum salmon - a small spawning run on the Liard River (Mackenzie River drainage) in northern British Columbia (McLeod and O'Neil, 1983); and, a single individual from Cache Creek (Big Fish River at 68 17 N and 136 21 W) in 1986 (Reist, 1987). 2) Coho salmon - a mature male from Great Bear Lake from 1987 (Reist unpublsihed data), and traditional knowledge reports of a potential spawning run in the lake. 3) Sockeye salmon (kokanee) -Great Slave Lake in 1991 (Reist unpublished data).

In addition to the above, a number of sockeye salmon occurred in several areas on the western Canadian Arctic in 1993. Aboriginal fishermen as well as staff of the Department of Fisheries and Oceans encountered fish near Sachs Harbour, Holman and in the Mackenzie River basin. The presence of increased numbers of occasional sightings as well as the presence of possible spawning runs suggests the geographic distribution of these fish is shifting, perhaps in response to trends in climate change, or variability associated with climate change.

natural mortality rates and later ages of maturity. Hence, extensions and contractions of particular climatic zones could be accompanied by shifts in the life history characteristics of stocks “typical” of a particular geographic area. While it is not clear how such shifts would affect partitioning of available ecosystem production among fish species, it will have important implications for harvesting strategies since the complex of life history characters typical of cold water habitats confer on their possessor an inordinate sensitivity to exploitation (Roberts, 1997).

Populations living near the edge of the zoogeographic range of the species often exhibit greater year-to-year variation in abundance than populations living near the centre of the range (Shuter and Post, 1990, Myers, 1991). Hence, when a southern boundary retracts northward, populations which, historically, have had relatively stable abundance levels, may become more variable through time.

In addition to changes in ranges of individual species, climate warming may eventually lead to an increase in the number of fish species found in individual bodies of water. Both Mandrak (1995) and Minns and Moore (1985) found that the number of fish species resident in Ontario lakes increased with mean annual air temperature. Based on these findings, Minns and Moore (1995) forecast that an increase in mean annual air temperature of 4.5°C would allow the fish species count in an average northern Ontario lake (three to six species) to increase by approximately three species. Realisation of this potential increase in diversity would, of course, depend on the absence of physical barriers that could impede invasions by new species.

In freshwater systems, species diversity is influenced by the diversity of thermal guilds. This, in turn, is a function of thermal heterogeneity. In southern Canada, warming will tend to decrease thermal heterogeneity in some freshwater systems. Thus, there is a possibility that climate warming may lead to decreases in species diversity in some systems. In dimictic lakes, stratification creates and maintains thermal diversity, and hence will preserve guild diversity in the face of climate warming. In rivers, stability of head water temperatures and presence of groundwater seepage areas will also tend to preserve guild diversity (Meisner, 1990). However, in northern Canada, moderate warming will increase thermal diversity in many lakes by causing them to stratify in summer (Meyer *et al.,* 1994) - species diversity could increase for such systems.

Interactions With Effects of Other Stresses and Responses of Other Sectors

Climate Change as a Factor that Mitigates or Intensifies Impacts of Other Ecosystem Stressors on Fish

Most studies (Firth and Fisher, 1991; Carpenter *et al.*, 1992) suggest that impacts of climate change on aquatic ecosystems are likely to exacerbate the impacts of existing stressors on aquatic ecosystems (Table 5.11). Many non-climatic stressors continue to impact many fish populations across the country. Exploitation is at, or above, sustainable levels for many populations. Water quality changes associated with long-range transport of sulphur acids, nitrogen acids, and volatile organic contaminants have only been partially addressed and many lakes in eastern Canada are still acidified. The rate of invasions, intentional and accidental, of exotic species is growing, with serious consequences for ecosystems (e.g., zebra mussels in the Great Lakes). Habitat destruction and alteration is continuing wherever human developments are concentrated. The growth of eutrophication of freshwaters was been checked in recent decades but population growth in many urban areas may be out-stripping the capacity of previously-upgraded sewage treatment plants. The extent and rate of all existing non-climatic ecosystem stress patterns have increased markedly in the 20th century.

The patterns of non-climatic stresses on ecosystems and their impacts on fishes and fisheries have developed in the context of the norms of climate conditions prevailing in this century. Significant departures from those norms (warmer or colder, wetter or dryer) will tend to intensify the impacts of these patterns. For example, a general trend to warmer, drier conditions leading to reduced flow rates and water levels in rivers and lakes will almost certainly lead to increased concentrations of a wide range of contaminants, given no change in existing dumping rates. Similarly, increased uncertainty in the environmental conditions that determine oceanic productivity will exacerbate the problem of managing exploitation of marine populations at sustainable levels.

Table 5.11 Potential interactions between existing ecosystem stresses and expected elements of climate change (DOC = dissolved organic carbon, OC = organic carbon, UV = ultra-violet)

Ecosystem Stress	Climate Change Element	Linkage Implication	References
Ozone depletion - UV radiation	• Reduced runoff and dryout of upland wetlands	• Decreased DOC/Colour, increased UV penetration, and increased biotic damage	Williamson *et al.,* 1996, Fee *et al.,* 1996, Clair and Ehrman 1996, Vinebrooke and Leavitt, 1996
Acidic sulfur deposition	• Reduced runoff	• Increased acidity and increased concentrations of other chemicals	Schindler *et al.,* 1996
Contaminants	• Increased temperatures	• Increased methyl-Hg production, greater OC mobility, increased food-chain transfer rate	Michmerhuizen *et al.,* 1996
Exotic invasions	• Increased temperatures	• Enhanced invasion prospects for species from lower latitudes	Mandrak, 1989
Habitat degradation and loss	• Rising or falling water levels • Altered runoff levels and seasons	• Loss of shallow water habitats due to increased hardening of land surfaces and water boundaries in densely populated areas	Minns *et al.,* 1995
Eutrophication	• Decreased runoff • Increased temperatures	• Increased nutrient concentrations • Increased algal blooms and busts, greater hypolimnetic oxygen depletion	Schindler *et al.,* 1996
Over-exploitation	• Increased temperatures	• Faster growing, fecund species favoured over slow growing small brood species	Roberts, 1997
Structure and function	• Changing temperature • Altered lake mixing regime • Reduced stream flow	• Changes in zooplankton species richness and composition • Altered nutrient cycling and bioproduction rates • Water chemistry changes	Stemberger *et al.,* 1996 Chen and Folt, 1996 Porter *et al.,* 1996 Schindler *et al.,* 1996 Webster *et al.,* 1996

Climate Change as a Factor that Provokes Other Social Sectors to Act in Ways Inimical to Fish

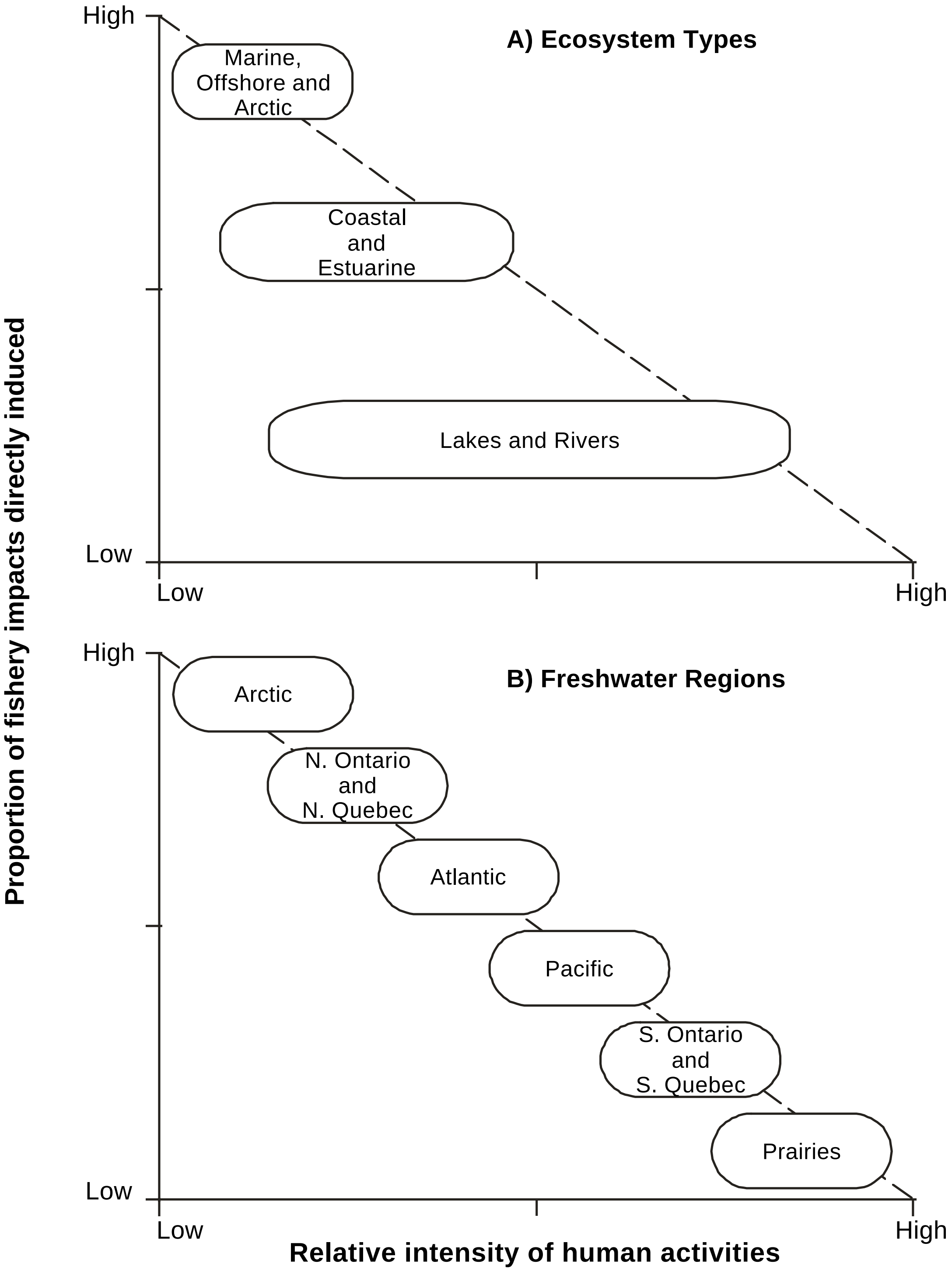
Past events have shown that human water uses, inimical to fish, often take precedence over the conservation and protection of habitat necessary to sustain natural fish production. As climate change places new pressures on other sectoral interests, fish and fisheries will face additional impacts. The immediate economic benefits of fisheries are perceived to be small compared to the advantages gained from hydroelectricity, irrigation, navigation, and water quality control (Ford and Thornton, 1991). Such conflict will be particularly acute in freshwater systems located near human population centres (e.g., Great Lakes watershed, Okanagan Valley in British Columbia) where competition for both water and habitat between humans and fish may well be intensified by climate change (Magnuson *et al.*, 1997).

In general, there will be a trade-off between the relative importance of direct and indirect impacts of climate change on fish and fisheries (Figure 5.3). Where the concentration and intensity of human activities is low, a greater proportion of impacts will be directly climate-induced. Where existing human activities are already intense, indirect impacts due to human adaptation in other sectors will likely be greater than direct impacts. This distinction is useful to recognise as indirect effects arising from human adaptive responses in other sectors can be managed and/or mitigated.

Direct climate-induced effects are not dealt with so easily. The relative importance of direct and indirect effects of climate change will vary across ecosystem types and will exhibit strong regional differences (Figure 5.3). Direct effects will dominate in offshore marine and arctic areas, while coastal and estuarine areas, plus lakes and rivers, will exhibit a greater range of indirect effects, depending on local intensities of human activity (Figure 5.3a). Freshwater systems will exhibit the greatest regional differences in the relative importance of direct and indirect effects (Figure 5.3b). On the prairies, water use for irrigation is intense and climate change is expected to reduce the water supply. Increased demand for water by the agricultural sector may well impose greater impacts on Prairie fisheries than the direct effects of climate change itself.

In North America generally, reductions in runoff will negatively impact existing hydro-electric power production, thus creating a demand for new damns (e.g. James Bay region, Churchill Falls in Labrador). The hydrological disruption caused by such projects could have very serious repercussions for both freshwater and coastal marine fisheries.

Figure 5.3 **Relative importance of direct and indirect effects of climate change for different aquatic ecosystems and different geographical regions of Canada.**



IMPACT ON FISHERIES

The relative magnitude of different aquatic ecosystems varies among regions in Canada. On an areal basis:

(i) lake ecosystems are double the size of Pacific waters within the 200 mile limit (Figure 5.1);

(ii) lake ecosystems are most prominent in central Canada and least prominent in British Columbia, Alberta, the Northwest Territories and New Brunswick (Figure 5.2);

(iii) flowing water systems (rivers and streams) are most prominent in British Columbia and the Atlantic region and least prominent on the prairies (Figure 5.2);

(iv) freshwater runoff into Arctic and Atlantic coastal waters is much greater than for Pacific waters (Figure 5.1); therefore changes in runoff driven by climate change will likely have their greatest effect in these waters.

The economic importance of different kinds of fisheries also varies considerably. Based on biomass landed, the commercial fishery dwarfs the recreational fishery (1000 k-tonnes vs. 70 k-tonnes), with the Atlantic commercial fishery double the Pacific and both much larger than the freshwater commercial fishery (Table 5.2). Therefore, climatic effects on commercial fish harvest will likely be driven by biological impacts on marine populations. However, based on economic value, the primarily freshwater recreational fishery is roughly twice as important as the commercial fishery (Table 5.4). Therefore climatic effects on the simple dollar value of Canadian fisheries will be driven by changes in both freshwater and marine populations.

Assuming that climate change will manifest itself as warmer air temperatures, drier watersheds and higher sea levels, important biological impacts are summarised regionally in Table 5.12 and the resultant impacts on fisheries are summarised in Table 5.13.

Table 5.12 Examples of biological impacts of climate change by region.

Type of Impact	Pacific	Prairies	Arctic	Ontario/Quebec	Atlantic
Change in overall fish production	Marine: • decrease in coastal regions where influence of freshwater runoff important • potential change in pattern of decadal variability associated with Aleutian low Freshwater: • decrease due to water level decrease	Freshwater: • decrease due to water level decreases	Marine and Freshwater: • potential increases due to longer warmer growing season + less ice cover means more intense nutrient recirculation from wind-generated turbulence + higher fish species diversity	Freshwater: • decrease due to water level decrease • increase in smaller lakes due to increase in both temperature and nutrient availability • no change or decrease in larger lakes as nutrient availability fails to keep pace with water temperature increase	Marine: • decrease in coastal waters where influence of freshwater runoff is important; • potential change in pattern of decadal variability associated with the North Atlantic Oscillation
Change in population-specific production	Freshwater: • increases in potential production for warm and cool water fish; decreases for cold water fish in the developed areas of the south • decreases for diadromous salmonids (particularly coho and sockeye) due to changes in seasonal flow patterns in rivers + overall reductions in river flow + contractions of marine feeding areas	• general decreases for coldwater fish, general increases for warmwater fish	• general increases for warm-, cool- and coldwater fish; potential declines for members Arctic thermal guild	• decreases for coldwater fish, particularly in streams and small monomictic lakes • increases for warm and coolwater fish particularly in smaller oligotrophic lakes	Marine: • decrease for populations whose productivity is strongly dependent on freshwater flow from St. Lawrence estuary Freshwater: • concurrent changes in abundance of many Atlantic salmon stocks depending on changes in size of wintering area in Labrador sea
Change in distribution of individuals	Marine: • increased abundance of hake off Vancouver Island in summer Freshwater: • coldwater fish: in summer, increased concentration in refuge areas (groundwater sources, higher elevation streams)	• coldwater fish: -in summer, increased concentration in refuge areas (groundwater sources, higher elevation streams)	• distributional shifts follow changes in location of ice edges and polynyas	• coldwater fish: in summer, increased concentration in refuge areas (groundwater sources, higher elevation streams)	Marine: • changes in location of members of many species populations (e.g., Atlantic cod, Arctic cod, capelin, mackerel) depending on short term shifts in annual water temperature patterns
Change in boundaries of species' distribution	Marine: • northward retraction of salmonid bounds, particularly sockeye and pink salmon + increased variability in abundance of southern populations • northward extension of bound for petrale sole Freshwater: • northward extension of bounds for warm and cool water fish BUT realization of extension limited by physical barriers in mountainous regions	Warm and coolwater fish: • extension of bounds northward may be limited or slowed by the predominance of east/west drainage patterns	• establishment of self-sustaining pacific salmon populations, particularly sockeye	Warm and coolwater fish: • extension of bounds northward	Marine: • complex shifts in locations of species distributions (e.g., Atlantic cod, Arctic cod, capelin, mackerel) arising from future behaviour of "natural" long-time scale variations in climate (e.g., North Atlantic Oscillation)

Table 5.13 Regional examples of impacts of climate change on fisheries.

Type of Impact	Pacific	Prairies	Arctic	Ontario/Quebec	Atlantic
Change in overall Sustainable harvest	Marine: • decadal pattern of variation for offshore and salmonid harvest will track variation in Aleutian low • decrease for coastal harvests dependent on freshwater runoff	• decrease likely, due to water level declines in lakes and streams	• increase for many marine and freshwater: populations	• north: increases possible • south: decreases possible, particularly if invasions by fishable species (e.g. striped bass) are prevented	Marine: • decadal pattern of variation in waters outside the Gulf of St. Lawrence may track changes in the NAO • decrease in St. Lawrence and Gulf of St. Lawrence possible due to declines in freshwater flow from the Great Lakes basin
Change in species-specific sustainable harvest	• decrease possible for diadromous salmonids, particularly sockeye and pink • increases for some marine species (e.g. hake, petrale sole); increases for warm and cool freshwater species	• decrease for cold water species; increase for warmwater species, particularly in the north	• increases for all thermal guilds	-decreases for stream dwelling salmonids, particularly in the south -increases for warmwater species, particularly in the north -decreases for endemic species of all guilds may be forced by invasions of exotics	• changes for many species possible depending on how climate change affects the complex interaction of warm and cold currents that determine thermal conditions in the region
Changes in location of "good" fishing grounds and in catchability of fish	• diadromous salmon: high sustainable harvests may be associated with more northern rivers	• coldwater species: catchability will increase in summer when individuals are concentrated in summer refuge areas	Marine: • useable fishing grounds may shift further offshore with changes in the location of highly productive areas such as ice edges and polynyas	• coldwater species: catchability will increase in summer when individuals are concentrated in summer refuge areas	• catchability will increase or decrease if new water temperature patterns tend to concentrate or disperse the individuals in a population

Table 5.14 Classification of adaptation options for Canadian fisheries (After Burton *et al.*, 1993).

Adaptation Strategy	Specific Option	Elements of Fishery Sector	Past Examples of Option	Limitations
Choose/Change:				
1. Location	Encourage fishery to track changes in location of habitat areas preferred by fish as these likely equate to changes in location of good fishing grounds	Marine offshore/ distant fishers	Expansion of Canadian fleet to exploit EEZ	Global fisheries largely overfished already; few "new resources" to develop
2. Use	Exploit previously un-used or under-used resources	Existing or new participants in sector	Expansion of shrimp and lobster harvests off E. Coast since the cod fish closure	Part of multi-species fishing up sequence, leading to exploitation lower in foodweb with increased impacts on other species
Reduce Losses:				
3. Prevent Effect	Not Possible	N/A	N/A	N/A
4. Modify Effect	Accelerate local rates of species invasions or introduction	Freshwaters especially northerly, isolated, lower diversity areas (e.g. NWT, N. Quebec)	Intentional exotics for aquaculture end up in ecosystems alongside accidentals	Careless actions will exacerbate problems
	Alter whole ecosystems with new communities, nutrients, habitat creation	Freshwaters: isolated, northerly habitats, as above; coastal marine habitats	Marine and freshwater reef creation projects widespread	Human attempts at creation of self-sustaining ecosystems has low success rate
	Reduce impacts from other agents of stress	All fisheries especially those in areas of high human population density	Efforts to reduce impacts of acid rain on freshwaters	Limited willingness of humans to change the potentially destructive ways they interact with nature
	Eliminate over-exploitation	Relevant for all fisheries	Exclude foreign vessels, fishery closures both coasts	Requires fundamental changes in the attitude of humans towards nature, in their behaviour and in the regulation of that behaviour
	Increase aquaculture as more manageable source of fish protein	Lakes and coastal marine systems	Rapid growth of industry on both coasts; interest building in freshwaters, particularly the Great Lakes	Reliance on fishmeal food may make such activities self-limiting; increased rate of exotic invasions with negative ecosystem impacts
Accept Losses:				
5. Share Loss	Compensation / insurance programs	Commercial fishing; commercialized angling	Assistance program for cod fishery workers since closure	Such actions can only provide short term mitigation, if the precipitating environmental changes are permanent
6. Bear Loss	Do nothing to save species or stocks	All ecosystems	Previous extinctions such as blue pike in Lake Erie, Great Lakes coregonids	Default outcome

ADAPTATION OPTIONS

Generic frameworks for assessing and classifying ways that humans can adapt to the effects of environmental changes have been put forward by several authors (Smit, 1993). We use the scheme developed by Burton *et al.* (1993) to organise our discussion of the options for adaptation that are appropriate for use in the fishery sector. Several options are identified for various fishery contexts. Past and present experience with such options sheds light on both their practicality and their limitations. Systemic challenges to the potential efficacy of adaptation options are discussed and the influences of geographic and social scales on evaluations of adaptation strategies are also discussed.

An Adaptation Framework for Fisheries:

Burton *et al.* (1993) present three pairs of options based on the themes of changing use, reducing losses, and accepting losses (Column 1 Table 5.14). The themes cover a spectrum from no response (accept effects of environmental change), through modification (reduce or prevent effects of environmental change), to adaptation (alter human activities directly impacted by environmental change). The fisheries adaptation options we discuss were obtained from previous adaptation reports, other climate change impact assessments and from the groups of fisheries experts consulted across Canada by the study team. In most instances, the adaptation options are modelled on actions that have already occurred in Canadian fisheries in response to other stresses and changes (Table 5.14). Such precedents include the gearing up of Canadian fleets to take advantage of the extended economic zones when they arose, and the expansion of shrimp and lobster harvests that accompanied the collapse of the cod fishery on the East Coast (Table 5.2). General efforts to prevent climate change cannot be associated specifically with fisheries, however there are ways of trying to modify the impacts of climate change on fisheries by manipulating ecosystems, and many of these manipulations have been attempted (reef creation, aquaculture, limited efforts to control other stressors, introductions, etc.). Acceptance of losses is the default option. We have already accepted the extinction of some fish species and many others are at risk. In the case of closures of larger fisheries, governments have often provided assistance programs from tax revenues, thereby sharing the loss.

Based on past experience, all of these options have limitations and can generate additional difficulties. For instance, economic compensation programs can keep people tied to failed fisheries, thus maintaining the pressure to reopen those fisheries before they have had a chance to recover.

Systemic Challenges

The adaptation framework, and its options, need to be assessed in a broader context. The framework contains implicit assumptions about the relationship between man and nature that should be examined. These assumptions can be formulated as questions: 1) Is there a consensus on the philosophical and ethical foundations of an adaptationist view? 2) Are there agreed goals and objectives for Canadian fishery resources? 3) How dependent upon assumptions about future climate "norms" are adaptation options? 4) Is there a robust "no regrets" strategy (i.e., a strategy that will have positive effects in the absence of climate change, as well as in its presence) that is broadly applicable to the fisheries sector?

1) Is there a consensus on the philosophical and ethical foundations of an "adaptationist" view?

The adaptationist approach being followed for the climate change issue is primarily oriented to human use of the biosphere and therefore conforms to a utilitarian view of nature. Debate over the “proper” relationship between humans and nature is long standing and ongoing. Traditionally, the debate was polarised between those with utilitarian views and those with aesthetic-spiritual views. The utilitarian view is based on an underlying assumption that nature is there to be exploited and modified as humans wish, for human purposes. This view is related to ideas that the human species is valued above all other species. The aesthetic-spiritual view places humans on a par with other species and, in various ways related to consciousness or religious belief, places humans in a custodial role. Since these views arise from metaphysical origins, they cannot be reconciled using logical, rational analysis. With the rise of the science of ecology and, particularly ecosystem ecology, a third view has emerged. That view recognises that, for human uses to be sustainable in the long-term, substantial, natural structural and functional features of ecosystems must be conserved and protected. This view accepts the interdependency of humans and other species, and that human uses of natural biological systems will be bounded by the need to maintain the integrity of the ecosystems that support those uses. Acceptance of this third view as a basis for an adaptation strategy would emphasise bounding the underlying human causes of climate change itself. Also, since our knowledge of ecosystems is limited, this approach mandates a precautionary approach to fisheries management in general. For example, such an approach would require that allowable yield be held below a fixed proportion of total production or that population biomass be maintained above a fixed proportion of the mean unexploited biomass.

2) Are there agreed goals and objectives for Canadian fishery resources?

Many fisheries are beset by excessive exploitation, water diversions and other causes of habitat degradation and destruction, exotic species transfers and excess chemical loadings. These problems, among others, have led to a generally depressed state in many fisheries, a state that strongly suggests present management systems are not able to effectively meet goals that include population preservation and sustainability. Without the means to effectively enforce such goals and objectives, adaptation actions consistent with the preservation of ecosystem integrity are unlikely to be effectively applied.

3) How dependent upon assumptions about future climate “norms” are the adaptation options?

Most planning for adaptation to climate change has been based on the assumption that changes will occur in a relatively slow, orderly fashion. Attention has been focused on climate means changing in a linear fashion over 50-100 years. Even these rates of change exceed the rates typically faced by animals over evolutionary time scales. However, there is growing concern that changes will occur in a more abrupt and chaotic fashion, often accompanied by changes in levels of variability. Efficacy of human adaptation options should be evaluated with this possibility in mind.

4) Is there a robust "no regrets" strategy that is broadly applicable to the fisheries sector?

Some branches of science are founded on the expectation that ever-growing inputs of information can be effectively translated into increasingly accurate predictions of the future. Given the uncertainty of occurrence for climatic events that can significantly impact aquatic ecosystems, and the uncertainty of ecosystem responses to such events, it is likely that the gains in predictive accuracy attainable from increasingly detailed "real-time" information on ecosystem status are severely limited. An alternative approach is to place increased emphasis on understanding the processes that drive ecosystem responses to both climatic and human impacts and to use that knowledge to formulate robust management practices which do not depend on the accuracy of short-term predictions. Robust management would be grounded in assessments of the long-term performance of the managed systems. Aspects of a "no regrets" approach to managing under a climate change scenario might include:

- ensuring that no practice applied for a short time will be able to produce extreme outcomes;
- reducing negative impacts of other anthropogenic stressors, such as acidification;
- maintaining exploitation rates at levels that include a safety margin based on a cumulative appreciation of historical uncertainties in stock performance (Roberts, 1997);
- initiating concerted efforts aimed at reducing capitalisation in a fishery when it becomes apparent that the capability to exploit exceeds the capacity of the population to sustain exploitation.

Scales of Assessment and an Adaptation Strategy

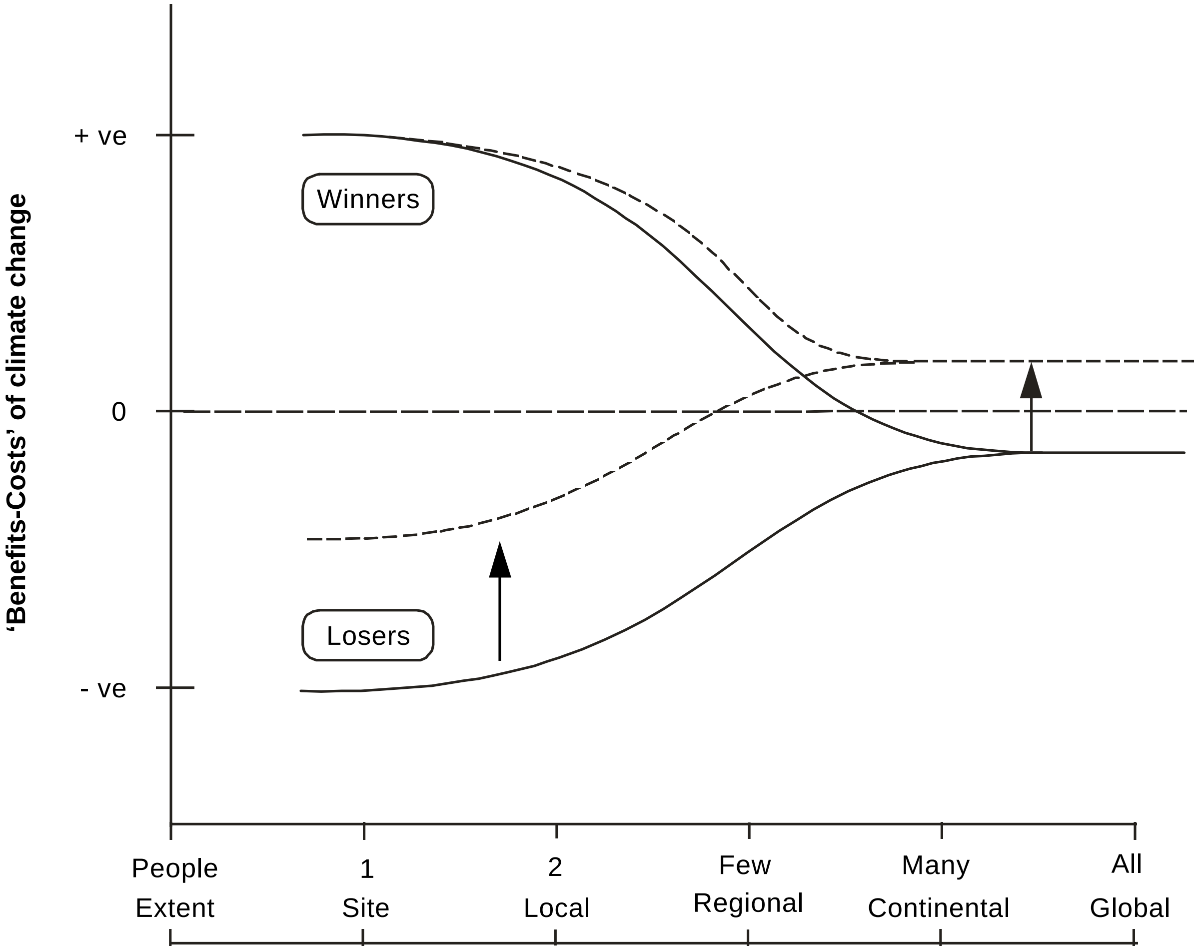
The history of people engaged in aboriginal, commercial and sport fisheries provides many examples of their resourcefulness and adaptation. Fishing methods are quickly adapted to new challenges and opportunities. As some species have declined, often as a result of overfishing, effort has been redirected to other species. Fisheries will adapt to changes in the mean and/or variability of the climate. This does not mean effects of the changes on members of the fishery sector will be neutral. The scale of assessment is important. On the local scale, involving individuals and small groups, there will be winners and losers (Figure 5.4). As assessment results are integrated over larger spatial scales and for larger groups of fishers, the extremes in both costs and benefits narrow. The hardships imposed on "losers" on the smaller scales can be ignored or forgotten if assessment stresses the "big picture". The primary objective of an adaptation strategy for fisheries should be to narrow the range of net gains and losses on smaller scales and aim for a net gain overall (Figure 5.4).

A recent series of newspaper articles about the town of Salvage, Newfoundland (Simpson, 1997a,b,c) provides an excellent example of the scale issue in adaptation. Simpson assessed the well-known collapse of the cod fishery on the East Coast which has caused tremendous hardship for many fishers and fish processors, particularly in small communities like Salvage. Single individuals negatively affected by the cod collapse, yet tied both to their communities and to large fishery-related investments, are unable to find new sources of income. Larger entities like Fishery Products International (FPI), a major fish buyer and processor, have been less affected as they have diversified by buying fish from elsewhere and upgrading plants. Hence FPI is not dependent on the state of cod stocks off Newfoundland. In the same period, other fisheries for lobster and shrimp have expanded considerably off Newfoundland (Table 5.2). The income losses of those tied to cod have been shared via government assistance programs. Simpson also pointed to the arguments that successive assistance programs have delayed a wider adaptation by the small communities to a much reduced role for fisheries in their local economies.

Whilst there are many difficulties associated with the adaptation options we have identified, the consideration of scale provides some guidance to the essential features of an effective adaptation strategy:

- As adaptation takes place on smaller scales, minimising the net losses to individuals and places must dominate whilst aiming for no net loss overall.
- Given that uncertainty is likely to increase, increased diversification and flexibility at the local level is needed.

Figure 5.4 Effects of geographic/economic scale on net gain (benefits minus costs) arising from effects of climate change on society and the role adaptation might play in mitigating the more negative outcomes.



RESEARCH GAPS AND MONITORING

Bella *et al.* (1994) identify two contrasting research frameworks, the predictive model (PM) framework and the system response (SR) framework, for generating science that is relevant to decision-making. To date, most research efforts on climate change have followed a PM framework. The PM framework generates unrealistic expectations for precision and accuracy. The resultant emphasis on uncertainty delays or inhibits preventative actions. The use of a PM framework has also caused most attention to be focused on large scale climate phenomena and earth processes, and away from local and regional impacts. The alternate SR framework places greater emphasis on improving understanding of the responses of ecological systems to climatic change through an integrated long-term program of monitoring and analysis of ecological changes that have followed historical variations in climate. The SR framework places less emphasis on prediction and more on the development of reliable ecological indicators of change. The shift in attention from climate phenomena to impacts dictates a shift from the PM framework towards a SR framework as a basis for prioritizing research and monitoring activities. This PM-SR shift is also needed with respect to setting goals and targets. To date emission control targets have been linked to estimated changes in climate phenomena, like mean temperature, and not explicitly to thresholds that will elicit specific social or ecological responses (Parry *et al.*, 1996).

The time-space horizons of everyday life prevent humans perceiving the consequences of climate change caused by anthropogenic effects and mean that humans must rely on science-based constructs of climatic change (Stehr and Storch, 1995). Most humans have no understanding of the science and consequently have difficulty devising and assessing adaptation options. In the fisheries sector, increased research is needed into both ecological and social responses to climate change. Priority areas for future research are identified below:

Knowledge Initiatives

Sentinel Programs: Long term commitment to extensive, comprehensive and continuous environmental tracking programs is an essential part of an SR framework for research. Such programs act as sentinels: they keep watch on significant ecological systems, to prevent surprise, and they track natural experiments to provide greater understanding of how these systems function. Available physical and biological time-series are too few and too short to detect recurrent patterns or to confirm long term trends in behaviour. There is a need for environmental resource and management agencies (both federal and provincial) to co-operate in establishing and sustaining long-term physical, chemical and biological monitoring programs at representative locations in all major ecosystems, freshwater and marine, across Canada. In freshwater ecosystems, the following monitoring needs exist:

- For time-series, existing sites with 10 or more years of relevant data (e.g., Dorset in central Ontario, ELA in northwestern Ontario, Project Quinte on Lake Ontario, Experimental Ponds Area in north-central Newfoundland) are valuable information resources that should be maintained; this existing network of sites should be expanded cover a wider range of geographic areas, for example, at least one Arctic site should be established.

- For regional populations of lakes, surface water temperatures, the start and end of the ice-cover season and water levels are among the easiest indicators to monitor at a reasonable cost, using remote sensing.

Comparative Studies: Because the experimental approach is difficult to apply in the study of natural ecosystems, comparative studies of similar and contrasting systems can provide valuable insights into likely responses of such systems to climate change and the processes that will determine those responses. Examples of comparative studies that would provide valuable insights into potential effects of climate change on fish include:

- Latitudinal comparisons of life history differences among populations of economically valued species, e.g. west coast salmonids, east coast gadoids, coregonids and percids in freshwaters.
- Latitudinal and altitudinal comparisons of nutrient and mixing regimes in lakes that differ both in their area, and in the size and soils characteristic of their watersheds.

Spatial Distributions of Populations and Species: It is important to increase knowledge of the relationships that link the environmental characteristics that determine habitat to the spatial distributions of fish. This will permit more accurate identification of populations, and species, that will be adversely affected by climate change and hence will require adjustments to the management protocols that regulate their exploitation.

Salmonids: Useful research initiatives, focused explicitly on salmonid species, include:

- Establishing a comprehensive, international monitoring program for salmonid populations, a World Salmon watch (Maitland *et al.*, 1981; Regier, 1992).
- Developing comparative case histories for populations distributed over the latitudinal range of a species; focus on documenting near-extinction events and differences in inter-annual variations in growth and abundance.
- Generating comprehensive, species-specific descriptions of the complex of temperature dependencies that define and control physiological rates (e.g., growth) and behavioural activities (e.g., temperature thresholds for reproduction).

Interactive Effects of Other Environmental Stressors: Effects of climate change are difficult to prevent and may exacerbate negative effects of other, controllable environmental stressors (e.g. exploitation). Hence, it is important to develop sufficient knowledge regarding the nature of these interactions to establish justifiable guidelines for regulating the activity of the controllable stressor, once the effects of climate change begin to be felt.

Ecosystem Design and Exotics: In the Arctic, climate warming may provide the opportunity to "construct" more productive and more diverse lake and stream ecosystems. In the south, existing ecosystems may be exposed to invasion by a whole new set of exotic species, as northern zoogeographic boundaries are relaxed. To avoid repetition of the many mistakes associated with exotic species introductions in the past, current efforts to understand the mechanisms determining success of introductions and the occurrence of negative impacts need to be expanded and broadened beyond the reactive responses now triggered by each new invader. Accidental introductions via routes such as shipping and bait-buckets and intentional ones, often arising from aquaculture or put-grow-take stocking, need to be assessed together. Stronger federal legislation is needed to regulate the importation and inter-provincial movements of aquatic exotics.

Ecosystem Initiatives

Marine Ecosystems: Increased understanding of the mechanisms that drive low frequency variation in marine production systems is required. The role of climate in these mechanisms, and the likely impact of climate change on such systems, should be established.

Freshwater Ecosystems: Sufficient evidence exists to show that nutrient loading from lake catchments, along with thermal and mixing regimes (horizontal and vertical) and associated nutrient recycling processes, play major roles in determining the productivity of lake ecosystems and the fisheries they support. The way freshwater fish production is controlled by these processes must be better understood in order to predict effectively the impacts of climate change on such systems and to understand how to ameliorate/take advantage of such impacts. "Our present level of understanding of lake catchment and in-lake processes remains too naive to allow us to make robust predictions or models about responses of freshwaters to climatic change. For the foreseeable future, careful monitoring of the responses of aquatic ecosystems to actual climatic variability must underpin our attempts to understand the consequences of increasing green house warming for freshwater ecosystems (Schindler *et al.*, 1996)". Similarly, increased understanding of factors determining overall fish production in rivers and streams is required.

Arctic Systems: Current understanding of the basic biology of many marine and freshwater species is minimal, as is basic understanding of arctic aquatic ecosystems (Clarke, 1993). However, large effects of climate warming on the Arctic are expected. Useful forecasts of the consequences of such changes require greater understanding of the biology of the systems that will be effected.

Estuaries: Track the position of the interface between salt and freshwater in major estuaries, such as the St. Lawrence and Fraser, as an earlier warning indicator of climate change. The salt-fresh water interface in an estuary is a major ecotonal boundary. The position of the boundary in the estuary is determined by the sea level and the discharge rate of the river. In a warmer, drier world, sea level would tend to rise and discharge would tend to fall, hence both factors would tend to drive the interface inland. Hence, the position of the interface in the river should be a sensitive indicator of climate change.

Institutional Initiatives

New Management Practices: New regulatory practices for fisheries must be developed which define management actions that are robust in the face of the highly stochastic nature of fish production systems. Such practices should explicitly take account of stochastic variation operating at various time scales, from interannual to decadal and longer. Such practices should recognize that transitions between environmental states can be rapid and that persistence of new states can be prolonged. Such practices would not rely as heavily on accurate short-term forecasts of behaviour, as current practices.

Valuing Fisheries: Comprehensive and accurate data on the size of the harvest taken by subsistence and native fisheries is required to permit comparison of these fishing sectors with the others. These sectors may be marginally important by simple economic measures, but the lives of many of their members depend on fish for food. Better ways of assessing the overall value of fisheries need to be developed that go beyond the immediate values or costs of the catch to take account of the ecosystem's capacity to sustain catches.

Upper Bounds for Sustainable Fisheries: Estimate upper limits on sustainable harvests for all Canadian fisheries based on fundamental ecosystem inputs such as light, heat, nutrients, and mixing. Tools are in place to do this (Thiebaux and Dickie, 1993). These values will provide reference points for future decision-making as climate change stresses are added to those already present (cf. Pauly and Christensen, 1995).

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CHAPTER SIX

THE IMPACT OF CLIMATE CHANGE ON CANADIAN FORESTS

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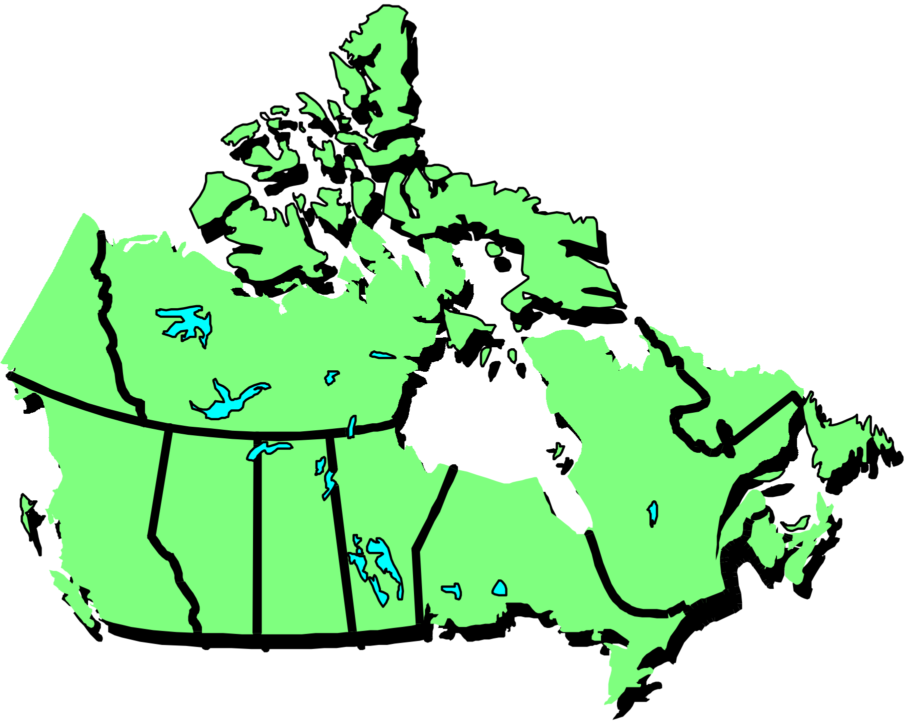

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EXECUTIVE SUMMARY

Recent studies of the Earth's climate suggest that increases in carbon dioxide and other anthropogenic gas concentrations are at least partially responsible for a warming trend that differs from the Earth's past temperature fluctuation patterns. Increases in the concentrations of these "greenhouse" gases will have impacts on Canadian forests both directly and indirectly through changes in nutrient availability, physiological processes, ecological disturbances, wildlife habitat, and the supply and demand for forest resources. Some of the anticipated impacts of climate change on the Canadian forests are as follows:

1. Canada's forests sequester significant quantities of carbon due to the slow rate of soil organic mass decomposition but the extent to which they serve as a net source or sink varies by region and over time and is influenced by natural disturbance processes such as fire and insects. Increased temperatures would increase the rate of decomposition. The extent to which that will make Canada's forest ecosystems a carbon source or sink depends upon the rate of temperature increase. This, in turn, will determine the rate of soil organic matter decomposition, and the ability of the forest ecosystems to incorporate new carbon in the production of biomass.
2. Expected climate change will lead to an increase in the occurrence of droughts in continental areas, more frequent and severe storms and wind damage in coastal areas, drought stress due to the redistribution of precipitation patterns, and an increase in both the frequency and severity of fire.
3. Increased temperatures will lead to an increase in vegetation growth rates.
4. Increased atmospheric carbon dioxide concentrations will lead to an increase in plant water use efficiency, and may increase productivity due to carbon dioxide fertilization.
5. Shifts northward (and to higher altitudes) in the current ranges of individual species and species associations are expected. Some species may become extinct at the edges of their current range. Northern expansion will be curbed by geographical and anthropogenic obstacles and lower solar radiation rates.
6. The boreal forest is expected to undergo an extensive reduction in size. Grasslands and temperate deciduous species will invade from the south and northern expansion will be hampered by poor soils and solar radiation regimes.
7. The effectiveness of wildlife habitat and reserves will be diminished by decreases in connectivity, invasions by exotic species, loss of wetlands , and the disequilibrium between biotic habitat conditions and climate.
8. The forest industry may be able to adopt new technologies and utilize different tree species and implement long range planning for the efficient location of fibre processing centres and harvesting operations that will enable it to continue under new climatic conditions. However, its ability to do so will ultimately depend on the rate, magnitude, and location of the climate change.

Authors have identified many forest-climate related research needs, most of which can be attributed to the current lack of knowledge concerning large spatial- and temporal-scale processes and their impacts. While some of the effects of such processes can be broken down into sub-processes to simplify analysis, predictions based on the analysis of such subsystems need to be related back to the process as a whole (Walters, 1986). Prominent among research needs are:

1. a standardized international climate database,
2. a better understanding of the basic biological processes within individual plants and forests,
3. regional climate models that provide regional strategic-level information, including the occurrence of extreme events (such as wind and rain storms) which significantly influence ecosystems on both regional and local scales,
4. models that merge climate and ecological processes,
5. dynamic models that describe the transition phase of climate change and their dynamic relationship to ecological processes, and
6. the inclusion of land use change into vegetation distribution models.

INTRODUCTION

This chapter reviews our current knowledge concerning the impact of climate change on Canadian forests, as part of the Canada Country Study. It builds upon Shugart *et al.* (1986) with a focus on the forests of Canada. It is a broad overview that is designed to complement the more detailed regional analyses of forestry presented in the six regional volumes (Arctic, Atlantic, Ontario, Pacific and Yukon, Prairies, and Québec) of the Canada Country Study.

Expected Climate Change

Recent increases in the atmospheric concentrations of carbon dioxide and other anthropogenic gases appear to be associated with corresponding increases in mean global temperature. Models of the Earth's climate suggest this warming trend can at least be partially attributed to these "greenhouse gases".

The world's mean temperature is known to vary due to the Earth's orbit eccentricity, tilt, and the procession of the equinox (Webb, 1992); but, human-induced atmospheric changes are also thought to be affecting global temperatures (IPCC, 1996). Long-term changes in climate can be tracked by analysing pollen-fossil records, ice core data, bore hole data, and other techniques. Deming's (1995) analysis of bore hole data revealed temperature increases of 0.8°C to 1.5°C starting as early as 1860 and as late as 1948 over various regions of Canada, and Schneider (1989) found a global increase in both the ambient temperature and the atmospheric concentration of carbon dioxide (CO_2) since the industrial revolution. Studies of tree-ring data of the world's northern boreal forests (D'Arrgio and Jacoby, 1993; Jacoby and D'Arrgio, 1989; Jacoby and D'Arrgio, 1995), ocean current temperature data (Hill, 1995), and lake water temperature (Schindler *et al.*, 1990) all show a recent global warming trend which exceeds the level that might be expected due to natural climate variability or the recovery from the Little Ice

Age - 1840 to 1880 (D'Arrgio and Jacoby, 1993; Jacoby, D'Arrgio and Davaajamts, 1996). Thomson (1995) noted that climatic phase patterns have been changing at unprecedented rates since the 1940’s, and that this change in seasons cannot be attributed solely to solar variability but corresponds with changes in the atmospheric concentrations of CO_2. Although no relationship of causality is known for past data, it is commonly accepted that CO_2 contributes to the rise in temperature by trapping heat radiated from the earth in the atmosphere (Schneider, 1989; Houghton and Woodwell, 1989). This effect is supported by several general circulation models (GCM’s) which found that trace gases concentrations in the atmosphere affected climate (e.g., Hansen *et al.*, 1988; Manabe and Wetherald, 1987). These GCM’s used to simulate the Earth's climate serve as the main tool in predicting future climate trends under varying scenarios of CO_2 concentration. A good overview of current GCM's is given in Sulzman *et al.*, (1995). Future greenhouse warming is expected to be greatest in the higher latitudes (e.g., Houghton and Woodwell, 1989; Manabe and Weatherald, 1987; Rosenzweig and Parry, 1994) and increased CO_2 is expected to lead to lower global precipitation levels (Houghton and Woodwell, 1989). Canada will experience a warmer, drier climate during the next 50 years (Sulzman *et al.*, 1995). Global mean temperature increases are forecasted to be 1°C to 3.5°C by the year 2100 (IPCC, 1996), while summer and winter mean temperatures may increase by as much as 2°C to 6°C and 8°C to 12°C respectively (Ryan, 1991). Simulations of the expected global climate under a doubling and quadrupling of current CO_2 ($2xCO_2$ and $4xCO_2$) suggest that the distribution of these changes will not be uniform. In fact, while some areas become warmer and drier, others will become cooler and wetter (Manabe and Wetherald, 1980). Some evidence suggests that an abrupt climatic change is also possible (Crowley and North, 1988). This heightens concern because a more rapid change is more likely to result in unanticipated and possibly catastrophic ecosystem changes, than a slow, gradual change (e.g., Walker, 1991; Webb, 1992; Grabherr *et al.*, 1994; World Wildlife Fund (WWF), 1994; Malcolm and Markham, 1996; IPCC, 1996).

Increased concentrations of atmospheric carbon dioxide, the most common greenhouse gas, will have impacts on Canadian forests both directly, through physiological processes, and indirectly, through ecological disturbance, habitat changes, and the supply of and demand for forest resource products.

While the “greenhouse effect” is enhanced by methane, nitrous oxide, and chlorofluorocarbons, it is the release of CO_2 from the burning of fossil fuels that is thought to contribute most to the Earth's "radiative climate forcing" (Jenkinson *et al.*, 1991). Deforestation is also thought to be a contributing factor and trends in the tropical forest alone are thought to account for 20% - 30% of the current CO_2 build-up (Dobson *et al.*,1989). Current literature predicts that the concentration of atmospheric CO_2 will increase steadily and double by the second half of the twenty-first century (Pollard, 1985; Roberts, 1988; Horgan, 1989; IPCC 1996). The increase in concentration is expected to increase global mean temperature, sea levels (Horgan, 1989; Manabe and Stouffer, 1993), influence the extent of wetlands (Horgan, 1989; Poiani and Johnson, 1991), rates of extinction (Horgan, 1989), levels and distributions of precipitation (Joyce et al., 1990), soil moisture and distribution (Manabe and Weatherald, 1987; Rind *et al.*, 1990; Neilson and Marks, 1994), and biome distribution patterns (Rizzo and Wiken, 1992; Monserud *et al.*, 1993; Neilson and Marks, 1994). In a recent project in which GCM and vegetation models were linked, large (38-53%) gains or losses of forest area were predicted (VEMAP Members, 1995).

Forests are expected to be affected greatly by changes in mean temperature and available soil moisture, although direct effects of CO_2 increases are also predicted (Musselman and Fox, 1991).

Recent ecological events may be early indicators of anthropomorphic climate warming.

Numerous events, including the Laser Ice Shelf crack, declines in glaciers, declines in the California Current zooplankton, and the increase of extreme climatic events in the United States suggest that the greenhouse effect is already affecting our environment (Gelbspan, 1995). Terrestrial ecosystems are also being influenced. For example, a recent survey of flora species at summits exceeding 3,000 m in the Alps found that species have migrated upwards along the slopes to cooler micro-sites, evidence that a warming climate trend has already influenced these alpine vegetation communities (Grabherr *et al.*, 1994).

Carbon Pools in Canadian Forests

Canadian forests constitute a significant terrestrial carbon pool.

Canada’s forests are estimated to have 12 petagrams (Pg) and 211 Pg of carbon in their vegetative and soil biomass, respectively (Dixon *et al.*, 1994). The soil and vegetation components of Canada’s temperate forest region, an area of 26.8 million hectares (ha), alone hold a carbon pool of approximately 3.9 Pg (Heath *et al.*, 1993). Hendrickson (1990) estimated that carbon storage in Canadian forests averaged 31 metric tons per hectare compared with the global average of 14.5 metric tons.

Carbon sequestering ability is influenced by several ecological and management factors.

The distribution of carbon reserves between soil and vegetation varies with forest cover type (Birdsey, 1990) and regions with cooler climates generally have more carbon stored in their forest soils (Hendrickson, 1990). Compared with young forests, the ability of older forests to sequester carbon is diminished (Hook, 1990; Kurz and Apps, 1993). A simulation of climate change showed that extra-tropical forests may experience an increased rate of carbon release due to increased soil biomass decomposition and forest dieback over a 50 to 150 year time frame, which may be as high 3 Pg per year, adding to the “greenhouse effect” (King and Neilson, 1992). Disturbances, such as harvesting and fire can be viewed as movements of carbon from one state to another, in the latter case from the biosphere to the atmosphere (Birdsey, 1990; Hendrickson, 1990; Kurz and Apps, 1993; Kohlmaier *et al.*, 1995).

Kurz *et al.* (1995) found that natural disturbance processes (i.e., fire and insects) have very significant impacts on the carbon budget of Canada’s boreal forest. They found that all Canadian forests (including the portion of the boreal forest that lies within Canada) acted as a carbon sink during the period 1920-1989, but that natural disturbance appears to have shifted it to a state when it began to function as a modest source due to fires that occurred during the 1970-1989 period.

Kurz and Apps (1995) found that the extent to which the Canadian boreal forest will act as a source or sink in the future will depend upon the joint impact of natural disturbances and forest management practices. Greenough *et al.* (1997) used the carbon budget model of the Canadian Forest Sector to illustrate how carbon flux estimates from forests are influenced by the procedures used to assess flows.

The Canadian Forest Industry

Forests have long been a part of the Canadian economy.

Forests have long played an important role in Canada’s economy and culturally they help define our social identity. Of Canada’s 417.6 million ha of forested land (42% of the total land area), 119 million ha are managed for timber extraction while another 50 million ha are protected from harvesting through legislation. Forest ecosystems support 1 in 15 jobs and over 200,000 wildlife species that are found in Canada. Canada's vast forest area has been partitioned into smaller regions by Rowe (1972) based on species associations and geographic characteristics. Because species distributions tend to be correlated with mean maximum or minimum temperature isotherms (Mikola, 1962; Root, 1988; Arris and Eagleson, 1989; Cannell *et al.*, 1989; Singh and Wheaton, 1991), Rowe’s regions are characterized by a north to south banding in eastern Canada and an altitudinal banding in the mountainous regions of western Canada.

Changes in the location and productivity of the forest resource due to climate change will influence forest management decisions.

Many of the factors used in making management decisions are likely to be influenced by global warming including appropriate ecotypes, timber harvesting, silvicultural prescriptions, and market demand. Uncertainty concerning climate change adds significant uncertainty to models used to project forest growth, timber harvest scheduling, and supply and demand analyses (Rose *et al.*, 1987).

FORESTS IN A CHANGING CLIMATE

Forest responses to climate change can be classified as either direct changes induced by increased concentrations of greenhouse gases, or indirect changes caused by the greenhouse gas-induced climate change - changes in the level and distribution of global mean temperature and precipitation (Watt, 1947). Analyses of forest responses to environmental change have been undertaken using gap-models that simulate succession-interactions in forest stands (e.g., Bray, 1956) or biogeographical models that simulate responses to nutrient and/or water cycling and availability (e.g., Neilson and Marks, 1994).

Ecological changes in the geological past have resulted in shifts of species ranges, changes in community composition, and species extinctions, and such responses can be expected under climate change. Impacts are expected to be most severe under higher rates of change (Peters, 1990). A possible synergy between climate change, habitat destruction, and slow dispersal rates may hamper expansion into new habitats and result in species extinction (Peters, 1990). Climate change also has the potential to introduce new physiological stresses and new sets of competitive interactions (Peters and Darling, 1985).

Eco-physiological

Tree Responses to Temperature and Water Availability

Changes in mean temperature and water availability influence strongly forest productivity, distribution, and health.

Tree growth is heavily influenced by climatic conditions including both temperature and water balance. A review of old acclimatization (provenance) tests in Finland showed that trees transplanted from their native region to one with a temperature profile similar to that expected under “greenhouse effect” conditions responded favourably in growth to the temperature increase, although soil nutrient limitations were still a factor (Beuker, 1994). Tree ring analysis in eastern North America showed that current and previous summer temperatures, along with precipitation, have a direct influence on the radial growth of such species as hemlock* and red spruce (Cook and Cole, 1991). Gholz (1982) found that net primary production of above ground ecosystems in the Pacific Northwest was strongly correlated with mean winter air temperature and growing season water balance. Moisture stress in high-latitude sites appeared to be a factor limiting growth increases in response to warmer weather (Jacoby and D'Arrgio, 1995). Stephenson (1990) found that a measure of the water balance better describes North American plant communities than mean temperature requirements because of the incorporation of both water and energy availability in the water balance measurement unit. In the American Appalachians and Finland, warmer winter temperatures were linked to tree dieback due to early bud break leading to bud frost damage (Johnson *et al.*,1988; Hänninen, 1991). Winter bud damage may explain why temperature variation had a greater effect on vegetation than precipitation variation when climate change impacts were simulated for forested areas.

Vegetative Response to Increased CO_2

Empirical studies of increased CO_2 *concentrations in agricultural settings showed increased biomass accumulation.*

Cure and Acock (1986) reviewed literature on the effect of doubling CO_2 concentration on crop plants (e.g., corn, wheat, sorghum). These plants increased their CO_2 exchange rate by as much as 29%. An improvement in growth was also noted, although it was limited by the availability of soil moisture and nutrients. A study of semiarid grasslands found that changes in precipitation produced more dramatic vegetation responses than changes in atmospheric CO_2 concentrations (Hunt *et al.*, 1991). Carbon dioxide fertilization was also noted in arctic environments (Oechel and Vourlitis, 1994), but in those areas in which atmospheric CO_2 is already present in sufficient concentrations for physiological processes, little impact was observed in doubling the CO_2 (Billings *et al.*, 1984).

Simulation studies of increased CO_2 concentrations showed increased ecosystem net primary production.

Lüdeke *et al.* (1995) compared vegetation responses using the Frankfurt Biosphere Model with and without CO_2 fertilization. At triple current CO_2 concentrations, a 22% decrease in net primary productivity (NPP) was noted with no fertilization vs. a 9% increase with CO_2 fertilization. The difference was attributed to autotrophic respiration and water limitation when CO_2 fertilization was omitted from the model. Melillo *et al.* (1993) used a process-based model which included the cycling of carbon to estimate NPP and soil nitrogen cycling. In response to the expected climate change of a $2xCO_2$ scenario, NPP increased between 20% and 26%. A similar initial increase in NPP was also predicted by Comins and McMurtrie (1993), although their model showed the increase dropping to less than 10% after five years of increased CO_2 levels. This drop was attributed to a constant nutrient supply level whose productivity capacity was quickly reached, leading to nutrient stress. An increase in forest NPP was attributed to increased temperature and enhanced nitrogen availability in the northern temperate ecosystems (Comins and McMurtrie, 1993).

Increased CO_2 concentrations modify plant biological processes.

Allen (1990) found that in most plants surveyed to date, CO_2 fertilization was expressed through increased photosynthetic rate (also McConnaughay *et al.*, 1993), leaf area, biomass and biomass yield, and a decrease in transpiration rate per leaf area unit (also Eamus and Jarvis, 1989; Mooney *et al.*, 1991). Increased CO_2 resulted in a decrease in stomatal aperture which decreased the intake of other airborne pollutants, increased the rate of carbon assimilation, and increased water use efficiency (Eamus and Jarvis, 1989; Allen, 1990; Idso and Idso, 1994). Where plants suffer from water or nutrient stress, increased levels of CO_2 increased photosynthetic efficiency resulting in an increase in biomass in both above and below ground systems, as well as increased nitrogen fixation and compensation for light shortage (Kienast and Luxmoore, 1988; Eamus and Jarvis, 1989; Idso and Idso, 1994). Kienast and Luxmoore (1988) found that CO_2 fertilization was more likely to occur in open forest stands with moderate climatic stress than stands under low or high stress. Recent laboratory studies indicate that increased CO_2 triggers a nutrient sequestering mechanism in the micro flora leading to nutritional limitations on plant growth. Mycorrhizal species were better able to absorb nutrients but non-mycorrhizal species suffered nutrient limitations (Diaz *et al.*, 1993). Long (1991) noted that the increase of CO_2 may in fact cause the optimum atmospheric carbon dioxide absorption temperature to rise by as much as 5°C depending on the interaction between temperature and carbon dioxide concentration. Such interactions may alter both the magnitude and direction (biomass gain or loss) of the CO_2 fertilization effect.

Increased CO_2 concentrations are predicted to increase carbon cycle amplitude.

Keeling *et al.* (1996) found changes in the annual CO_2 flux amplitude and attributed them to increased carbon dioxide assimilation by forest ecosystems. In modelling an annual carbon budget, Kurz *et al.* (1992) found that a 10% increase in biomass led to a 10% increase in carbon uptake, a 10% increase in carbon release due to disturbances and a 2% increase in the soil carbon flux. They concluded that climate change will impact soil and forest carbon sequestering dynamics and that a negative feedback may exist between CO_2 and tree growth rates.

Interactions between the carbon, nitrogen, and other nutrient cycles may reduce any possible fertilization effects.

Interactions between carbon and nitrogen cycling modelled by Luxmoore, Wullscheleger and Hanson (1993) showed no growth enhancement due to carbon fertilization. However, Pastor and Post (1988) noted a positive feedback between the two cycles, which were constrained by soil moisture and temperature. Rastetter *et al.* (1995) modelled the possible interactions of the carbon and nitrogen cycles and noted that the impact of the interaction will depend on the future vegetation structure in the long-term. Such interactions between carbon and other nutrient cycles was also deemed important by Shaver *et al.* (1992).

Potential Biome Distributions

Biome distributions are determined in part by climatic factors.

It is well recognized that biome distributions are determined mainly by climate (Neilson, 1986 and 1987). Biome distributions are determined by both the ecological requirements of species (mean temperature and nutrient and soil moisture availability) and ecological interactions between species and their environment (Pastor and Post, 1990). Suffling (1995) found that 61% of variation among forest types within the boreal forest could be explain by fire disturbance frequency alone. A high disturbance rate changes the species composition of a forest region and increases the rate of response to climatic change (Overpeck *et al.*, 1990).

Tree species and species-associations are expected to shift to areas that currently have cooler climates.

Greenhouse warming is expected to change the current location of biomes. Increased mean temperature is expected to shift the tree-limit upwards in altitude and latitude (Wheaton and Singh, 1988; Singh, 1988; Kullman, 1990; Leemans and van den Born, 1994). In their analysis of the impact of doubling CO_2 concentrations on the boreal forest of Scandinavia, Prentice, Sykes and Cramer (1991) found that the zone shifted over 1,000 km north over a period of 150 to 200 years. In a study by Franklin *et al.* (1992), the authors predicted that a 2x CO_2 scenario (i.e., +2.5°C to +5°C) is equivalent to moving current climatic conditions 500 m to 1000m up in altitude, or 200-500 km north. In a biogeographic model that included relative humidity, vapour pressure, temperature, and wind speed, Neilson (1993b) predicted vegetation distribution under various 2x CO_2 scenarios and predicted major forest dieback due to drought conditions that result when evapotranspiration rates exceed precipitation. Simulation of vegetation shifts in eastern North America under three different GCM's of doubled CO_2 show that the expected change in distribution over the ensuing 200 to 500 years is equal in magnitude to the distribution changes which occurred over the past 10,000 years (Overpeck *et al.*, 1991). Predicted shifts in forest climate zones northward (Houghton and Woodwell, 1989), along with noted expansion of the northern treeline (Lescop-Sinclair and Payette, 1995; Malcolm and Markham, 1997), are expected to result in a reduction of the tundra and subarctic biomes, and an increase and northward shift in the boreal, temperate, and grassland regions (Leniham and Neilson, 1995). However, predictions concerning the distribution of boreal and temperate forests and grasslands, vary depending on the general circulation model, vegetation bio-geographic model, and other input data (e.g., VEMAP Members, 1995). Urban *et al.* (1993) found shifts of 500 m to 1000 m in elevations for ecozones using steady-state gap models. They also noted that changes in age-structure and species composition had a strong effect on the timing of canopy replacements and whether replacement occurred on an individual or community basis. The shift in community composition will be partially driven by species which become out-competed or are unsuited for the new climatic conditions. For example, *Picea* sp. may be driven out of the boreal-broadleaf transition zone because it is unable to regenerate in warm winters (Prentice *et al.*, 1993). However, Perry *et al.* (1990) suggested that while range limits will change on the basis of individual species, species which have long been associated with one another may not migrate independently, resulting in future species associations on new sites which are similar to those on existing sites further south. Changes in tree species range may lag decades or centuries behind climate change (Brubaker, 1986; Sirois *et al.*, 1994). Simulations showed that community responses to change continued for as much as 300 years after the climate was stabilized. These changes included increases in tundra and boreal biomass and shifts in forest composition (Solomon, 1986).

The changes in population distributions will vary from species to species.

Biome vegetation communities will change as individual species respond to climate change (Kullman, 1990; Franklin *et al.*, 1992) and migrate into new areas (Neilson, 1987). Pollen records show that past biome communities were vastly different than today's, with white spruce dominating the boreal forest, *Thuja* sp. dominating the Ontario clay belt, and eastern white pine populations 140 km north of its current range limit (Liu, 1990). Plant communities themselves are in many cases, temporary assemblages of species formed by current environmental conditions and these associations will change with climate (Huntley and Webb, 1989).

The rate of climate change will affect establishment ability.

The biggest factor affecting future biome distributions appears to be the rate of future climate change (Solomon and Bartlein, 1992). However, Starfield and Chapin (1996) predicted that the conversion of the southern tundra to a forest ecosystem in Canada would take 150 years, and that whereas the rate of climate change affected when current vegetation responded, it did not affect the time required for the overall change in biome type.

Tree Species Distributions

Species distributions are responsive to climatic conditions.

Species range boundaries are often highly correlated with temperature and precipitation extremes (Davis *et al.*, 1986; Graham and Grimm, 1990; Davis and Zabinski, 1992). Studies found a correlation between the tree line in North America and exposure to different air mass types

(Larsen,1971; Scott *et al.*, 1988). As well, transplanting experiments to determine climatic dependency of seedling establishment of *Quercus* sp. found that increased summer drought stress, and spring cold stress defined upper and lower elevational range limits (Neilson and Wullstein, 1983). This correlation of plant species to climate is made use of in the climate envelope modelling technique (Morse *et al.*, 1993). Prentice *et al.* (1991) constructed a distribution model based on mean July and January temperatures and annual precipitation to predict past species ranges. Incorporating climate changes due to the Earth's orbital variation, they found that forest species are continuously responding to climate change through migration, thus adjusting their ranges to climatic conditions. Pollen records in eastern North America and Europe show that plant species have expanded their ranges to the north and west during inter-glacial periods causing some species to become extinct as others shifted (Davis, 1983). A pollen record study transecting the current treeline in Northern Québec showed that the treeline has shifted north and south in response to climatic change (Lavoie and Payette, 1996). The risk of extinction depends on the distance that regions of suitable climate are displaced northward and the rate of habitat displacement (Davis and Zabinski, 1992) and possibilities for movement/migration in the intervening landscape. Climate change is expected to affect populations at the range limits of the species most profoundly (Cannell *et al.*, 1989; Davis and Zabinski, 1992; Thomas *et al.*, 1994), with changes in nutrient availability due to increased soil decomposition allowing for the introduction of nitrogen enhancing species and new competitive relationships (Pastor and Post, 1988; Pastor and Post, 1990). In modelling species range response for eastern hemlock, yellow birch, beech and sugar maple to climate change, Davis and Zabinki (1992) found that within a few decades seedlings better suited to the new climate dominated the forest floor.

Past species migration rates have been measured through studies of fossil pollen deposits.

Most studies of past tree species distributions are based on pollen deposits in lake and stream beds. Since mature tree populations may take 100 to 200 years to respond to a significant climate change, these pollen records are incapable of recording reactions to short climatic events (<200 years duration), but they are useful in tracking long-term trends in species composition (Davis and Botkin, 1985). Gear and Huntley (1991) found that a population of *Pinus sylvestris* became extinct in northern Scotland due to climatic cooling. The species' rate of migration (375 m to 800 m per year) was shown to be too slow by an order of magnitude when compared with the rate of the climate change that had occurred. A study of boreal species at the treeline found pollen record evidence that species have responded to rapid climate change within 150 years, a period comparable to that used by current models (MacDonald *et al.*, 1993), and that when aided by wind and flat terrain, seed dispersal can occur at much faster rate (Ritchie and MacDonald, 1986). Further studies of pollen records show that taxa have migrated in the past at rates of 100 m to 1000 m per year and that migration rates are similar within taxa (Huntley and Webb, 1989). Boreal tree species have been found to have migration rates as low as 0.015°C per 10 years (WWF, 1994). Some plants may become extinct due to their extremely low rate of migration, the lack of seed propagules and increased landscape segmentation caused by human activity (Matlack, 1994).

The impact on mature trees is not likely to be noticeable until biological thresholds are surpassed, leading to dieback.

Mature forest stands showed little or no evidence of CO_2 -enhanced growth, but it was clearly evident in seedlings grown in a CO_2 -enriched greenhouse environment (Luxmoore *et al.*, 1993). Mature trees are expected to be less susceptible to climate change since they are adapted to deal with varying climate over lifetimes of decades to centuries (Frankllin *et al.*, 1992; Woods and Davis, 1989). However, increased temperature and decreased precipitation will eventually impact mature trees as physiological thresholds are reached (Davis and Zabinski, 1992) and may lead to widespread die-offs (Neilson, 1995).

Ecological Processes

Changes in temperature and precipitation are known to affect abiotic factors such as permafrost, soil chemistry, and fire disturbance regimes.

A study of past and current permafrost cover of the boreal forest in Canada showed a decrease in the overall area covered by permafrost and a northward movement of the permafrost region (Halsey *et al.*, 1995).

Soil respiration is correlated strongly with mean temperature (Raich and Schlesinger, 1992; Oechel and Vourlitis, 1994) and controls the soil carbon flux. An increase in soil temperature, which is expected under future climate change, will increase carbon and methane turnover rates and may result in a positive feedback to the “greenhouse effect” (Christensen, 1991; Raich and Schlesinger, 1992; Lloyd and Taylor, 1994). A climate resulting in a wetter tundra soil regime will increase the methane flux, while a drier regime could lead to a methane sink (Christensen, 1991).

Climate change will affect disturbance regimes (Davis and Zabinski, 1992) including fire frequency (Stocks, 1993 and Stocks *et al.*, 1996), insect outbreaks and wind storm damage (Clark, 1988; Gates, 1990; Overpeck *et al.*, 1990; Franklin *et al.*, 1992). Changes in the disturbance regimes may be substantial enough to alter or destroy current forest ecosystems (Loehle and LeBlanc, 1996). Payette *et al.* (1989) showed that fire frequency regimes in the boreal forest follow a south-north banding pattern and suggests that the ability of *Picea* sp. to regenerate after a fire sets biome boundaries. Torn and Fried (1992; also Fried and Torn, 1990) modelled wildfire occurrence under a $2xCO_2$ climate scenario and found that compared to $1xCO_2$, fire frequency, area burned and number of escaped fires increased. A simulated tripling of the annual area burned resulted in a near doubling of carbon release from the system, indicating that climate-induced changes in the disturbance regime will significantly impact the carbon balance (Kurz *et al.*, 1992).

Forest pest outbreaks are expected to increase in severity for two reasons. First, milder winters will result in increased over-winter survival leading to an increase in the spring population (Franklin *et al.*, 1992). Secondly, drought-like conditions in the past have been associated with insect outbreaks, including forest tent caterpillar, spruce budworm, and birch borer, due to a decrease in the tree's defence mechanisms due to water stress (Gates, 1990; Franklin *et al.*, 1992).

An increase in wind-throw damage is expected as climate variability becomes more extreme, leading to more frequent and severe storms (Gates, 1990). Coastal storms are also expected to increase in severity as the contrast between oceanic and continental temperatures grows (Franklin *et al.*, 1992).

THE BOREAL FOREST REGION

Boreal Forest Ecology

The boreal forest region covers approximately 75% of Canada's forested area (Winjum *et al.*, 1993) in a band stretching from the coast of Labrador to the Northern Rocky Mountains. While this paper will treat this entire area as one region, there are large and sometimes dramatic differences between the various ecozones within the region.

The boreal forest is subject to long, cold, dry winters, and short, warm, moist summers.

The boreal forest's climate is typified by short, warm, moist summers and long, cold, dry winters. More than half the precipitation occurs in summer. Annual temperature ranges are as large as 100°C (van Cleve *et al.*, 1983; Bonan and Shugart, 1989). Mean annual temperatures range from –10°C to -4.5°C in the interior Yukon, 1°C to 5.5°C in northern coastal British Columbia and –4°C to 5.5°C in the extensive boreal shield ecozone (ESWG, 1996). The northern continental plain of the boreal forest retains ground snow cover for up to eight months of the year resulting in a short growing season, in comparison with the Avalon peninsula which experiences milder, wetter weather due to the buffering effect of the Atlantic ocean (ESWG, 1996).

The region is characterized by rolling topography, interspersed with lakes and rivers, and soils high in organic material.

Landforms range from mountains with high peaks and plateaus in the west to gently rolling topography over glacial moraine and lacustrine deposits of the Precambrian shield in central and eastern Canada, to an extensive sedimentary lowland plain in the Hudson Bay Lowlands. With the exception of the mountainous area in the west, this region experiences irregular drainage supporting many small to medium-size lakes in the south and large low-laying drainage basins in north (ESWG, 1996). Soil moisture regimes can be described as wet mesic to dry, with bogs common throughout (Payette *et al.*, 1989). These low-laying areas are subject to water-logging, periodic to permanent permafrost, and the development of peat. Lowland plains north of the Precambrian shield are 25% to 50% wetlands and support organic soils. Soil types of the region include Brunisols, Black Chernozems, Humo-Ferric Podzols, and Mesisols, with Organic and Cryosols dominating in the north (ESWG, 1996). The thick moss and organic soil layer found throughout the region controls soil energy flow, nutrient cycles and keeps soil temperatures low, which inhibits organic matter decomposition (Payette *et al.*, 1989).

The boreal forest is characterized by monotypic stands that originate from large disturbances.

This forest region is characterized by large, often monotypic stands of white and black spruce, jack pine, balsam fir, and tamarack. Historically, this predominantly coniferous forest had a minor component of trembling aspen and balsam poplar (Rowe, 1972). An increase in the black spruce and tamarack species component occurs as the treeline is approached (ESWG, 1996). The southern transition zone in the west incorporates an increasing amount of trembling aspen, balsam poplar, and willow. The transition to steppe-like vegetation is made across a 2ºC mean temperature increase (Singh and Wheaton, 1991). In the east, the southern transition zone is characterized by the intermingling of temperate species as eastern white and red pine, yellow birch, sugar maple, and black ash (Rowe, 1972). The harsher climate at the northern transition zone, accompanied by lower soil temperatures, results in an open wooded lichen landscape, which slowly merges into the tundra (*Ibid*.).

The boreal forest is home to a diverse array of plant and animal species.

Representative mammal species of the boreal forest include woodland caribou, moose, marten, lynx, and black bear. The western mountainous regions also support grizzly bears, Dall's sheep, and barren-ground caribou in their foothills. Other species include mule and white-tailed deer in the continental south, elk in the northern plateaus, and walrus and seal along the northern marine coastline (ESWG, 1996). Bird species include willow, white-tailed and rock ptarmigan, spruce and blue grouse, boreal and great-horned owl, arctic, red-throated and common loon, red-tailed hawk, Steller's jay, bald eagle, peregrine falcon and osprey. As well, natural reserve areas as Wood Buffalo National Park and Yukon's Old Crow Flats along with the abundant wetlands make it an important nesting and stop-over habitat for migrating songbirds, shorebirds, and waterfowl (ESWG, 1996). Kirtland's warbler is a well studied boreal forest bird species which uses stands of jack pine as its breeding habitat. In 1989, a rapid decline in its population lead to management conservation plans in both Canada and the United States (Botkin *et al.*, 1991). Survival of caribou herds is highly related to the availability of seasonal forage. Deep, ice-crusted snow limiting accessibility to winter forage and low precipitation reducing abundance of summer forage influences herd size and productivity (Maarouf *et al.*, 1994).

Fire is a key ecological process in the boreal forest.

The establishment of boreal tree species often relies on post-fire conditions through seedbed mineral soil exposure (Payette *et al.*, 1989). Soil nutrient release and vegetation composition is governed mainly via fire (van Cleve *et al.*, 1983; Bonan and Shugart, 1989). The fire cycle increases in a northerly gradient from a 100-year cycle in the central latitudes to an estimated 9,320-year cycle near the treeline (Gagnon and Payette, 1985; Payette *et al.*, 1989). Post-fire species composition contains a greater fraction of paper birch and balsam poplar. Historical records show that these deciduous species extended their range into the tundra stepwise through long seed dispersal after each fire (Landhäusser and Wein, 1993). Payette *et al.* (1989) found that species recovery after a fire depended on the structure and composition of the forest before a fire. Post-fire vascular plant biomass at the treeline recovered to pre-fire level within 22 years (Landhäusser and Wein, 1993).

Wildlife interactions also modify the forest structure.

Grazing by species such as moose also play a role in species composition and quality. Grazing activity influences site productivity by increasing the amount of sunlight which reaches the ground and through preferential feeding on hardwoods (Wedeles and van Damme, 1995).

The northern treeline: interactions of climate and vegetation.

Tree populations at the treeline were found to be relics of populations from times with warmer climates (Elliott, 1979). In the Northern Québec treeline, wind exposure is a source of growth-stress (Payette and Gagnon, 1985) with branches below snow level developing better due to winter wind protection (Payette *et al.*, 1989). Studies in Finland found that the northern treeline separating the boreal cover type from the tundra coincides with the 10°C mean warmest month isotherm (Mikola, 1962). A study of mountain white birch at the treeline showed that bud mortality was directly related to weather and that recruitment relied on sheltered individuals as seed sources (Maillette, 1987). In the Canadian northern boreal forest, studies showed that fire plays an important role in the distribution of forest species in the vicinity of the treeline as seed germination depends upon post-fire mineral-soil exposure (Payette and Gagnon, 1985).

Socio-Economic Description

The boreal forest region is home to approximately 3.6 million people or about 15% of Canada's population. Mining and forestry are the main economic activities with local sport fishing, hunting, tourism, and ecotourism also contributing to the economy. Hydroelectric power stations support some northern communities and oil and gas exploration contributes to communities in the prairie provinces. While most communities are supported by one of the above industries, subsistence fishing, hunting, and trapping are still common in the northern ecozones. Forest industry activities are centred primarily on timber harvesting for pulp and paper production (ESWG, 1996).

The main method of timber harvesting in the boreal ecosystem is clearcutting. Operations have shifted over time from manual felling with chainsaws and cable skidders to mechanical harvesting using feller bunchers and grapple skidders. In some places, feller forwarders which carry the wood to the loading area and reduce on-site impact, are used. Recently, the transportation of wood to the mill shifted from pulp bolts and long-logs to pulp chips produced in the woods or at centralized sites located throughout the timber harvesting operations area. Large clear-cuts in some areas are being replaced by modified clearcutting methods which include careful logging techniques to preserve snags and large downed logs and bolts as well as retaining scattered whole trees to serve as seed-trees for regeneration (Sauder, 1994; Weetman, 1994). Shelterwood and selection cutting is carried out on sites of higher value (Weetman, 1994) or those in which the forest has a mixed wood rather than a monodominant structure. In response to a shift in species composition to a higher aspen fraction in areas that have been harvested in the past, companies have expanded the number of species which they will harvest and modified the products they produce by including aspen board products (Sauder, 1994). Forest management practices follow, to some extent, ecological guidelines which consider the impact of timber harvesting on other forest users. For example, attempts have been made to modify timber operations to discourage woodland caribou from abandoning areas in which harvesting has taken place (Cumming and Beange, 1993).

Nontimber uses of the boreal forest include hunting and sport fishing featuring remote lodge operations accessed by float-planes. Hunting and fishing is also carried out for sustenance and recreation. In 1993, hunting of moose, bear, and deer in Ontario contributed a total of over $CDN 300 million (1993 dollars) to the provincial economy, and created 2,289 person-years of employment (Legg, 1995). Hunting and other wildlife-related activities are important to nearby communities because these communities have a narrow breadth of economic opportunities due to their remoteness (Filion *et al.*, 1988). Commercial and sustenance hunting and trapping of small game also occurs. Non-consumptive activities include canoeing, camping, and hiking. Tourism is limited by a low level of infrastructure and service due to the vastness of the region and remoteness of specific sites, reducing potential market appeal and visitor flow (Lungren, 1995).

Ecological Climate Change

Temperature, Water and Soil Nutrients

Increased soil nutrient availability is expected as a result of increased soil decomposition.

In a gap model analysis of the boreal region, responses to climate change were driven by moisture regime changes (Bonan *et al.*, 1990). Interaction between vegetation and nutrient availability resulted in increased productivity where soil moisture was available and decreased productivity where soil moisture was limited (Pastor and Post, 1988). Experimental warming in the arctic resulted in increased availability of nitrogen as soil decomposition was increased, improving the levels of available nitrogen phosphorous in the soil and soil solution (van Cleve *et al.*, 1990). Increased temperature increased soil nitrogen mineralization and increased plant sensitivity to soil nutrient availability and lead to an increase in the abundance of deciduous species and a decrease in biodiversity (Chapin *et al.*, 1995). Such a shift in species composition will enhance nitrogen availability due to the higher content of nitrogen in the leaf litter of deciduous trees (Pastor and Post, 1990). Current studies suggest that the Canadian boreal forest acted as a carbon sink up until 1969, but there is evidence that increased fire and insect activity beginning in the 1970’s has modified its structure such that it may now be functioning as a modest carbon source. No evidence of a CO_2 fertilization effect has been noted (Apps *et al.*, 1993).

Vegetation

Soil moisture availability will control species migration and composition change.

It is thought that changes at the northern forest limit will be dependent on temperature and permafrost whereas changes in the south will be limited by soil moisture (Kauppi and Posch, 1988). On well drained soils, simulated climate change resulted in reduced soil moisture and a shift in species composition to a higher percentage of aspen and steppe-like vegetation. On poorly drained sites, increased fire severity augmented a shift to mixed forests (Emanuel *et al.*, 1985; Bonan *et al.*, 1990).

A decrease in the extent of the boreal forest and possibly increased productivity are projected.

Singh (1988) noted that the area of boreal forest in Québec is expected to decrease by as much as 20% due to climate change. Greatest growth-response sensitivity is expected to occur at the northern limits of the boreal forest (Kauppi and Posch, 1985). Wheaton and Singh (1988) observed that productivity is expected to decrease by as much as 12% in the southern limit of the boreal forest, but is expected to increase in its central region be as much as 50%. A 1ºC increase is expected to increase boreal radial growth rates by 12% to 15% and photosynthetic activity by 12.5% in the middle of the boreal range (Kokorin and Nazarov, 1995). Hartley and Marshall (in press) found that the increase in fire disturbance lead to an increase in simulated forest productivity due to the increase in the number of younger establishing stands. Plöchl and Cramer (1995) used an ecosystem model to locate tundra and taiga distributions under a 2x CO_2 scenario and suggested that both biomes will lose area due to a shifting northward. Solomon and West (1987) simulated tree dynamics in northwestern Ontario and found that dominance of spruce was slowly lost as an increasing proportion of sugar maple and white pine entered the canopy under a $2xCO_2$ scenario. A decrease in NPP was observed due to a shift into unfavourable light conditions. While no conclusive evidence of current warming was found in the productivity of northern boreal tree species (Payette *et al.*, 1989), it is expected that increased temperatures will lead to greater shrub production and lower the proportion of nonvascular plants (Chapin *et al.*, 1995). However, a study of photosynthetic activity from satellite data acquired over a 10-year period suggested, that changes in growth patterns are occurring, including an increase of 12 days in the length of the growing season north of the 45°N (Myneni *et al.*, 1997). This study also showed that a trend of increasing photosynthetic activity is occurring north of 45°N with significant increases in the forested regions of Northwest Canada, but little change in areas around the Hudson Bay. Based on pollen records, species are likely to shift northward with increased temperatures and may adapt to be more efficient at carbon accumulation (Oechel and Vourlitis, 1994). In the northern regions, species richness was lost through the loss of less abundant species and a move to species characteristic of other biomes (Chapin *et al.*, 1995).

Pests and Pathogens

Changes in the climate will also impact forest pest population dynamics.

Temperature triggers insect life cycle development including spring emergence and the rate of growth and development. In a literature review by Gilbert and Raworth (1996), over 300 species showed a linear increase of developmental rates with an increase of temperature. However, as “average daily temperatures became higher than those normally experienced” developmental rates declined. Populations of spruce budworm, the major pest in the boreal forest, are affected more by the availability of habitat than by climate fluctuations (Martinat, 1987). Faster tree growth reduces the period in which young needles are available to the pest and may result in changes in population dynamics (Fleming and Volney, 1995). A study comparing populations from Alaska and Michigan of Canadian tiger swallowtail, by Ayres and Scriber (1994), found that host quality became increasingly important with increased temperatures. Temperature increases increased the rate of larval development but host quality and population origin modified this effect.

Pests are highly adaptive and will probably be able to avoid or exploit the impacts of climate change.

Insect pathogens typically have a large population size, are highly mobile, and undergo sexual reproduction with large fecundity, all factors which help the organism adapt to climate change (Fleming and Volney, 1995).

Fire

The fire season is expected to increase in severity.

A study of the fire Seasonal Severity Rating index (SSR) by Flannigan and Van Wagner (1991) found that under a 2xCO_2 scenario, the SSR increased by 46% with the biggest increases occurring in areas currently showing a low SSR. In this study, temperature proved to be a more relevant factor than relative humidity and the daily sequence of precipitation was found to be more significant than the amount. Thus fire occurrence was strongly correlated with long sequences of dry days - less than 1.5 mm rain per day or 60% relative humidity (Flannigan and Harrington, 1988). However, Starfield and Chapin (1996) found that fire occurrence frequency was more affected by changes in vegetation than changes in climate variables. In an examination of the forest weather index (FWI) for the 2xCO_2 scenario, Bergeron and Flannigan (1995) found that the FWI decreased in the eastern boreal forest but increased in the west. A similar study in the Mackenzie Basin concurred with an increase in fire danger and found that most of this increase occurred in the months of May and June (Kadonaga, 1997). Overall, these expected changes will lead to a longer fire season with lower fuel bed moisture than currently experienced, and to a disproportionate increase in escaped fires (Stocks, 1993). Increases in the boreal fire regime would lead to increases in the amount of carbon released to the atmosphere. Kasischeke *et al.* (1995) found that a 50% increase in the area burned in the boreal forest would release an additional 27.1 to 51.9 Pg of carbon into the atmosphere.

Fire and pests will interact to make predictions of climate change impacts more difficult.

Jack pine budworms depend on the availability of jack pine flowers which develop at *circa* 20 years of age. Favourable outbreak conditions become available after a fire triggers jack pine regeneration and the creation of large stands which then become susceptible to the pest. At the same time, intensive fire protection maintains a greater fraction of the forest in the jack pine budworm susceptible age classes (Volney, 1988).

Wildlife

Replacement of dominant overstorey tree species reduces associated wildlife species habitat.

A simulation of expected climate response of several boreal and deciduous forest species in central Michigan under 2xCO_2 scenario showed a remarkably rapid decline in the jack pine basal area. The results suggested that within 90 years of the onset of climate change, jack pine basal area dropped to 25% of its original level and was replaced by trembling aspen and oak. This would effectively reduce and possibly eliminate Kirtland's warbler breeding habitat in Michigan (Botkin *et al.*, 1991).

A decrease in the abundance and quality of the wetlands in the grassland-forest transition zone is expected.

The abundant wetlands of the transition zone between prairie and forest are an important resource for the continent's waterfowl populations, especially further south in the Great Plains during dry years (Larson, 1995). Detailed hydrological studies of potential climate change impacts on a small prairie wetland (Poiani and Johnson, 1993) showed that warmer annual temperatures similar to those predicted by various climate models resulted in drier conditions irrespective of whether more or less precipitation was received on average. The net result was less open water and greater vegetative cover. The study suggested that the smaller wetlands that are disproportionately important for waterfowl (Diamond and Brace, 1991; Poiani and Johnson, 1991) are especially vulnerable to global warming. Larson (1995) obtained similar results when examining potential climate change impacts on the number of wetlands in the northern prairies. Increases in temperature that lead to a decrease in wetlands were only partially compensated for under scenarios of increased precipitation. A general conclusion was that the wetlands in the transition zone may be even more sensitive to warming than prairie potholes, perhaps because of large evapotranspirative demand of willows and other tree species that border the wetlands (Larson, 1995). Overall, the loss of wetlands at the prairie - boreal ecozone can be expected to lead to a dramatic decline in the quality and quantity of habitat for breeding and migrating birds (Poiani and Johnson, 1993; Larson, 1995) and can be expected to contribute to recent waterfowl declines observed due to agricultural encroachment and drought-related wetland loss (Bethke and Nudds, 1995).

An interdisciplinary study of past and future climate in the Mackenzie River Basin is illustrative of climate change predictions that are typical of the boreal region (Cohen, 1997). Hydrological models predicted that water levels would decline to a point which would not be offset by the projected increases in precipitation. Water levels were predicted to be even lower than the extremely low levels of 1995, especially in the important waterfowl regions of the southern parkland zone. Perhaps most seriously, the study predicted a decrease in forest productivity in the region. The decline was due to a combination of factors including a doubling of the annual area burned by 2050, massive drought-related die-offs of coniferous trees, and increased susceptibility to insect pests. Several studies of global warming in the boreal forest have likewise predicted longer fire seasons and potentially more frequent and larger fires due to more severe fire weather, changes in fire management practices, and possible forest decline or dieback (King and Neilson, 1992; Flannigan and Van Wagner, 1991; Wotton and Flannigan, 1993; Price and Rind, 1994; see section 3.3.4). Increases in forest fire activity coupled with widespread timber harvesting can be expected to lead to a transition to a landscape of younger and regenerating forests and to negative impacts on wildlife species that specialise on mature and old-growth forests such as marten, fisher, and caribou (Wedeles and Van Damme, 1995).

THE WESTERN PACIFIC FOREST REGION

Western Pacific Forest Ecology

A highly heterogeneous landscape makes it difficult to generalize climatic change predictions.

This region of colluvium and rock outcrop mountains includes intermontane valley covered by glacial moraine and some fluvial deposits. At the coast, the mountains are cut with fjords and glacial valleys over igneous and sedimentary bedrock. Brunisols and Podzols dominate with Chrenozem soils in the lower valleys supporting grassland vegetation. Unique soil and vegetation characteristics occur in the Queen Charlotte islands and parts of Vancouver island which did not experience glaciation, leading to endemic habitat conditions (ESWG, 1996). The mountainous environment is characterized by marked diurnal and seasonal cycles of high variability (Price and Haslett, 1993) making vertical temperature profiles, essential to the construction of circulation models, difficult to measure (Price and Haslett, 1993). Mean annual temperatures range between 0.5°C and 7.5ºC in the interior mountain range and between 4.5ºC to 9ºC in the coastal region (ESWG, 1996). Mean annual precipitation exceeds 1500 mm on the coast and at locations within the cordilleras, but drops to below 300 mm in the arid valley in the Rockies' rainshadow (ESWG, 1996). For this reason, special models like PRISM (Daly *et al.*, 1994) have been developed. These techniques use digital elevation models to distribute point data of elevation and precipitation over a grid of cells to allow for the estimates of precipitation at different sites on the slope.

The Western Pacific forest region encompasses Rowe's (1972) Subalpine, Montane, Coast, and Columbia forest regions.

The Subalpine forest covers the mountain uplands of Alberta and British Columbia and is a transition zone between the Boreal and the Montane forest regions. It is characterized by the presence of Engelmann spruce, alpine fir, and lodgepole pine along with the boreal species of black and white spruce, trembling aspen, and mountane species such as Douglas-firs. The Montane forest region occupies the dry interior plateau of British Columbia and other mountain valleys in the province and in Alberta. Characteristic species are the interior Douglas-fir, lodgepole pine, and trembling aspen. In river valleys, extensive grassland communities are found (Rowe, 1972). The Coast forest region is part of the Pacific Coast forest of North America and covers the southern half of the British Columbia coast and its islands. Characteristic species are western red cedar, western hemlock, Sitka spruce and coastal Douglas-fir which grow to a large size and great age (Waring and Franklin, 1979). Broadleaf trees represent a minor component of the species composition (Rowe, 1972). The Columbia forest region covers the inland "wet-belt" produced by the Rocky Mountains. It is similar to the Coast forest region but does not exhibit the same richness in species composition. Characteristic species are the western red cedar and western hemlock and associated species include the interior Douglas-fir, Engelmann spruce, and western larch.

The forest region holds large carbon pools in above-ground resources.

The remaining old growth forests contain a large pool of carbon and an age-class distribution determined by high-intensity fires (Johnson and Larson, 1991). The most important factor affecting forest composition is thought to be the effective moisture regime during the relatively dry summer of the mountainous environment (Franklin *et al.*, 1992) which is characterized by marked diurnal and seasonal cycles of high variability (Price and Haslett, 1993). Forest communities are a patchwork of species-associations dependent on soil-water availability (Kimmins and Lavender, 1992). Conversion of old-growth Douglas-fir stands to plantations results in a short-term increase of carbon dioxide sequestering which is reversed in the long-term (Oliver *et al.*, 1990).

The fire cycle is strongly affected by the moisture regime.

Investigation of the fire cycle history of Chutney National Park found that the 1928-1988 fire cycle of 60 years was not modified by the introduction of a fire suppression program or the completion of a highway, but that a wetter climate reduced it from 130 years between 1788 and 1928 (Masters, 1990).

The highly heterogeneous landscape results in a variety of available habitats and contributes to the richness of wildlife species.

Characteristic mammals include woodland caribou, moose, mountain goat, California bighorn sheep, black and grizzly bear, hoary marmot, black-tailed, mule and white-tailed deer, wolf, and otter. The marine coast experiences a large fresh water discharge from mountainous drainage basins which contributes to a rich and diverse marine life. This includes northern sea lion, northern fur and harbour seal, killer, sperm, grey, Pacific pilot, and blue whale, and several species of salmon. Along with blue grouse, Steller’s jay, and black-billed magpie, characteristic bird species to this area include black oystercatcher, California and mountain quail, tufted puffin, chestnut-backed chickadee (ESWG, 1996).

Loss of habitat due to human activities is threatening species.

The province of British Columbia has compiled lists of terrestrial wildlife species and subspecies according to their extinction danger rating. Species for which management is restricted to the assurance of available habitat are listed in the Green list, those which are managed at the population level and are not considered at risk are placed in the Yellow list, species considered threatened or vulnerable to extinction are on the Blue list, and those which are endangered are on the Red list. Nineteen percent of all species in the province were ranked in the 1993 edition of the lists. Species on the Red list include four amphibians, four reptiles, 31 birds, and 25 mammals. Among these are the leopard frog, short-horned lizard, American white pelican, peregrine falcon, sage grouse, spotted owl, sharp-tailed sparrow, southern red bat, snowshoe hare, mountain beaver, Townsend’s vole, sea otter, wood bison and Dall’s sheep. The blue list of vulnerable species includes two amphibians, five reptiles, 53 birds and 27 mammals. These include tailed frog, western yellow-bellied racer, great blue heron, trumpeter swan, southern red-backed vole, grizzly bear, woodland caribou, and Rocky Mountain bighorn sheep (Harper *et al*., 1994).

Socio-economic Description

The Western Pacific forest region is home to approximately 3.25 million people or about 13% of Canada's population. Forestry, mining, oil and gas production, tourism and fishing are significant economic activities. The coastal lowlands represent some of the richest agricultural land in the country. National and provincial parks have been established in the eastern Rocky and Columbia mountains to provide for wildlife habitat and reserves as well as tourism and recreation opportunities. The main economic activity is commercial forestry (ESWG, 1996).

This ecologically diverse and highly productive region of Canada contains approximately 9% of the total national land base but supports almost 50% of the country's softwood timber volume. About one third of the carbon released in the timber harvesting of these old-growth forests is attributed to harvesting equipment fossil fuel consumption (Smith *et al.*, 1992). Forest harvesting is carried out using partial cutting or clearcutting. Partial cutting is designed to maintain the forest's structural attributes. About 90% of the regions harvesting is done using clearcutting. Cut wood is brought to roadside staging areas by skidding or, where the slope prohibits vehicle access, by cable yarding. Site preparation activities include scarification and burning in order to expose mineral soil. Reforestation efforts concentrate on the encouragement of natural regeneration and seedling planting. Species selection for planting sites are now based on ecological suitability (Harding, 1994).

Nontimber uses of the Western Pacific forest include sport and commercial fishing, hunting, and trapping. Its heterogeneous topography and the diverse number of wildlife species it supports has resulted in a diversified international ecotourism sector based on non-consumptive activities including down-hill skiing, hiking, camping, bird watching, white water rafting/canoeing, and kayaking.

4.3. Ecological Climatic Change Impacts

4.3.1. Temperature, Water and Soil Nutrients

The evapotranspiration rate will eventually be regulated by the soil moisture availability because increased evapotranspiration due to increased temperature will lead to an increased probability of drought stress conditions (Franklin *et al.*, 1992). Increased soil temperatures will lead to greater soil decomposition, possible increases in available nutrients, and lower soil carbon sequestration (*Ibid.*).

Variations in water availability strongly influence seedling establishment. During the spring, conditions suitable for planting at low elevations occur as infrequently as five out of every ten years. Studies indicate that a fall planting would provide suitable regeneration conditions at a more reliable rate. As well, variations in available water impacted annual basal area increments suggesting that drier, warmer summers would decrease forest productivity (Spittlehouse, 1992).

Vegetation

Growth of alpine forests responded positively to CO_2 increases.

In a study of the Subalpine forest, LaMarche *et al.* (1984) found that forest growth trends were more closely associated with the trends in atmospheric CO_2 than with temperature trends. This led the authors to believe that sub-alpine forests are suffering from a CO_2 deficiency. Price and Haslett (1993), as well as Dale and Franklin (1989), found that increases in CO_2 contributed to species-dependent radial growth increases. High altitude plants have been found to use CO_2 more efficiently than low altitude plants, and a more pronounced response to increased CO_2 is expected (Körner, 1992).

Species will migrate up-slope.

Some species may migrate out to higher altitudes, but the high variability in topography may result in similar landscape-scale species composition (Kimmins and Lavender, 1992). Dale and Franklin (1989) predicted a more aggressive invasion of western hemlock and a decrease in stem density under a $2xCO_2$ scenario. A replacement of evergreen species with deciduous shrubs is also thought possible (Körner, 1992). In the Coast region, the current area of productive forest will be reduced by incursion of sage-brush steppe species. Species shifts upslope will be eased by the relative proximity of suitable climate to seed sources (Franklin *et al.*, 1992).

In refining the ZELIG model with species-specific phenological traits, Burton and Cumming (1995) found that most of the western pacific forests will increase in productivity due to the expected climate change. The exceptions were the lowland coastal forest which is expected to undergo stress due to the lack of winter chilling required to induce frost hardiness, and the interior sub-alpine forest which remains stable in productivity but is gradually replaced with vegetation of lower elevations.

Pests and Pathogens

Warmer climate will make trees more susceptible to pests and pathogens and in the Montane region. A decrease in snow-pack depth and elevation may result in winter root damage (Kimmins and Lavender, 1992). As well, warmer conditions may result in better pathogen wintering habitat/conditions and increased temperature stress on forest species, leading to increased suitability to insect and pathogenic outbreaks (Franklin *et al.*, 1992).

Fire and Wind

The most rapid change expected is in disturbance regimes (Franklin *et al.*, 1992). Increased fire intensity and frequency is expected with shorter fire cycles shifting northward to areas of high current biomass. Johnson and Larson (1991) found that the fire cycle in the Canadian Rockies increased from 50 years before 1730 to 90 years due to a cooler wetter climate after 1730. This supports predictions that a hotter drier climate would increase fire frequency and severity in the region (Kimmins and Lavender, 1992). In the Coast region, the increased contrast between the ocean and land air temperatures may lead to more intense storms and increased wind damage (Franklin *et al.,* 1992).

Wildlife

Several studies in mountainous regions of the western United States have identified threats to wildlife that apply to Canada as well. Small changes in the amount of snowfall and the timing of snow melt could have major implications for high altitude and wildlife species that depend on them (Inouye and McGuire, 1991; Galen and Stanton, 1993). As well, in mountainous regions where climate and ecosystem gradients are often marked, climate change can be expected to result in major changes in the spatial distribution of wildlife habitat. For example, MacDonald and Brown (1992) examined the impacts of a 3^{o} C temperature increase on montane mammals of the Great Basin of the southwestern United States. The isolated mountain ranges of the Basin provide the cool mesic conditions required to support a remnant boreal mammal fauna originally derived from the large major mountain ranges to the east (the Rocky mountains) and west (the Sierra Nevadas). Under warming-induced reductions in area of the montane systems due to upslope migration of ecosystems, individual mountain ranges lost anywhere from 35-96% of their boreal habitat and 9-62% of their boreal mammal species. Three of fourteen mammal species were predicted to become extinct across the entire Great Basin. In Yellowstone National Park, continuation of current warming and drying climate trends under global warming is predicted to lead to an increased frequency of larger, stand-replacing fires. This in turn would lead to a replacement of old-growth forest stands by younger tree age-classes and a reduction in habitat available for old-growth forest species such as northern twinflower, fairy slipper, pine martin, and goshawk (Romme and Turner, 1990).

The habitat of salmonoid fish in the Rocky Mountain Region is limited to those streams where the July air temperature is lower than 22ºC. Increases of 1, 2, 3, 4, or 5 degrees caused habitat losses of 16.2, 35.6, 49.8, 62, and 71% respectively. Increased warming forced populations to higher elevations and away from main river channels into headwater streams (Keleher and Rahel, 1996).

Large carnivores in the Rocky mountains include wolves, cougars, wolverines and grizzly bears. Of these species, the wolverines and grizzly bears are most vulnerable to changes in their environment due to their needs for scavenging opportunities and high quality forage in the spring and fall respectively. A limited reproductive potential and dispersal pattern further hinders the grizzly from adapting to new environmental stress (Weaver *et al.*, 1996).

THE TEMPERATE DECIDUOUS FOREST REGION

Temperate Deciduous Forest Ecology

The Temperate Deciduous forest region is characterized by gentle topography, a climate moderated by large bodies of water, and rich fertile soils.

The eastern half of this region takes in parts of the Appalachian Uplands and the Northumberland Coastal plains with uplands that are composed of hard crystalline rocks. The western half is an association of level plains and gently rolling hills over a carbonate-rich Palaeozic bedrock. Luvisols derived from sedimentary bedrock in the east and lacustrine, moraine, and estuarine deposits in the west are joined by Gleysols and Brunisols (and Podzols in the northern range) as the main soil types. The climate of the Temperate Deciduous forest region is moderated by the Atlantic Ocean in the east and the Great Lakes in the west. The mean annual temperature ranges between 3.5ºC and 8ºC. The eastern half lies within one of North America's major storm paths and experiences a more variable weather pattern. Mean annual precipitation ranges from 720 mm to 1500 mm, with the eastern half receiving more precipitation than the west.

The Temperate Deciduous forest region is comprised of Rowe's (1972) Deciduous, Great Lakes-St. Lawrence and Acadian forest regions.

The Deciduous forest region occupies a relatively small area in southern Ontario in the vicinity of Lakes Huron, Ontario, and Erie, and is a continuation of the northern deciduous forests of the United States. Characteristic species include sugar maple, beech, white elm, basswood, red ash, white oak, and butternut. Individuals representing northern range limits of tulip-tree, cucumber-tree, black gum and sassafras are found in the southern deciduous forests. Conifers are relatively few in number and scattered. The Great Lakes - St. Lawrence forest region lies along the St. Lawrence river valley and the valley of the Great Lakes. It is characterized by a relatively balanced mixture of both broadleaf and coniferous species including red and white pine, eastern hemlock, yellow birch, sugar maple, red maple, red oak and white elm. Located between the Deciduous and the Boreal forest regions it contains species representative of both. The Acadian forest region covers the greater part of the maritime provinces. Characteristic species are red spruce, balsam fir, yellow birch and sugar maple (Rowe, 1972).

Regional boundaries are correlated with temperature thresholds.

The northern limit of this forest region is correlated with the – isotherm (Arris and Eagleson, 1989). The high correlation with temperature is due to the temperature requirement of broadleaf trees for flowering, seed formation, ripening (Cannell *et al.*, 1989) and pollen tube extension (Pigot and Huntley, 1981). Seedling experiments showed a reliance on a short-day sequence accompanied by a specific temperature range to trigger bud formation (Heide, 1974). Budbreak was also found to be dependent on a cooling period followed by long days, a requirement which safe guards against frost damage (Heide, 1993). Individual species ranges, such as black cherry, are often best described in terms of evapotranspiration and growing degree days (Shao and Halpin, 1995).

Historical ranges from pollen records of species such as beech and hemlock show a spread pattern which implies the effect of seed carrying agents like jays and pigeons (Webb, 1987). These records show migration rates of 20 to 25 kilometres per century, considerably less than the 100 kilometres that would be required to accommodate a 1ºC increase in mean temperatures (Davis, 1989). Additional limitations on the establishment of Acadian taxa included local environment, fire and insect outbreak cycles, and interspecific competition (Green, 1987).

Characteristic mammals include white -tailed deer, raccoon, moose, bobcat, skunk, vole, grey and black squirrel, eastern cottontail and woodchucks. Bird species include whip-poor-will, rose-breasted grosbeak, blue heron, red-shouldered hawk, and red-headed woodpecker. Rare bird species of the area include the Carolina wren, bobwhite and green heron. Marine birds including double-crested cormorant, Atlantic puffin, thick-billed and common murre, and razorbill, all established in breeding colonies in the eastern part of this region. Along the Atlantic coast and the St. Lawrence Seaway, marine species include killer whale, northern bottlenosed whale and various seal species (ESWG, 1996).

The western section of this region, which spans the northern shores of the Great Lakes, is the most urbanized area in Canada and most of its natural forests have been removed to make way for farms, orchards, roads and cities (ESWG, 1996). Large cities and satellite centres throughout this ecological region make it essential to include sociological and economic considerations in forest management decisions. This management approach may be applied to such issues as municipal watersheds, wildlife habitats, outdoor recreation opportunities, production of wood fibre and the recycling of municipal waste.

Socioeconomic Description

The Temperate Deciduous forest region is home to approximately 16.5 million people or about 67% of the total Canadian population. In the east, forestry, agriculture, mining, and commercial fishing are the main economic activities, with recreation, ecotourism and tourism also playing a role. Service industries and manufacturing play the biggest economic role in this region, which holds almost one half of Canada’s entire population (ESWG, 1996).

Commercial timber harvesting activities are relegated almost entirely to small privately owned woodlots. Forest products include fuelwood, pallets, saw timber, pulp and board product as well as nontimber products like maple syrup and nuts. Timber harvesting is carried out mechanically using chainsaws, feller-bunchers or harvesters, and wood is moved to a road-side loading point using grapple or chain skidders or modified tractors.

Nontimber activities include trapping, small game, and hunting. Natural areas within this highly urbanized region are used for many recreational activities throughout the year. Prominent uses near urban centres include horseback riding, day camping, picnicking, cottaging, mountain biking, snowmobiling, cross-country skiing, and hiking. Forests farther from urban centres support such activities as canoeing, overnight camping, and bird watching.

Ecological Climatic Change Impacts

Temperature, Water and Soil Nutrients

In their study of hardwood species dieback in the past century (1910-1990), Auclair *et al.* (1996) found that thaw-freeze and root-freeze associated with extreme weather conditions played key roles in triggering forest dieback, and that such frost damage correlated highly with drought and heat stress dieback. The extreme weather causing such damage was strongly correlated to an increase in mean global temperature.

Vegetation

After the year 1400, dominant species in southern Ontario changed as *Fagus* was replaced first by *Quercus* and then by *Pinus strobus,* a shift reflecting a move towards warmer drier weather after the Little Ice Age (Campbell and McAndrews, 1993). LeBlanc and Foster (1992) found that an increase in temperature with no change in the mean precipitation would cause an increase in growing season respiration with no increase in photosynthesis. This in turn would lead to a decrease in radial growth and an increase of climatic stress in oaks, resulting in increased mortality in dry upland sites in the middle of the species range.

Pest and Pathogens

A recent study of paper birch linked warmer growing seasons and lower soil moisture availability to increased vulnerability to pest activity (Jones *et al.*, 1993).

Wildlife

The remaining forests of the Temperate Deciduous region are in many cases, islands of biodiversity in a landscape that is subject to numerous environmental stresses associated with development. In the geological past, when forest species were able to shift their ranges in response to climate change, they did so in the absence of modern-day barriers to movement such as roads, railways, agricultural fields, cities and suburbs. The threat of climate change strengthens calls for increased investment in reducing fragmentation and degradation of habitat and increasing functional connectivity among remaining stands (Markham, 1996; Malcolm and Markham, 1997).

Urbanization

Urbanization fragments the forest landscape (Pearce, 1993) with roads, buildings, utility right-of-ways, and other human disturbances (Dorney and Leitner, 1985). Small, isolated habitats are further stressed by larger concentrations of pollutants found near industrial sources. Species fight a losing battle for habitat with urban sprawl and industrial development which continually reduce what little forest cover remains (Riley and Mohr, 1994). While some wildlife species adopt city life, those that cannot face decreased habitat availability, lack of migration corridors, and the risk of being managed as a “nuisance” species. Vegetation species are unable to migrate at rates sufficient to outrun urbanization and face extinction unless provided with reserve networks which would provide them with suitable habitat.

POTENTIAL FOREST SECTOR IMPACTS

Impacts in the global timber market.

Sohngen *et al.* (in press) and Perez-Garcia *et al.* (in press) found that the "greenhouse effect" has the potential to increase harvest volumes and reduce prices. Perez-Garcia *et al.* (in press) compared the impact of climate change on the global forest sector where timber harvesting levels in major producing countries were confined to the previous annual allowable cut level or where this restriction was not applied. This latter scenario allowed for the exploitation of the increased productivity due to climate change and increased productivity in areas not currently exploited. They found that regardless of the GCM used and the economic scenario studied, Canada's production of sawlogs, lumber, pulpwood and plywood either increased or stayed the same, and that timber owners in Canada suffered due to lower prices. In his analysis of the global forest sector, Binkley (1988), found that coniferous pulpwood and sawlogs harvests in Canada rose an average of 27.3% and 36.5% respectively, while their market prices dropped an average of 44.5% and 19.5% respectively.

Impacts in the United States timber market.

A simulation of the American forest sector carried out by the USDA Forest Service found that while forest growth and inventory rose by as much as 24% and 35% respectively, consumption rose by only 1% to 3%. This difference was attributed to the increase in inventory of young stands not yet eligible for harvest as the full impact occurs 50 years after climate change (Joyce *et al.*, 1995), and the time required to modify the capacity and technology of processing centres to take advantage of varying species and quantities (Joyce, 1995). Mills and Haynes (1995) and Joyce *et al.* (1995) noted that an abundance of softwoods, due to the increase in inventory, will drive prices down and reduce hardwood consumption as some paper products will be made with greater proportions of softwood fibres. As well, Canadian imports were predicted to decrease to as little as 18% of the American market as the United States Pacific Northwest forests' harvestable inventory increases by the year 2040. Sohngen and Mendelsohn (in review) noted that a mild warming of (3ºC) is more economically beneficial to the U.S. timber market than a stronger warming (6ºC).

Impacts in Canada's timber market.

Changes in such factors as expected forest growth, predicted volume, reestablishment time of stands, economic, and operational operability and losses to fire and insects due to climate change will influence directly or indirectly, the annual allowable cut which determines to a large degree, the level of harvest in most of Canada's managed forests (Rothman and Herbert, 1997). Simulated productivity of the American forest showed a significant increase in the northern and high alpine forest ecosystems with the northern softwood forests increasing NPP by as much as 40% (Joyce *et al.*, 1995). Such increases may be matched or exceeded by forests laying even further north than those included in the study since the expected greenhouse effect increases with latitude. Van Kooten (1990) estimated the potential increase in the Canadian harvest level at 7.5% rather than the 3% estimated for the United States by Joyce *et al.* (1995). Binkley and van Kooten (1994) found that overall impact on the Canadian forest sector would not be significant. This was attributed to the ability of the forestry sector to adopt to whatever species does prevail during and after climate change, the ability to salvage cut dying stands, planting of cut areas with species that are better adapted to the forecasted climate, and an ability to move to locations where resources are more plentiful. As well, the level of contribution of the forestry sector to most developed countries' economies is small (Binkley and van Kooten, 1994). However, long run sustainable yield levels may be reduced due to increased losses to fire and insect outbreak. In the Mackenzie Basin project, a general decline in forest productivity was predicted due to a combination of factors including increased area burned, increased susceptibility to pests and drought related die-offs (Cohen, 1997).

Impact on Canadian welfare (overall gain to consumers and producers) depends on the domestic market's sensitivity to changes in the supply and demand levels (van Kooten and Arthur, 1989). Simple market solutions such as arbitrarily freezing timber supply levels may cause more harm than good as prices will become more volatile (Brazee and Mendelsohn, 1990). An analysis carried out by van Kooten (1990) showed that due to the Canada-U.S. Free Trade Agreement, and assuming that export levels to the U.S. are maintained, Canadian welfare can increase only if U.S. production does not increase. Forestry-dependent communities will be most affected as social factors directly and indirectly related to economics will deteriorate should forest products producers be forced to reduce employment (Beckley, 1995).

Impacts on nonconsumptive activities.

Climate change may also impact nontimber activities within the forest including downhill skiing and camping. In the southern boreal forest the downhill skiing opportunities may be wiped out entirely due to a lack of required snow cover. However, this can be mitigated with the shift to a more intensive use of man-made snow or slope relocation to higher altitudes. A warmer drier climate would expand the reliable camping season which may increase its appeal not only as a single activity but also as a "base" activity from which other recreational activities such as hiking, canoeing, and bird watching, can be organized. This would increase the economic activity in communities surrounding camping regions, but will do so at the risk of increasing environmental degradation to those locales (Wall, 1988).

SUGGESTED ADAPTATION AND MANAGEMENT STRATEGIES

Influencing Carbon Flux

Reducing GHG Emissions

Adaptation strategies could include human intervention to increase carbon sequestering (Apps and Kurz, 1991). Political commitment is needed to support strategies which include reducing urban development, moving to sustainable forest practices, and supporting studies that inventory and preserve genetic and biological resources (Ehrlich and Wilson, 1991). Clearly, policies that reduce the emissions of greenhouse gases need to be established (van Kooten *et al.*, 1992). Limitations on the use of fossil fuels (Dudley *et al.*, 1996) along with emission regulations (Horgan, 1989), would help decrease the concentration of pollutants in the atmosphere and reduce impacts on Canadian forests.

Encouraging Carbon Sequestering

Developing alternatives to fossil fuels and forest products in conjunction with the development of fuel-wood plantations on denuded lands would allow more forested area to serve as a carbon sink (Heath *et al.*, 1993). Sohngen and Mendelsohn (in press) found that the United States forests could act as a carbon sink in both the short and long run. Carbon storage in wood products can be extended by decreasing the product's rate of decay (Dewar, 1990). A shift to "forest product management" which matches species rotation with the final product and effectively maintains the carbon sequestered within the wood would allow more carbon to be sequestered in the post production state (Dewar, 1990). However, burning of fossil fuels produces a much more significant flux of carbon than could be balanced by long-term silvicultural means (Oliver *et al.*, 1990). However, in the short term, the management of forests for carbon sequestering is much more cost effective than alternatives such as introducing new efficient technology or alternative fuel sources, compared at US$6/megagramme (Mg) and US$11/Mg for silvicultural options to between US$34/Mg and US$363/Mg for the adaptation of new technology (Winjum *et al.*, 1993). Forestation of abandoned agricultural areas is a widely proposed, cheap, and effective way to curb the current carbon flux from terrestrial ecosystems (Birdsey, 1990; Hendrickson, 1990; van Kooten, 1991; van Kooten *et al.*, 1992; Dudley *et al.*, 1996). Sedjo (1989) examined the feasibility of such a project on a global scale. As well, managing forests for maximum biomass, not maximum sustained yield, and over longer rotations would increase the amount of carbon sequestered per unit area (Cooper, 1984; Hook, 1990). Finally, the use of wood as a last resource luxury item and finding ways to reduce the human demand for fuel and food, would reduce the amount of carbon released from forests due to human population demands (Oliver *et al.*, 1990). Mitigation strategies of reforestation may result in better forest management and must be considered for their long-term impacts (Sohngen and Mendelsohn, in press). It is important to note however, that researchers have paid little attention to fire control issues - namely the cost and ability of forest fire management agencies to maintain fire losses in carbon sequestration forests at levels that will sequester carbon to the extent that has been predicted.

Biodiversity and Reserve Management

Biodiversity and extinction

One of the greatest challenges in maintaining biodiversity is the we do not know what a “normal” or “functional” level of biodiversity is (Giles, 1994). Biodiversity management should centre on an ecosystem level approach since this ensures the preservation of habitats and processes (Franklin, 1992). All forest resources (including wildlife, timber extraction, tourism and biodiversity) should be managed in a holistic and integrated manner (Clark *et al.*, 1996). Recent extinction rates are thought to be 100 to 1000 times those of the pre-human era and future rates may be 10 times the current. While the number of species of an isolated ecosystem is related to its area (Wilson, 1989), its potential extinction rate is more closely related to the proportion of endemic species rather than the total number of species (Pimm *et al.*, 1995). At present, timber and wildlife management policies affect vegetation as much if not more than climate change (Starfield and Chapin, 1996), and a change in vegetation implies a change in the habitat of many species and will undermine the ecosystem's health and biodiversity (Graham and Grimm, 1990; Pimentel *et al.*, 1992). The loss or decline of one species may result in the loss of an entire food-web branch as prey-predator, pest-host relationships are broken (Paine, 1995). This is well illustrated in a 40% decline in the abundance of zooplankton eating birds which was noted after an 80% loss of the zooplankton population in the California current when a 1.4ºC mean temperature increase occurred (Hill, 1995). In general, isolated populations such as those on islands (or in an isolated reserve patch) are more vulnerable to extinction (MacArthur *et al.*, 1973). Species living in the same area interact with each other so that one species' activities greatly effects another's survival. For example, prairie dog poisoning has been linked to the near extinction of black-footed ferret (*Mustela nigripes*). Such strong relationships provide the main argument for maintaining biodiversity as the loss of a single species may cause a domino effect leading to the loss of many associated species (Miller *et al.*, 1994).

While climate change may occur over a few decades, vegetation response to these shifts can take a few centuries (Solomon, 1986). This causes a mismatch or disequilibrium between the biotic and physical aspects of a species habitat, a disequilibrium which is more pronounced under higher rates of climate change. This situation increases the threat to species extinction and a reduction in biodiversity (Malcolm and Markham, 1996). In restoring habitats which compete with anthropogenic uses, for example waterfowl breeding habitat and agriculture, efforts should be concentrated on those areas where habitat value is high and agricultural value is low making it less probable that the habitat will be encroached upon in the future (Bethke and Nudds, 1995).

While most species could and will adjust to gradual climatic change, evolutionary responses are limited if the change occurs rapidly. Climate change could affect physiological processes like respiration rates and increased energy allocation to maintaining body temperature at the cost of energy stored for migration. Indirect effects could lead to loss of food supply and accessibility of water. Loss of keystone species will lead to a cascade effect in the biological web of interactions (McAllister and Dalton, 1992).

Nature Reserves

Current reserves are often isolated areas with small populations that may experience genetic isolation. Climate change brings new physiological stress and competitive interactions which put peripheral populations, geographically localized species, and genetically impoverished populations at greater risk of extinction (Peters and Darling, 1985; Malcolm and Markham, 1997). The carrying capacity of a reserve is not related only to area size, but also to the number of different habitats it contains (Graham, 1988). Reserves are vulnerable to climate change in two ways. First, climatic change may reduce the reserve's effective habitat area due to activities in buffer zones, and secondly, climate change may cause all or part of the reserve to lose the favourable habitat-climate conditions which it was originally established to protect (Graham, 1988; Murcia, 1995). For these reasons, a landscape management approach in the design of reserves must be taken with the goal of assisting in species migration to more suitable climate (Webb, 1992; Dudley *et al.*, 1996), realigning reserve boundaries with natural topographic features, and constructing ecological right-of-ways through or around man-made structures like highways and dams (Harris and Cropper, 1992). Such an approach would utilize a network of reserves and corridors and incorporate a variety of topological and soil types (World Resource Institute, 1990) thus increasing the number of possible species associations and decreasing habitat patchiness, reducing the probability of species extinction (Graham and Grimm, 1990). For this reason, networks of reserves and corridors should be established connecting reserves to each other and to sustainably manage forests which may serve as transient or permanent habitat to some species.

Markham and Malcolm (1996) noted that "maintaining ecological complexity and ecosystem resilience are the most important factors in decreasing the impacts of climate change". They suggest that a strategy which would accomplish this goal would involve a network of reserves which incorporates habitat redundancy, low fragmentation and high connectivity, along with policies to reduce anthropogenic stresses and conserve biodiversity.

Resource Management

Silvicultural Strategies

Under the expected climatic change, forest managers will encounter shorter planting seasons, increased fire and insect activity, and increased drought-related mortality (Farnum, 1992). Farnum (1992) suggested that forest managers may be able to cope with these changes by dividing their strategies into three phases. The first includes the use of silvicultural prescriptions like thinning which may help the current growing stock deal with increased temperatures. The second considers genetic programs to locate or improve drought resistant seedlings for the next 10 years (also Horgan, 1989; Harding, 1994). The third deals with long range programs which incorporate the possible genetic and physiological needs of trees beyond the next 10 years (Farnum, 1992). As well, efforts are required to use better suited species, under-plant mixed stands, and utilize diverse species and seed sources (Ledig and Kitzmiller, 1992) to increase genetic variation, and the use of natural succession in silvicultural prescriptions (Heath *et al.*, 1993). In conjunction, the use of salvage cutting, new species utilization, and the use of reconstructed wood (Pollard, 1991) will help in increasing forest rotations. Longer rotations will increase forest roles in carbon sequestering and decrease the vulnerability of wildlife species to extinction.

Pest outbreak management decisions must take into account the increased vulnerability of water stressed trees to plant-eating insect infestations (Mattson and Haack, 1987).

Farnum (1992) suggested that staying abreast of the technology and identifying threats to the forest during greenhouse-like years could be used in prioritizing research programs to emphasize those projects which would help in dealing with the impacts of climate change.

Disturbances

Both insect outbreaks and fire frequency increase with increased drought conditions and higher than normal temperatures. Since the expected increase in carbon release due to the increase in these two disturbances and increased soil decomposition are not expected to be significantly reduced by carbon sequestering activities, a positive feedback is possible between climate change and forest disturbance regimes (Kurz *et al.*, 1995).

Fire management will likely become more intensive around concentrated high value resources and an increase in the use of prescribed fire to lower fuel load in the less valuable areas may be encouraged (Stocks, 1993). Obviously, management plans should not produce irrevocable damage to the forest's resiliency (Pollard, 1991) and protect against deforestation and degradation (Heath *et al.*, 1993).

Management Approaches

In managing, we must be aware of the amount of stress the ecosystem can absorb before it exhibits severe damage (discontinuity) and the possible synergy of interacting factors (Malcolm and Markham, 1996); these are good reasons to apply "no-regret" solutions. For example, although reforestation of abandoned agricultural land to promote carbon sequestering does not provide a long-term solution to increasing atmospheric CO_2 concentrations, it provides other benefits including additional recreational areas and merchandisable biomass (Myers, 1995) and higher forest connectivity. Ecologically sustainable management and the use of biological control will help ensure future forest ecosystem health regardless of possible climate change (Pimentel *et al.*, 1992). Adapting different strategies for different sections of a species range such as shorter rotation on the southern edge to minimize loss and intensive restocking in the centre of the range may also provide "no-regret" policies. Concentrating investment in those areas least susceptible to climate change, incorporating new species or varieties, and planning for industrial technical and operational changes which may include the relocation of mills will all reduce expected losses (or costs) due to climate change (Singh and Wheaton, 1991).

Recognizing Knowledge Limitations

Franklin *et al.* (1992) noted that "surprises will be the rule since we are unable to model all environmental variables and (their) species interactions". We know that climate change is coming but we do not know how it will impact the forest environment. For this reason, we should not be limited to one possible scenario or adaptation strategy (Pollard, 1987). We must also recognize that climate change is but one unknown in forest management (Pollard, 1991). Perhaps because of this, Kurz and Apps (1993) suggested that managers should abandon the thought of managing a steady state since it implies no change in disturbance regimes. Similarly, Franklin *et al.* (1992) believed that a philosophical shift to one of maintaining a complex ecosystem from the simplistic approach of re-establishing trees is needed. All of these proposed changes in the management theory incorporate Holling's (1973) suggestion that ecological systems should be managed based on their resilience rather than their stability. Resilience is the persistence of relationships within the ecosystem in the face of change. This approach stresses keeping future options open and assumes very little is known about the way in which the ecosystem will react to a given change.

Thus, a shift in the management approach is required, away from the concepts of stability and management for equilibrium levels, maximum allowable cut, and constant harvest yield.

RESEARCH AND KNOWLEDGE GAPS

Improving the Knowledge

A great deal of uncertainty still exists with regards to CO_2 *fertilization, carbon uptake, and interactions with other nutrients and their availability.*

Given that both climate and vegetation models rely to some extent on nutrient cycles, more research is needed into the interaction of CO_2 with other emissions, because the increase in concentration is occurring concurrently (Allen, 1990). Detailed knowledge is needed on the carbon, methane, and nitrogen cycles (Woodwell, 1987; Christensen, 1991; Bonan, 1993), and the interaction between the soil ecosystem's physical (e.g., surface albedo, temperature profile) and biological processes (e.g., nutrient cycling, decomposition) in order to improve current biological models (Dixon and Turner, 1991). These combined impacts of CO_2, soil nutrients and climate on the forest ecosystem are not well known (Oechel, 1990). A better understanding of the interaction between plant demography, physiology, and ecological conditions such as species competition, gene pools, site succession variance and host-pathogen interaction on the carbon cycle and sequestering potential is also needed (McGraw and Fetcher, 1992; Heath *et al.*, 1993). Improved knowledge of the relationship between climate and tree growth is also needed (van Kooten, 1991) in order to better predict physiological climate thresholds for mature trees (Dobson *et al.*, 1989; Peine and Martinka, 1992). An increase in long-term studies (longer than one or three growing seasons) would help in the prediction of long-term impacts such as the acclimation of photosynthesis to higher temperatures (Eamus and Jarvis, 1989).

As well, a better understanding of the controls of flora and fauna migration rates is needed (Oechel, 1990). A better understanding of population biology including ecosystem processes of recruitment, establishment, growth, mortality, fire and pest disturbances, and wildlife is required (Neilson and Running, 1996). Difficulties in assessing the impact of climate change on flora and fauna include insufficient knowledge about species distributions and an accurate measure of the relative importance of species to ecosystem health (Pimentel *et al.*, 1992). Also, more information is needed on the impact of climate change on habitat quality, including the impact on wetlands (Poiani and Johnson, 1993), and its interaction with species composition (Oechel, 1990). A more detailed look should also be taken at the impact of forest removal on climate change (Woodwell, 1987; Dobson *et al.*, 1989). Finally, a better understanding is needed of the interactions of air pollution and nutrient cycling with non-climatic factors such as global population growth and distribution (Heath *et al.*, 1993). All of these gaps point to a lack of understanding of the causal effects of climate change (Parry *et al.*, 1996). Particularly severe are the knowledge gaps resulting from a lack of interdisciplinary and inter-regional research as well as the lack of methodology to extrapolate site-specific data to the regional level and vice versa (Graham *et al.*, 1990).

Improving Data Collection and Sharing

Some of these research gaps can be filled by increased monitoring efforts. Monitoring of meteorological phenomena should become systematic on a global scale (Woodwell, 1987) and include the collection of parameters on different spatial scales as well as vertical profiles (Dobson *et al.*, 1989; Lawford and Cohen, 1991). Data is greatly lacking in the troposphere (Michaels and Knappenberger, 1996). Biological monitoring should include species composition, the rate and location of deforestation (Woodwell, 1987), and improved measurements of hydrological interactions (Lawford and Cohen, 1991). Monitoring of climate sensitive areas (e.g., northern and alpine tree-lines) and processes (e.g., fire cycle, seedling establishment, and storm intensity) will provide much needed data on ecological response (Graham *et al.*, 1990). Improved data on forest biomass growth, mortality, and disturbance would contribute to better vegetation and carbon sequestering models (Heath *et al.*, 1993). Monitoring ecosystems already under stress will help define physiological thresholds for water availability, temperature, and their interactions (Davis and Zabinski, 1992). Observations of ecozones where changes will be encountered first (Heath *et al.*, 1993) and of ongoing vegetation changes can be used to monitor the progress of climate change (Körner, 1992).

In order for climate change research to be effective it must be: (1) carried out in a manner which is flexible enough to assist and encourage interdisciplinary study (Dobson *et al.*, 1989), and (2) incorporated into a policy framework which allows unified implementation of globally and regionally defined solutions (Woodwell, 1989; Oechel, 1990).

Improving Current Models

Most predictions concerning climate change come from the incorporation of current knowledge into models of climate or vegetation changes. Current GCMs are not designed for use at regional levels since they ignore local processes and geography (Sulzman *et al.*, 1995). These require increased resolution to improve predictive capabilities concerning regional and seasonal scales and extreme events (Markham, 1996).

The majority of current vegetation models employ climate response functions which implicitly assume that tree species will occur wherever suitable habitat is present, and that suitable habitat is defined solely by climate (Loehle and LeBlanc, 1996). These models can be improved by increasing their scope and the number of key processes they include. Improved interaction of climatic and biological models can be accomplished (Heath, 1993) by establishing links through biochemical processes to better simulate carbon and nitrogen cycling (Bonan, 1993). Work towards this goal includes that of Alcamo *et al.* (1994a and 1994b) and the prediction of vegetation types by linked models by Neilson (1995). The lack of such detailed interactions is noted by Claussen (1994), among others, as a result of comparing independent and integrated runs of vegetation (BIOME) and climate (ECHAM) prediction models. A next step would be to incorporate disturbances and their interactions with both vegetation and climate (Overpeck *et al.*, 1990). Because an increase in natural disturbances is widely accepted as the first sign of climate change, this is an important model improvement (Joyce *et al.*, 1990). One way of integrating climate and vegetation models, which would improve both, is through the inclusion of water balance modules (Stephenson, 1990). Along with vegetation changes, models should incorporate wildlife population processes and the magnitude of habitat/climate disequilibria (Malcolm and Markham, 1996). In order for such improvements to be made, knowledge gaps identified in the literature must be filled. As well, models which include non-climatic factors are required in the assessment of the role which climate change will play in affecting future forest management practices (Zuidema *et al*., 1994). Models of ecozones and their responses to climate change are needed, as these would provide better insight into the transition phase which may already be upon us, as opposed to an equilibrium condition which may never come (Neilson, 1993a).

CONCLUSIONS

Climate change is an important factor to be considered in current and future forest management in Canada.

Canadian forest management is currently undergoing a shift from an emphasis on timber production towards the management of ecosystems. In recent years, provinces have developed strategies to increase the amount of protected areas and have introduced, through their forest ministries/departments or professional organizations, codes of forestry practice and new forest management legislation emphasizing resource sustainability and biodiversity. The industry has gone through several softwood lumber disputes with the United States and now faces increased competition in the global market from tropical plantations (Rothman and Herbert, 1997; Sohngen *et al.*, in press). Climate change is prominent in the background of such social, political, and economical changes.

What we don’t know may hurt us.

"Among environmental problems ahead, the most important ones could be those that are still unknown to us", and research efforts should concentrate on increasing our knowledge rather than investigating details of the current knowledge (Myers, 1995). Climate change represents another stress on Canada’s forest ecosystems. Although it may appear to be insignificant today, it has the potential to enormously influence the future health of Canada’s forested ecosystems.

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APPENDIX 6A - COMMON AND SCIENTIFIC NAMES FOR THE SPECIES REFFERED TO IN THE TEXT

Plants

Sorghum	*Sorghum bicolor* (L.) Moench	*Panicoideae*
Corn	*Zea mays* L.	*Panicoideae*
Wheat	*Triticum aestirum* L.	*Pooideae*
Northern twinflower	*Linneea borealis*	*Caprifoliaceae*
Fairy slipper	*Calypso bulbosa*	*Orchicaceae*
Red maple	*Acer rubrum* L.	*Aceraceae*
Sugar maple	*Acer sacharum* Marsh.	*Aceraceae*
Yellow birch	*Betula alleghaniensis* Briton	*Betulaceae*
Mountain white birch	*Betula cordifolia* Regel.	*Betulaceae*
Paper birch	*Betula papyrifera* Marsh.	*Betulaceae*
Cedar(s)	*Thuja* sp.	*Cupressaceae*
Western red cedar	*Thuja plicata* Donn	*Cupressaceae*
Beech	*Fagus grandifolia* Ehrh.	*Fagaceae*
White oak	*Quercus alba* L.	*Fagaceae*
Red oak	*Quercus rubra* L.	*Fagaceae*
Butternut	*Juglans cinerea* L.	*Juglandaceae*
Sassafras	*Sassafras albidum* (Nutt.) Nees	*Lauraceae*
Tulip-tree	*Liriodendron tulipifera* L.	*Magnoliaceae*
Cucumber-tree	*Magnolia acuminata* L.	*Magnoliaceae*
Black gum	*Nyssa sylvatica* Marsh.	*Nyssaceae*
Black ash	*Fraxinus nigra* Marsh.	*Oleaceae*
Red ash	*Fraxinus pennsylvanica* Marsh.	*Oleaceae*
Balsam fir	*Abies balsamea* (L.) Mill.	*Pinaceae*
Alpine fir	*Abies lasiocarpa* (Hook.) Nutt.	*Pinaceae*
Tamarack	*Larix decidua* L.	*Pinaceae*
Western larch	*Larix occidentalis* Nutt.	*Pinaceae*
Engelmann spruce	*Picea engelmannii* Parry	*Pinaceae*
White spruce	*Picea glauca* (Moench.) Voss.	*Pinaceae*
Black spruce	*Picea mariana* (Mill.) B.S.P.	*Pinaceae*
Red spruce	*Picea rubens* Sarg.	*Pinaceae*
Sitka spruce	*Picea sitchensis* (Bong.) Carr.	*Pinaceae*
Jack pine	*Pinus bankisiana* Lamb.	*Pinaceae*
Lodgepole pine	*Pinus contorta* Dougl.	*Pinaceae*
Red pine	*Pinus resinosa* Ait.	*Pinaceae*
Eastern white pine	*Pinus strobus* L.	*Pinaceae*
Scots pine	*Pinus sylvestris* L.	*Pinaceae*
Douglas-fir	*Pseudotsuga* Carr.	*Pinaceae*

Interior Douglas-fir	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco.	*Pinaceae*
Coast Douglas-fir	*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco	*Pinaceae*
Eastern hemlock	*Tsuga canadensis* (L.) Carr.	*Pinaceae*
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.	*Pinaceae*
Black cherry	*Prunus serotina* Ehrh.	*Rosaceae*
Poplar(s)	*Populous* sp.	*Salicaceae*
Balsam poplar	*Populous balsamifera* L.	*Salicaceae*
Trembling aspen	*Populous tremuloides* Michx.	*Salicaceae*
Willow(s)	*Salix* sp.	*Salicaceae*
White elm	*Ulmus americana* L.	*Ulmaceae*
Basswood	*Tilia americana* L.	*Tiliaceae*

Insects

Coleoptera

(Bronze) birch borer	*Agrillus anxius* Gory	*Buprestidae*
White pine cone beetle	*Conophthorus coniperda* Schwarz	*Scolytidae*
White pine weevil	*Pissodes strobi* Peck	*Curculimidae*

Lepidoptera

Forest tent caterpillar	*Malacosoma disstria* Nort.	*Lasiocampidae*
Canadian tiger swallowtail	*Papilio canadensis* R. and J.	*Papilionidae*
Spruce budworm	*Choristoneura fumiferana* Clem.	*Tortricidae*
Jack pine budworm	*Choristoneura pinus* Freeman	*Tortricidae*

Amphibians and Reptiles

Tailed frog	*Ascaphus truei*	*Ascaphidae*
Leopard frog	*Rana pipiens*	*Ranidae*
Short-horned lizard	*Phrynosoma douglassi*	*Iguanidae*
Western yellow-bellied racer	*Coluber constrictor mormon*	*Colubridae*

Birds

Anseriformes

Canadian Goose	*Branta canadensis*	*Anatidae*
Trumpeter swan	*Cygnus buccinator*	*Anatidae*

Caprimulgiformes

Whip-poor-will	*Caprimulgus vociferus*	*Caprimulgidae*

Charadriiformes

Razorbill	*Alca torda*	*Alcidea*
Atlantic puffin	*Fratercula arctica*	*Alcidea*

Tufted puffin	*Fratercula cirrhata*	*Alcidea*
Thick-billed murre	*Uria lomvia*	*Alcidea*
Common murre	*Uria aalge*	*Alcidea*
Black oystercatcher	*Haematopus bachmani*	*Haematopodidae*
Ciconiiformes		
Great blue heron	*Ardea herodias*	*Ardeidae*
Green heron	*Butorides virescens*	*Ardeidae*
Blue heron	*Egretta caerulea*	*Ardeidae*
Falconiformes		
Red-tailed hawk	*Buteo jamaicensis*	*Accipitridae*
Red-shouldered hawk	*Buteo lineatus*	*Accipitridae*
Bald eagle	*Haliaeetus leucocephalus*	*Accipitridae*
Osprey	*Pandion haliaetus*	*Accipitridae*
Peregrine falcon	*Falco peregrinus*	*Falconinae*
Goshawk	*Accipiter gentilis*	*Accipitridae*
Galliformes		
Ruffed grouse	*Bonasa umbellus*	*Phasianidae*
California quail	*Callipela californica*	*Phasianidae*
Sage grouse	*Centocercus urophasianus*	*Phasianidae*
Bobwhite	*Colinus virginianus*	*Phasianidae*
Spruce grouse	*Dendragapus canadensis*	*Phasianidae*
Blue grouse	*Dendragapus obscurus*	*Phasianidae*
Willow ptarmigan	*Lagopus lagopus*	*Phasianidae*
White-tailed ptarmigan	*Lagopus leucurus*	*Phasianidae*
Rock ptarmigan	*Lagopus mutus*	*Phasianidae*
Mountain quail	*Oreortyx pictus*	*Phasianidae*
Gaviiformes		
Arctic loon	*Gavia arctica*	*Gaviidae*
Common loon	*Gavia immer*	*Gaviidae*
Red-throated loon	*Gavia stellata*	*Gaviidae*
Passeriformes		
Steller’s jay	*Cyanocitta stelleri*	*Corvidae*
Black-billed magpie	*Pica Pica*	*Corvidae*
Sharp-tailed sparrow	*Ammodramus caudacutus*	*Emberizidae*
Kirtland's warbler	*Dendroica kirtlandii*	*Emberizidae*
Rose-breasted grosbeak	*Pheucticus ludovicianus*	*Emberizidae*
Chestnut-backed chickadee	*Parus rufescens*	*Paridae*
Carolina wren	*Thryothorus ludovicianus*	*Toroglodytidae*

Pelecaniformes		
American white pelican	*Pelecanus erythrorhynchos*	*Pelecanidae*
Double-crested cormorant	*Phalacrocorax auritus*	*Phalacrocoracidae*
Piciformes		
Red-headed woodpecker	*Melanerpes erythrocephalus*	*Picidae*
Strigiformes		
Boreal owl	*Aegolius funereus*	*Strigidae*
Great-horned owl	*Bubo virginianus*	*Strigidae*
Spotted owl	*Strix occidentalis*	*Strigidae*
Mammals		
Carnivora		
Wolf	*Canis lupus*	*Canidae*
Cougar	*Felis concolor*	*Felidae*
Lynx	*Lynx lynx*	*Felidae*
Bobcat	*Lynx rufus*	*Felidae*
Sea otter	*Enhydra lutris*	*Mustelidae*
Wolverine	*Gulo gulo*	*Mustelidae*
River otter	*Lutra canadensis*	*Mustelidae*
(American) Marten	*Martes americana*	*Mustelidae*
Pine marten	*Martes americana abietinodies*	*Mustelidae*
Fisher	*Martes pennanti*	*Mustelidae*
Skunk	*Mephitis mephitis*	*Mustelidae*
Black-footed ferret	*Mustela nigripes*	*Mustelidae*
Raccoon	*Procyon lotor*	*Procyonidae*
Grizzly bear	*Ursus arctos*	*Ursidae*
Black bear	*Urus americanus*	*Ursidae*
Chiroptera		
Southern red bat	*Lasiurus borealis*	*Vespertilionidae*
Lagomorpha		
Snowshoe hare	*Lepus americanus*	*Leopridae*
Eastern cottontail	*Sylvilagus floridanus*	*Leopridae*
Rodentia		
Mountain beaver	*Alpodontia rufa*	*Aplodontidae*
Voles	Fam. *Muridae*	*Muridae*
Townsend’s vole	*Microtus townsedni*	*Muridae*
Southern red-backed vole	*Clethrionomys gapperi*	*Muridae*
Prairie dog	*Cynomys* spp.	*Sciuridae*

Hoary marmot	*Marmota caligata*	*Sciuridae*
Woodchuck	*Marmota monax*	*Sciuridae*
Grey / Black squirrel	*Sciurus carolinesis*	*Sciuridae*
Artiodactyla		
Wood bison	*Bison bison athabascae*	*Bovidae*
Mountain goat	*Oreamnos amricanus*	*Bovidae*
California bighorn sheep	*Ovis canandensis californiana*	*Bovidae*
Rocky Mountain bighorn sheep	*Ovis canandensis canadensis*	*Bovidae*
Dall’s sheep	*Ovis dalli*	*Bovidae*
Moose	*Alces alces*	*Cervidae*
Elk / Wapiti	*Cervus elaphus canadensis*	*Cervidae*
Mule / Black-tailed deer	*Odocoileus hemionus*	*Cervidae*
White-tailed deer	*Odocoileus virginianus*	*Cervidae*
Caribou / Reindeer	*Rangifer taradus*	*Cervidae*
Woodland caribou	*Rangifer tarandus caribou*	*Cervidae*
Barren-ground caribou	*Rangifer tarandus groenlandicus*	*Cervidae*
Pinnipedia		
Seal(s)	Ord. *Pinnipedia*	*Pinnipedia*
Walrus	*Odobenus rosmarus*	*Odobenidae*
Northern sea lion	*Eumetopias jubata*	*Otariidae*
Northern fur seal	*Callorhinus ursinus*	*Otariidae*
Harbour seal	*Phoca vitulina*	*Phocidae*
Cetacea		
Blue whale	*Balaenoptera musculus*	*Balaenopteridae*
Pacific pilot whale	*Globicephala macrorhyncha*	*Delphinidae*
Killer whale	*Orcinus orca*	*Delphinidae*
Gray whale	*Eschrichtius robustus*	*Eschrichtidae*
Sperm whale	*Physeter catodon*	*Physeteridae*
Northern bottlenosed whale	*Hyperoodon amapullatus*	*Ziphiidae*
Primates		
Man / Human	*Homo sapiens*	*Hominidae*

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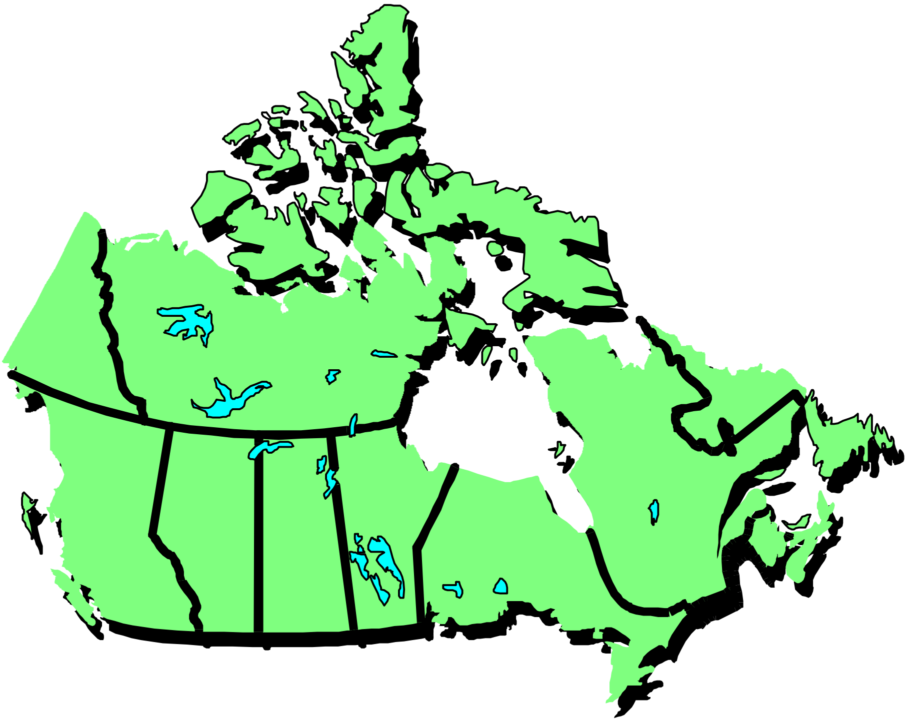
CHAPTER SEVEN

CANADA COUNTRY STUDY: CLIMATE IMPACTS AND ADAPTATION

ENERGY SECTOR

Gilles Mercier[1]



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EXECUTIVE SUMMARY

Canada is endowed with a variety of energy resources, although they are not evenly distributed across the country. Refined petroleum products and natural gas meet 60% of the total primary energy demand. The industrial sector is the dominant energy user. In terms of regional energy demand, Ontario occupies the first rank. Fossil fuels are the major anthropogenic source of greenhouse gases (GHGs). The transportation end-use sector is the main contributor of these emissions. Projections are that this energy picture would not change much by 2020.

Most studies in the literature cover impacts extrapolated from General Circulation Models whose calculations, in turn, are based on atmospheric carbon dioxide concentrations that are twice those of pre-industrial levels. These models suggest that all regions of Canada would have warmer temperatures. Southern regions could experience lower annual precipitation whereas other areas such as James Bay and Labrador could have higher precipitation.

Although the energy sector is not uniformly sensitive to climatic conditions, there is general agreement that hydroelectricity production and energy demand would be particularly affected. This is difficult to predict with confidence because of the degree of uncertainty of current climatic models. However, some studies indicate that hydroelectric generation potential would increase in Labrador and in Northern Québec in particular. Hydroelectric generation potential would likely be reduced in Ontario, in the Prairies and possibly in southeastern British Columbia due to reduced precipitation and increased reservoir evaporation from warmer temperatures. Energy required for space heating would diminish but higher demand for air conditioning in southern Canada would partially offset some of the energy savings.

Climate change could influence the offshore activities of petroleum companies because of such factors as reduced sea-ice and reduced severities of icebergs. In addition, the energy distribution infrastructure in Northern Canada could suffer because of permafrost thawing. Both the offshore and the energy distribution sectors might be negatively impacted if extreme weather events were to become more intense and frequent.

Potential changes to energy production, transmission and end-use would require adaptation measures if the sector is to be well sustained. There are few studies on adaptation as most of the literature focuses on mitigation. The scarce information on adaptation does not indicate which measures could be efficient and what would be the implementation costs. Stakeholders believe that the impact of potential GHG-limiting policies on the energy sector would be greater than that of the climate change itself. They are also of the view that adaptation capacity of the sector is high as long as climate change takes place gradually.

INTRODUCTION

Energy plays an important role in the life of all Canadians. Space heating, transportation, communication, manufacturing processes, and even leisure require energy. A large landmass, a rigorous climate, a dispersed population and energy-intensive industries make Canadians high energy users. The energy sector has become a major component of the Canadian economy. Anthropogenic greenhouse gas (GHG) emissions result mainly from the consumption of energy.

Canada's response to climate change may affect the way energy is produced and used in our country. This chapter describes the nature of this sector, briefly refers to its role in GHG emissions and then expands on the potential impacts of climate change.

Most studies in the literature address potential impacts based on results from General Circulation Models (GCM) which assume a carbon dioxide (CO_2) doubling in the atmosphere. Thus, the impacts described herein are generally, but not uniformly, based on this "2xCO_2" scenario.

Description of the Energy Sector

Canada, far more than most countries, is well endowed with a full range of energy resources. However, their distribution varies by region. Québec, British Columbia, Ontario, Newfoundland and Manitoba are endowed with hydrological resources. Fossil fuel resources such as natural gas, crude oil, oil sands and coal are found mainly in Alberta, British Columbia, Saskatchewan and Nova Scotia. Rich deposits of uranium are located in northern Saskatchewan. Offshore crude oil and natural gas deposits exist in the Atlantic provinces as well as in Northern Canada. Among these energy sources, fossil fuels are the main contributors of GHGs, particularly CO_2, because of their carbon content and their extensive use.

After production, these resources are either processed and used locally or transported as raw materials or refined products to other provinces and countries. Canada operates some of the longest pipelines in the world, and as a trading nation, is a net exporter of all energy sources. It is also a major exporter of energy embodied in non-energy products (i.e., products which require energy-intensive industrial processes, such as aluminum).

The combustion of fossil fuels allows the production of mechanical energy (e.g., vehicles) or electricity (e.g., thermal plants). Controlled nuclear reactions, fuelled with uranium, generate electricity. Renewable energy sources with high potential in Canada include wind, solar, hydro and biomass. They generate heat and electricity. Biomass can also be converted into transportation fuels.

Energy is an important component of the Canadian economy. In 1995, the value of total domestic energy production corresponded to 7.2% of Gross Domestic Product. The value of energy exports totalled $25 billion (9.5% of total exports). The energy sector included over 300,000 jobs, corresponding to 2.6% of the total labour force. All regions of Canada benefit directly or indirectly from the wealth generated by energy activities.

Energy is an important factor in the Canadian economy with variations in all regions which are subject to different supply-demand situations and energy prices. Fossil fuel heating of buildings, manufacturing and transportation activities are particularly sensitive to energy costs.

Coal

Canada possesses large resources of coal, located in British Columbia, Alberta, Saskatchewan and Nova Scotia. Remaining recoverable reserves of coal are over 100 times the amount currently produced annually. Most of the coal mined in Alberta, Saskatchewan and Nova Scotia is used for the generation of electricity. Because mines are not necessarily close to markets, a large transportation system involving trains and ships has been developed. British Columbia's production is largely exported overseas for steelmaking. Ontario imports coal for electricity generation and steelmaking from Alberta and the United States.

Coal production reached 75 million tonnes in 1995, representing sales of $2.4 billion. Alberta is the main producer and user of coal. Most of Alberta's (83%), Saskatchewan's (69%), and Nova Scotia's (74%) electric power is generated from coal.

Natural Gas

The main source of natural gas is derived from the Western Canadian Sedimentary Basin but offshore fields in the Maritimes (e.g., Sable Island in Nova Scotia) should be in production in 2001. Remaining proven conventional reserves from the Western Sedimentary Basin are estimated at 1.9 trillion cubic metres (Tcm), corresponding to about 12.5 years of supply at the current production rate. Natural gas reserves from non-conventional (frontier, coal seams) areas are estimated at 1.3 Tcm. Total gas resources may be much higher. Raw natural gas includes water vapour, hydrocarbon components heavier than methane and contaminants such as hydrogen sulphide and carbon dioxide which must be removed in order to meet the quality specifications required for pipeline transportation. A huge pipeline infrastructure allows the distribution of natural gas to customers in Canada and the United States. Natural gas is mainly used for building heating and for manufacturing processes. According to Natural Resources Canada, total demand for natural gas should increase from 148 billion cubic metres (Bcm) in 1995 to 195 Bcm in 2020, the domestic demand being roughly equal to exports. Natural gas is the least carbon intensive of the fossil fuels.

Crude Oil and Equivalents

This category includes light and heavy crude oil, pentanes plus (hydrocarbon component), bitumen (excluding oil sands) and synthetic crude oil (derived by upgrading crude bitumen from oil sands). Western provinces, particularly Alberta, are the main producers. Production is expected to start from the large Hibernia field off the East Coast in 1998 and additional production is planned from other fields such as Terra Nova. Table 7.1 illustrates the remaining established reserves in Canada. Conventional areas have a reserve/production ratio of about 8 years, a ratio that has been maintained for some years as additional conventional oil has been discovered.

Table 7.1 Crude Oil Reserves

	Remaining Established Reserves (Billion Cubic Metres)
Conventional Areas	590
Frontier	191
Oil Sands	575

Source: National Energy Board, 1994

Large oil sands deposits are located in northern Alberta and Saskatchewan. Oil sands are mined, the oil is separated from the sands and then upgraded to a synthetic crude oil. Oil sands can also be separated in-situ. Any separation process requires water. Oil sands will replace diminishing conventional oil production over the decades to come and Canadian net oil exports are expected to rise slowly over the next decade.

Like natural gas, a large pipeline infrastructure, mainly in the southern part of the country ensures that crude oil reaches refineries in British Columbia, Alberta, Saskatchewan, Ontario and Québec, and the United States. In the north, a pipeline stretches from Norman Wells (NWT) to Edmonton. However, one pipeline will be converted in 1998 to move oil imported through Portland, Maine, from Montréal to Sarnia, Ontario.

Crude oil is the most important source of energy in Canada, meeting 30% of the primary energy demand. Alberta accounts for 78 % of total production which reached 312 thousand cubic metres per day in 1995. Although Canada is a net oil exporter, oil is imported for geographical and quality reasons mainly from the North Sea to meet the needs of Québec and the Atlantic Provinces.

Electricity Production

Electricity is mainly generated from hydro, coal, and nuclear fuels. Total installed capacity is over 115 gigawatts (GW) of which 56% is from hydroelectricity. In 1995, provincial utilities owned around 83% of the total installed capacity. Total generation reached 535 gigawatt hours (GW.h) of which 43 GW.h were exported to the United States. Interprovincial trade amounted to 42 GW.h in 1995.

In Québec, British Columbia, Newfoundland and Manitoba production is largely hydroelectricity based. Most hydro-electric plants use dams but run-of-river facilities are common along the St. Lawrence River and in the Prairies. Canada was the world's largest generator of hydroelectricity in 1996.

In Alberta, Nova-Scotia and Saskatchewan, coal is the main fuel. Coal-powered thermal plants are preferably located near coal mines in order to reduce transportation costs. However, Ontario is the exception. Ontario Hydro has to import coal from the United States and western provinces because no coal resources are economically recoverable in Ontario.

Canada has 22 nuclear reactors which are mostly located in Ontario. Like thermal plants, reactors are located near rivers. Temporary technical problems have obliged Ontario Hydro and New-Brunswick Power to close some of their reactors for repairs. This has resulted in higher use of fossil fuels to generate electricity than anticipated and has led to higher emissions of CO_2.

Renewable Energy Sources

Renewable energy sources include small-scale hydro plants (defined here with a capacity lower than 20 megawatts), wind, solar (photovoltaics, active solar heating systems) and biomass. Large-scale hydro is also considered a renewable energy source. In this report, large-scale hydro is treated separately because of its relative importance in comparison with other renewable energy sources. Except for biomass, energy production from renewables does not emit GHGs. The biomass sources of energy are usually considered as neutral with respect to net emissions of CO_2 because the carbon they contain originates from the atmosphere. These resources and the efficiency and effectiveness of renewable energy technologies are highly dependent on weather and climatic conditions.

Small hydro installations are mainly located on small rivers. They are often run-of-river but, in some cases, dams are used. They account for a very small part of the installed hydroelectric capacity in Canada. Most installations are privately-owned. There is an increasing interest in small hydro because small rivers can be used for electric power generation and construction periods are shorter. Although capital costs per unit of capacity are higher than for large hydro plants, small hydro installations require lower initial investments.

Excluding large-scale hydro, biomass is the most important source of renewable energy. In this context, it includes biomass wastes from pulp and paper, forest and sawmill residues, municipal solid wastes, cereal materials and crop residues. Bioenergy, in the form of heat and electricity, accounts for about 6% of Canada’s total primary energy supply. The main producer and user of bioenergy is the pulp and paper industry. Wood accounts also for around 7% of primary residential heating. Anticipating an increased reliance on biomass, research is being carried out to develop tree plantations and forest management practices.

Wind and solar energy play marginal roles in the energy supply of Canada, even though the country possesses substantial wind and solar resources. The main barrier for deployment of wind and solar installations is the relatively low energy costs of our conventional energy sources. Nevertheless, there is a growing interest in wind energy farms across the country.

Any constraints on fossil fuels, that could develop from GHG limits, would place increasing demand on renewable energy resources.

Energy Demand

The industrial sector is the largest energy user in Canada, accounting for 43% of the total end-use energy demand. Pulp and paper, iron and steel, smelting and refining, petroleum refining and chemical industries are the main consumers. Natural gas and refined petroleum products satisfy over 56% of the energy demand. The transportation sector (25% of the total end-use demand) is mostly concentrated on road vehicles and consumes fossil fuels (especially, gasoline and diesel). The residential sector uses energy for, in order of importance, space heating, water heating, light and appliances, and space cooling. Natural gas and electricity meet over 80% of this demand. The commercial sector (commercial and institutional buildings) use primarily natural gas and electricity for space heating, lighting and auxiliary motors.

Total primary energy demand is expected to increase by about 23% by 2020. Demand for all energy sources, except nuclear, will grow over the next 25 years. The industrial sector will remain the most important energy user in Canada. Demand for energy in the residential sector is anticipated to decrease because of a slower growth in the housing stock, the implementation of initiatives encouraging owners to use energy more efficiently and the replacement of old appliances by new more efficient ones. The commercial sector’s share of energy demand will remain unchanged while in the industrial sector, a growth of 38% in the forecast period is seen. Transportation will maintain its share over time. Under current forecasts, the end-use demand shows only marginal changes of the fuel mix.

On a regional basis, Ontario is the most important energy user and projections show that it will maintain this position for the next 25 years (refer to Table 7.2). Total primary energy demand in this province is met mainly by refined petroleum products, nuclear electricity and natural gas. By 2020, natural gas and refined petroleum products will still remain the main sources of energy, satisfying 61% of the primary demand (compared to 55% in 1995).

Table 7.2: Primary Energy Demand by Region (Petajoules)

Regions	1995	2020	Annual Growth (%)
Atlantic	810	1045	1.02
Québec	1766	2132	0.76
Ontario	3789	4608	0.79
Prairies	3402	4007	0.66
British Columbia and Territories	1207	1657	1.28
Canada	**10974**	**13449**	**0.82**

Source: Natural Resources Canada, 1997

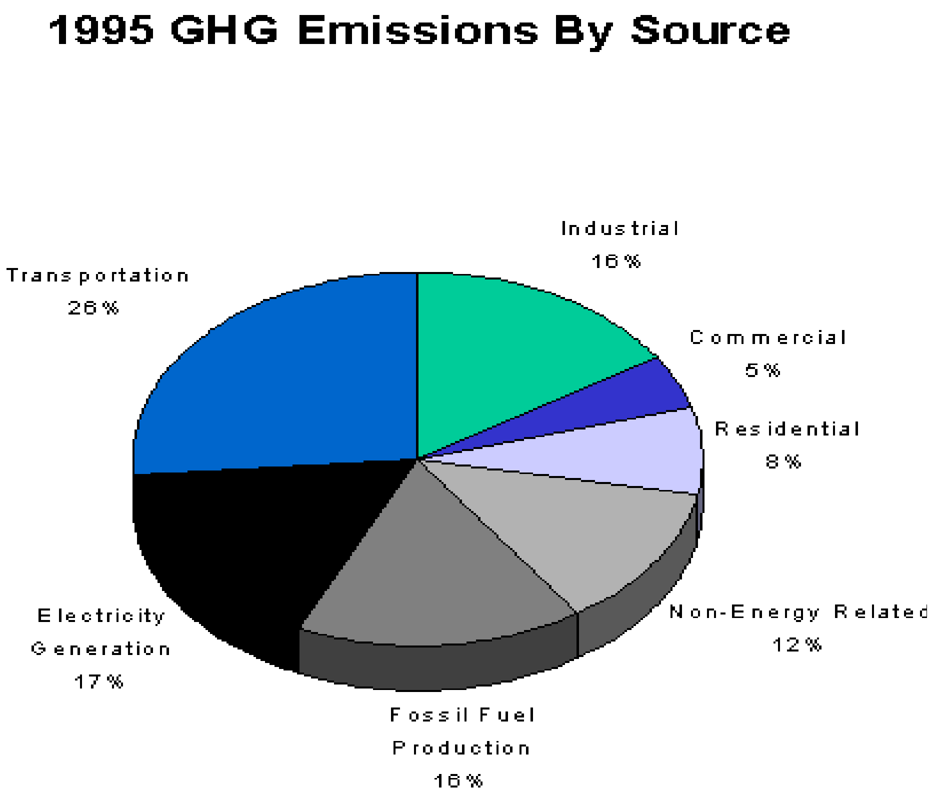
About 53% of the primary energy demand in the Atlantic provinces is met by refined petroleum products and this share would not change very much in the future. In Québec, refined petroleum products and hydroelectricity satisfy 73% of the demand. No shift is projected by 2020. Natural gas meets 50% of the primary energy demand in the Prairies and would continue to be the preferred energy source in the forecast period. Finally, refined petroleum products and natural gas dominate the other energy sources (meeting 64% of the demand) in British Columbia. Projections do not foresee major changes in the demand trend in this province.

As the reader can see, fossil fuels satisfy most of the energy demand in Canada. This situation is forecasted to remain the same for the next few decades.

Greenhouse Gas Emissions from the Energy Sector

Total Canadian GHG emissions reached 618.5 megatonnes CO_2 equivalent in 1995. Energy related emissions totalled 542 megatonnes in that year and CO_2 was the main greenhouse gas (81%) (Canada's Energy Outlook, 1996-2010, Natural Resources Canada, 1997). Refined petroleum products were the first source of GHGs. Natural gas and coal were second and third, respectively. As illustrated in Figure 7.1, transportation followed by electricity generation and fossil fuel production, were the main emittors of GHGs (CO_2 equivalent).

Figure 7.1 GHG Emissions by Source



Emissions from the end-use sector are forecasted to reach 416 megatonnes in 2020, a growth of around 23%. The transportation sector would remain the dominant contributor of GHGs for the period (50% of the total end use sector).

Around 80% of the electricity generation does not release GHGs in Canada, due to their generation from hydro and nuclear plants. For the remaining portion, coal is the main source of energy and GHGs. As illustrated in Figure 7.1, electricity generation accounts for 17% of the emissions, while coal is responsible for 14% of the emissions. Emissions from fossil fuel electricity generation (coal, fuel oil and natural gas) are projected to grow from 103 in 1995 to 147 megatonnes in 2020 (19% of total emissions). Coal remains the principal contributor of GHGs from the electrical sector for the forecast period.

Emissions from fossil fuel production include mainly CO_2 and methane. They result mainly from the use of fossil fuels in the exploration, development, production and transportation of crude oil (including oil sands), natural gas and coal. Their contribution could slightly decrease from 102 megatonnes in 1995 to 100 megatonnes in 2020.

Overall, GHG emissions from the energy sector are projected to increase in Canada by 22% by 2020. The above projections include the benefits of initiatives (regulations, R&D, financial incentives and information) which aim at reducing GHG emissions.

IMPACTS ON, AND ADAPTATION BY, THE ENERGY SECTOR

Assessing the impacts of climate change on the energy sector is not an easy task. This sector is very complex. Complexity is also a characteristic of climate change analysis. The main factors to take into account are: the nature, importance and regional distribution of energy sources; the foreseen demand for these energy sources; the nature and intensity of climate changes; and the sensitivity of energy supply and demand to climate change. Rarely, however, is it possible to quantify these effects at present with any degree of confidence.

This section of the report will describe the potential impacts of climate change on the main components of the energy sector: production, transmission and end-use as discussed in the literature. Included are potential adaptation measures which could be used to maintain a viable energy sector.

Energy Production

Fossil Fuels

Climate change is not expected to affect inland production of crude oil, natural gas and coal with the exception of greater precipitation in mountainous regions which could lead to increased erosion and more frequent landslides which, in turn, could damage coal mining and the infrastructure related to the production of hydrocarbons. Higher temperatures could lead to partial thawing of discontinuous permafrost zones. Production facilities in these areas would require special design techniques to prevent damages caused by soil instability.

Offshore oil and natural gas activities, which are foreseen to become more important in the Maritimes, are sensitive to icebergs, sea ice and storms. Models have predicted that warmer temperatures would result in a retreat in the southern ice boundary and in decreased iceberg formation although there may be short periods favourable to more frequent icebergs (Brown, 1993). Current GCM results are not considered reliable for addressing future iceberg severity.

Overall, interruptions of exploratory and production activities caused by icebergs could be reduced. Changes in the frequency of storms might impact on the operations at offshore platforms. However, it remains unclear whether extreme weather events will occur more frequently and intensely. Height of platforms above the water level could be increased in order to respond to higher sea level and waves. As a result of these changes, construction and safety standards for offshore structures and associated coastal facilities could be re-visited.

Offshore hydrocarbon resources exist in Arctic regions but, despite exploration projects carried out by petroleum companies for several years, production has been marginal due to low energy prices and development costs. Climate scenarios forecast higher temperatures in this region. This would result in less sea ice and thinner ice cover, in other words, a longer open water season (from 60 days at present to 150). This is seen as a positive impact by the petroleum industry as ice design requirements for offshore structures could be reduced and could translate into lower construction costs. According to Croasdale (1993), drilling costs could see a 30 to 50% reduction (assuming the use of drillships). However, warmer temperatures would have negative impacts as well. An increased sea level and higher waves would result in more stringent design standards for both offshore and coastal facilities. In addition, the use of spray ice platforms would become more difficult because of warmer temperature conditions and longer open-water seasons.

Electricity

As explained earlier, electricity is mainly generated from large hydro, nuclear reactors and coal plants and, to a lesser extent, from natural gas plants. Small hydro, solar energy, wind and biomass are small contributors of electricity production in Canada.

Hydroelectricity (small and large schemes), a major source of energy in Québec, British Columbia, Newfoundland and Manitoba, depends on water supplies which are influenced by precipitation and by evaporation. Impacts of a doubled CO_2 scenario on precipitation (rain and snow) and temperature in Canada would vary from one region to another.

According to GCM scenarios, it is estimated that runoff would be reduced by 20% in the Maritimes, whereas Labrador would see a 35% increase. Models predict higher precipitation (up to 20% according to certain models) and earlier spring runoff in Northern Québec, but precipitation remains unchanged in the southern parts. This would lead to an increased power output by about 15% in the James Bay region. The effect of a doubled CO_2 would be a drop in Great Lakes water levels by 0.5 to 1.0 m, resulting in a loss of hydropower capacity of 20% and corresponding financial losses of $111 million for Ontario Hydro. However, reduced energy demand under a doubled CO_2 scenario would result in savings of about $172 to 204 millions (1984 Canadian dollars), thus resulting in a net savings totalling $61 to 92 million annually (Sanderson, 1987). Glaciers in the Rockies are a major water source for the rivers in the Prairies. Scenarios project that glaciers in the Eastern Rockies would melt substantially as a result of warmer temperatures, thus causing higher stream flows in the next 20 to 30 years. However, the volume of water would decrease in the longer term because of the reduced glacial mass. These changes in the stream flows and more frequent summer droughts would actually lead to a reduction in hydropower generation. Higher water demand for irrigation in the Prairies would worsen this situation although Manitoba could be less affected due to its more abundant water resources. Climatic models forecast an annual temperature increase in all regions of British Columbia while precipitation would increase in all regions during spring, but would vary regionally for the other seasons. Glaciers in southern British Columbia could melt considerably. These potential changes would mean lower hydroelectricity generation in the southeast part of the province.

Impacts on large hydro would similarly apply to small hydro. Run-of-river installations would certainly be affected by variations in water levels and flows. One response to climate change by hydroelectricity managers could include better management of reservoirs. This would prevent floods in areas where increased runoffs are projected. Efficient storage management in areas of reduced precipitation could optimize the generation of electricity while managing other needs for water resources (e.g., navigation, irrigation, drinking water, industrial processes). Models for forecasting hydrological changes and managing their impacts could play a greater role in the future. Raban (1991) suggests developing a contingency plan to manage energy shortages; to improve information exchange on climate change issues; and to evaluate the effects of various climate change scenarios on drainage basins.

Solar (photovoltaics) and wind energy production are highly sensitive to weather changes. Climate change might mean modified wind regimes, more frequent storms and changes in the cloud cover. However, the intensity and the regional distribution of these changes in Canada are not well understood. The design, location and installation of solar and wind equipment might have to be adapted to new climatic conditions. For instance, windmills might have to be built to a higher standard to withstand more extreme storms.

Higher temperatures and lower precipitation could reduce the amount and the quality of water necessary for cooling purposes at *thermal and nuclear plants*, therefore, decreasing plant efficiency. New combustion technologies such as combined-cycles systems require less cooling water. The impact of changing water supplies could be lessened if these newer technologies could replace conventional systems.

Some thermal plants in Ontario use coal transported by ship from the United States. Lower Great Lakes water levels could negatively affect the economic supply of coal to these plants because the maximum loads carried on lake vessels would have to be reduced due to draft limitations in some channels. In addition, some coal could have to be moved by the more expensive railway mode of transportation.

Overall, these changes could result in a modified fuel mix across Canada as well as an increase in regional transfers of electricity. Assuming a stable demand for electricity in the future, a decrease of hydroelectricity capacity due to reduced availability of water in southern areas of Canada could mean higher reliance on current thermal plants and nuclear reactors, and additional imports from other provinces and, possibly, the United States. However, it is presently difficult to quantify these potential imports, especially in a context of growing degrees of interconnection and the projected trend to deregulating the energy industry.

Other Forms of Renewable Energy Sources

Biomass and, to a much lesser extent, active solar systems generate heat for space heating. Impacts of climate change on photovoltaics apply to active solar technologies as well. Biomass utilization for residential space heating would decrease as a result of warmer temperatures. If the Canadian boreal forest were to shift northwards, biomass could be used in new areas of Northern Canada.

Biomass can also be converted to biofuels such as methanol and ethanol. In Canada, ethanol production from agricultural crops (mainly corn) is increasing. Research is also being carried out on ethanol production by enzymatic processing of cellulosic materials. The competitiveness of biofuels is quite dependent on the feedstock cost. The availability of agricultural feedstock could be modified by higher temperatures and increased evaporation in southern Canada under climate change.

Energy Transmission and Transportation

Two main energy transportation systems exist in Canada: electric transmission lines and pipelines. Rail transportation is addressed in another chapter of the Canada Country Study.

Transmission Lines

The electric transmission infrastructure could be subject to more extreme weather conditions under climate change. Power lines, which would be exposed to higher temperatures in southern Canada, would see an increase in transmission losses since transmission line resistance increases with rises in ambient temperatures. Under extreme conditions, transmission lines would be more subject to sagging. Line icing in northern regions could be more frequent because of higher humidity conditions in warmer winters and increased number of days in the critical icing temperature range (Raban, 1991). Transmission lines could also be susceptible to disruption in mountainous regions because higher precipitation might cause increases in the rate of erosion and occurrence of landslides. In addition, if storms were to become more frequent under climate change, the probability of damage to the transmission lines could increase. Overall, transmission lines would become less reliable, especially over long distances, and strengthening of the infrastructure would be required.

Pipelines

Damages to pipelines would occur especially in discontinuous permafrost areas susceptible to thawing as a result of higher temperatures caused by climate change. The Norman Wells oil pipeline, located along the Mackenzie Valley in the Northwest Territories, is built in such an environment. The construction of new pipelines and transmission lines in discontinuous permafrost zones could become more complex in the future. At a lesser extent, another possible negative impact is the higher risk of breaks to pipelines which are crossing rivers. Higher flow rates of these rivers could cause more erosion to their banks and beds, and could uncover crossing pipelines. Structural designs and construction approaches would have to become more adapted to these conditions.

Other Considerations

Some remote communities are not grid-connected and rely on stand-alone diesel electric power generating systems. The supply of diesel fuel is dependent on winter roads and marine shipping, especially in Northern Canada. Higher temperatures under climate change could reduce the period during which winter roads can be used. Conversely, marine shipping could benefit in the future because of a longer open water season. Finally, as explained before, Eastern Canada is quite dependent on crude oil imported from the North Sea. Less severe ice conditions in Atlantic Canada under climate change would ease the tanker traffic. However, this benefit could be partially offset by higher frequency of storms in the future.

Energy Demand and Use

This sector is highly dependent on climatic conditions and it is probably where climate change could have very strong impacts. The regional consumption of energy could be modified significantly, thus affecting the future energy consumption behaviour of Canadians.

Residential and Commercial Sectors

The major impact would be on energy demand for space heating and for cooling (e.g., air conditioning, food refrigeration, etc.). Models foresee milder annual temperatures in all regions of the country. This would mean a lower demand for space heating (about 30% in southern regions of Canada, 20% decrease in northern parts) but higher energy needs for cooling (for instance, 7% increase in Ontario), thus resulting in net energy savings. These changes in energy demand could also lead to a transfer of some energy required for space heating from the winter to the summer and thus a better balance of annual loads on the electrical and gas supply systems.

The two main energy sources used in both sectors are electricity and natural gas. According to a study by Findlay and Spicer (1988), the individual residential consumption of natural gas in Canada would decrease by 10 to 20% by 2031. This decrease would be particularly marked in Ontario and in Québec (between 14 to 25%).

New building designs and codes could eventually be modified to respond to the new demand for space heating and cooling.

Industrial Sector

The impacts would especially affect electricity-intensive industries (e.g. aluminum production) in areas where electricity capacity would decline under climate change (e.g., southern Ontario). However, no data on specific impacts could be found during the literature search.

Transportation Sector

Studies on transportation indicate that higher temperatures would have some influence on fuel consumption in Canada. For example, the warm-up period of engines would be reduced, resulting in higher energy efficiency. However, warmer temperatures in the future would lead to increased use of air conditioning in vehicles and higher requirements for food refrigeration in the trucking industry. Changes in weather conditions under climate change would also affect transportation operations. For example, more snow, fog, rain or ice could slow down the flow of the traffic. However, no evaluation of this type of impact has been found during the literature search. In addition, warmer temperatures in southern Canada would result in less fuel needed for road maintenance in the winter and ice-breakers in waterways. Chapter 8 provides more detailed impacts of climate change on the transportation sector.

Overall, energy demand could be impacted at various levels across Canada because of higher temperatures, changes in precipitation and modifications of weather. The current energy use pattern would certainly change but the intensity of this change is not clearly known. Table 7.3

provides some estimates of the impact of climate change on energy demand in Canada. As the reader will notice, data tend to be scarce and inconsistent.

Table 7.3 Available Estimates of Climate Change Impacts on Energy Demand

Regions	Impacts on Energy Demand	References
Atlantic	N/A	
Québec	-25% in heating (Montréal) -35% in heating (Québec)	Singh, 1988
Ontario	-2 to -3%	Sanderson, 1987
Prairies	-0.5% of total electricity consumption -20% of natural gas demand +20% energy needs for irrigation	Goos, 1989
British Columbia	N/A	

Concluding Comments on Impacts on, and Adaptation by the Energy Sector

Various studies have attempted to evaluate the implications of climate change on the energy sector in Canada. However, most of the available information is in qualitative terms. Appendix A summarizes the available information and provides a list of the potential impacts.

Because mitigation measures may not be sufficient to limit GHG emissions, countries are also developing adaptation measures to respond to climate change impacts. It is acknowledged that a purposeful implementation of adaptive measures could become more important in the future. However, adaptation will not replace the need for mitigation. The adaptive capacity of the Canadian energy sector is high as long as climate change takes place gradually.

IDENTIFICATION OF KNOWLEDGE GAPS

In comparison with ecosystems and agriculture, there have been few studies on impacts and adaptation by the energy sector to climate change (IPCC, 1996). Most of the past research has focused on mitigation measures. This may reflect the perception that the energy sector is less sensitive to climate variables but more sensitive to policy implications of climate change (e.g. carbon tax) and to political events in the Middle East. However, this literature review shows that the Canadian energy sector could be impacted by climate change, especially hydroelectricity generation and changes in future energy demand patterns.

The following are gaps identified through this review:

a) *Information on potential impacts* is lacking in all parts of the energy sector. It is important to know the potential impacts before developing adaptation and mitigation measures. The estimate of regional distribution and intensity of climate change requires more research. This is particularly crucial for Canada because of its climatic diversity and the direct impact of climate on how energy is produced, transmitted and used.

b) *Lack of adaptation measures*. The past focus has been on mitigation measures. Adaptation measures have only been developed and implemented on a spontaneous and voluntary basis. Because mitigation would not be the sole solution to climate change, adaptation measures could play a growing role in the future.

c) *Cost estimates of impacts and adaptation measures* are scarce. Losses and gains in Canada due to climate change should be estimated in order to focus on measures which would have maximum benefits to the environment while ensuring a viable energy sector. In addition, cost estimates are critical to the design of efficient adaptation strategies.

d) *Lack of integration* between sectors should be addressed. Most studies have taken a single sector approach. Nevertheless, some interdependency exists between sectors. A negative impact on the energy sector may be positive for another sector. Moreover, an adaptation measure for a specific component of a sector may result in negative impacts on other components of the same sector. A more integrated approach addressing technological, social and economic issues should be adopted in future climate change studies.

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Appendix 7A Energy Production – Impacts and Adaptation

Regions	Fossil Fuel	Hydroelectricity	Other Renewables
Atlantic	• Less disruption of offshore operations due to reduced sea ice and icebergs. • More frequent disruptions due to storms • Height of platforms to adapt to higher water level and waves. • Revised construction and safety standards.	• Reduced hydro potential due to decreased runoff except in Labrador where potential should increase.	• Changes in wind regime, cloud cover, storms. • Modified biomass supply due to changes in regional diversity. • Reduced use of biomass for heating because of warmer temperatures.
Québec	N/A	• Increased potential in northern areas.	• Same as above.
Ontario	N/A	• Same as Québec.	• Same as above.
Prairies	• No major impact.	• Reduced hydro generation potential in most areas. Manitoba could be less affected.	• Same as above.
British Columbia	• More erosion and landslides could impact on coal mining and hydrocarbon production.	• Increased precipitation in spring. Regional variations for the rest of the year.	• Same as above.
Northwest Territories/Arctic	• Same as Atlantic. • Spray ice platforms to be negatively affected.	• Increased precipitation.	• Changes in wind regime, cloud cover, storms. • Modified biomass supply due to changes in regional diversity.

Appendix 7B Energy Transmission – Impacts and Adaptation

Regions	Transmission Lines	Pipelines
Northern Areas	• More line icing. • More storm damages.	• Higher potential for disruptions caused by permafrost thawing. • Increased erosion of rivers might result in damages to pipelines crossing rivers.
Southern Areas	• Loss in transmission capacity. • More sagging lines. • More frequent storm outages.	• No major impact.
Mountainous Areas	• Higher precipitation to cause more frequent landslides.	• Higher precipitation to cause more erosion and landslides.

Appendix 7C Energy Demand and Use – Impacts and Adaptation

Regions	Residential and Commercial	Industrial	Transportation
Atlantic	• Reduced demand for heating. • Higher demand for cooling in southern areas.	• No major impact.	• Reduced engine warm-up period. • Higher use of air conditioning. • Lower energy demand for snow removal. • Ice-breaking reduced.
Québec	• Same as above.	• Potential impacts on electricity-intensive industries.	• Same as above.
Ontario	• Same as above.	• Potential impacts on electricity-intensive industries.	• Same as above.
Prairies	• Same as above.	• No major impact.	• Reduced engine warm-up period. • Greater use of air conditioning. • Lower energy demand for snow removal.
British Columbia	• Same as above.	• No major impact.	• Same as Atlantic region.
Northwest Territories/Arctic	• Reduced demand for heating.	• No impact.	• Reduced need for ice-breaking. • Shorter winter road season (implies use of more costly transportation means).

CHAPTER EIGHT

CANADA COUNTRY STUDY: CLIMATE IMPACTS AND ADAPTATIONS

TRANSPORTATION SECTOR

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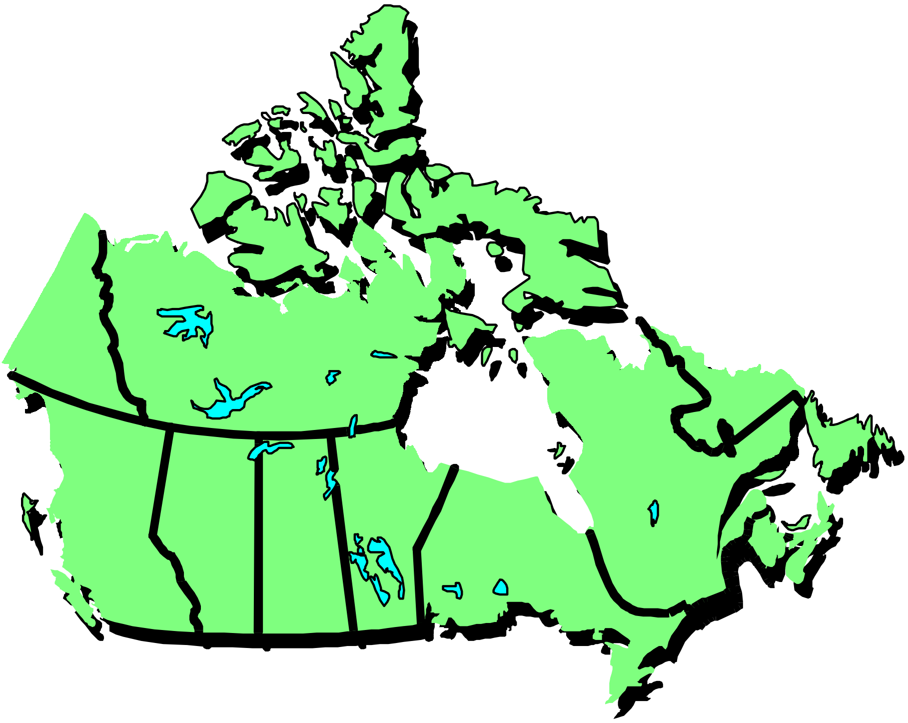

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EXECUTIVE SUMMARY

1. Transportation plays an important role in the economic and social well being of Canadians. Transportation industries account for approximately four percent ($23 billion) of Canada's gross domestic product, and four percent (440,000) of the Canadian labour force. The overall importance of transportation activities are much higher, however, due to the large volume of private transportation, especially by automobiles and trucks. The 1992 Royal Commission on National Passenger Transportation estimated that $103 billion was spent on transportation in 1989; this translates into an average of $3,800 per capita. Approximately four-fifths of this was devoted to road transportation.

2. In terms of climate change and transportation impacts, Canadian research has focused on the direct effects of climate change on: (a) shipping in the Great Lakes - St. Lawrence River system, (b) coastal infrastructure, and (c) northern roads. Each of these activities would be negatively affected by a changed climate. Reduced water levels would translate into significant, negative impacts (millions of dollars annually) on commercial navigation in the Great Lakes - St. Lawrence River system. In coastal regions, especially in Atlantic Canada, sea-level rise would be associated with billions of dollars of damage to road, rail and port infrastructure. In northern regions, such as the Mackenzie Basin, changes in temperature and/or precipitation would reduce the length of the ice-road season, raising the costs of winter transportation.

3. As for the dominant modes of transport in Canada-- automobile travel, trucking, rail, air, coastal marine-- little work has been done on the implications of climate change. There is, however, a high level of understanding regarding transport-related sensitivities to current climates. This information can be found in journals, conference proceedings, technical reports, standards and operating manuals, transcripts of inquests and other hearings, and media reports. Based on present sensitivities, it is expected that land-based transportation costs would be reduced by climate change because of shorter and/or less harsh winters. Coastal operations would also benefit from deeper drafts and reduced ice cover. The effects on aviation are undetermined. There is a need for more detailed impact analyses of each of these transport sectors. Such studies should be framed in the context of human adaptation, with the ultimate goal of building adaptive capacity in Canada's transportation sector. More attention also needs to be given to safety, which is both a transportation and a health-related issue. Finally, more attention needs to be given to extreme weather events and their disruptive capabilities.

4. Nationally, the net effect of climate change on transportation would likely be positive, due to the operational benefits of less harsh winters on land-based transport systems Vulnerabilities and potential impacts vary regionally, however. The most vulnerable areas include: the Great Lakes- St. Lawrence waterway; coastal areas in Atlantic Canada and southern British Columbia; mountainous terrain in western Canada; other areas susceptible to landslides; and northern settlements.

5. Climate-induced changes in regional economies and settlement patterns would have implications for transport demand. Our present understanding, however, does not provide a

basis for estimating the nature and magnitude of these effects. Multi-sector, integrated research is needed to address this knowledge gap.

6. Climate is an important consideration in transportation activities. Transport industries, government agencies and the Canadian public expend considerable effort and substantial sums of money (hundreds of millions of dollars) to reduce the risk of delay or incident due to inclement weather. No comprehensive inventory of these various adaptations exists, however, and the effectiveness of many of these measures is largely unknown. There is a pressing need for more action-oriented and evaluative research on human adaptation.

INTRODUCTION

It is well known that motorized transport accounts for a significant proportion of greenhouse gas emissions. In Canada, transportation accounts for about 30 percent of energy use and a similar proportion of carbon dioxide emissions (Nix, 1995; Liu, 1997). Thus, it is not surprising that this theme has dominated discussions on transportation-climate interactions at both the science and policy levels. This report does not deal with this issue, however. Rather the focus is on the effects of climate, especially a changed climate, on transportation infrastructure and operations in Canada.

All modes of transport are sensitive to weather and climate to some extent (Perry and Symons, 1991; Thornes, 1992). Indeed, earlier this century, Canadian meteorological services were concentrated in the federal Transport Department. Despite, the long affiliation between transportation operations and weather services, "No one knows what is the 'cost' of the present climate to transportation ..." Jackson (1990, 95). Nor is there a comprehensive, quantitative assessment of the magnitude of the potential costs of a changed climate on Canada's transport sector.

There have been, however, several qualitative summaries describing the vulnerabilities of transport-related activities to climate change as well as several quantitative impact analyses of climate change on selected transport infrastructure and operations. The goal of this report is to critically synthesize these materials in order to present a summary of the state of knowledge. This report is based mainly on articles and reports that were identified in computerized library and Internet searches and through telephone/personal contact with various government, industry and university groups. These are supplemented with examples of events or programs that illustrate the vulnerabilities and adaptations of Canadian transport activities to atmospheric conditions.

The remainder of the report is divided into four sections. Section 3 provides a detailed overview of the characteristics of transportation activities in Canada. Section 4 summarizes the current state of knowledge on the vulnerabilities and impacts of transportation to climate change. Adaptation is discussed briefly in section 5. In many cases, however, the distinction between impacts and adaptations is blurred, since impacts arise at least in part out of human choices and responses to present opportunities and risks. Knowledge gaps are identified throughout the document. Finally, references are listed in section 6.

It is also worth noting that the transportation theme is discussed in the regional components of the Canada Country Study, as well as in selected sectoral and cross-cutting reports including water (marine navigation), energy (pipelines), the built environment (infrastructure) and trade.

CANADA'S TRANSPORTATION SECTOR

Transportation and Canada's Economy

Canada's 30 million people are scattered across a vast geographic area, covering almost 10 million square kilometres and stretching 5,500 kilometres between the Atlantic and Pacific Oceans. An efficient transportation system is clearly necessary to connect the country's population centres and to stimulate economic development and foster social well-being. The importance of transportation has been acknowledged in a number of commentaries on the development of the nation. As Hoyle (1993, 148) noted, "transport has played a vital role in the agricultural development of the prairie provinces; in the emergence of the St. Lawrence axis as Canada's great transport artery to and from the North Atlantic; in the exploitation of the mineral and water resources of the Canadian Shield; and in the integration of Canada's industrial heartland in Ontario and Quebec". Today, Canada's transportation network continues to provide the crucial underlying structure required to support the nation's economic activities. This network allows for the movement of people and goods throughout the country and facilitates the transfer of Canadian products to international markets.

The private nature of many transport activities and the inclusion of transportation activities as sub-components of other industries hinders the accurate assessment of transport's importance to the Canadian economy through traditional data sources. In 1992, the Royal Commission on National Passenger Transportation, in an attempt to present a comprehensive portrait of this sector, examined the resources devoted to various transport activities. They estimated that $103.1 billion was spent on transportation in 1989, more than half of which was devoted to private automobiles and an additional 12.9 percent to other private transport, primarily private trucking (Table 8.1). For-hire carriers (all modes) comprised one-third of the total, and government expenditures accounted for the remainder. A correction factor was used to eliminate the double counting of hidden fees and taxes that are commonly recorded in more than one context, including vehicle permit costs and fuel taxes. The magnitude of Canadian expenditures on transportation indicates the overall importance of this sector, while the various categories in Table 8.1 highlight the many actors involved: the millions of drivers, the tens of thousands of businesses, and the thousands of government departments and organizations.

In terms of the economic importance of transport industries, two measures are commonly used: employment and gross domestic product (GDP). In terms of employment, transport industries in Canada provided jobs for nearly 439 thousand people in 1995, representing 4.1 percent of the total labour force (Table 8.2). This tally includes the key "Transportation Industries" as defined in government documents--bus companies, transit operators, trucking firms, airlines, railways, and marine carriers as well as several other related activities. As shown in Table 8.2, transport-related employment declined in the early 1990s, especially in rail and bus transport.

Table 8.1: Resources Devoted To Transport (billions of dollars)

Sector	Amount
For-Hire Carriers	34.5
-Road	15.3
-Rail	7.4
-Air	7.9
-Marine	2.0
-Pipeline	1.8
Private Car	58.8
Other Private Transport	13.3
Government Expenditures	12.5
Correction Factor	-15.9
Total	103.1

Source: Royal Commission, 1992, 4-6

Table 8.2: Employment in the Transportation Sector(thousands)

Sector	1988	1989	1990	1991	1992	1993	1994	1995
Air[1]	52.6	55.8	56.3	53.5	52.8	50.5	52.9	53.0
Bus[2]	32.7	30.6	31.2	32.1	35.6	34.8	21.0	n/a
Rail[3]	77.8	74.9	69.1	64.8	62.5	59.6	57.3	53.2
Shipping[4]	23.8	23.7	23.9	23.5	22.9	22.9	22.1	n/a
Transit[5]	36.8	38.8	39.1	39.5	38.3	38.1	37.8	38.9
Trucking[6]	97.9	98.1	n/a	93.0	93.3	96.5	100.6	n/a
Trans. Total[7]	462.5	472.1	472.7	441.6	433.4	431.1	434.6	430.8
Pipeline[7]	n/a	n/a	n/a	n/a	8.9	8.3	8.1	7.9

Sources: Statistics Canada [1]Catalogue 51-206 [2]Catalogue 53-215 [3]Catalogue 53-216 [4]Catalogue 54-205 [5]Catalogue 53-215 [6]Catalogue 53-222 [7]Catalogue 72-002

GDP describes the value added by each industry. It is a measurement of the value of sales minus the cost of goods purchased to facilitate these sales. In 1995, transportation (including pipelines) accounted for 4.3 percent of Canada's GDP (Table 8.3). The importance of transportation industries in the national economy has remained fairly stable over the past few decades, although the relative importance of different transport sectors has changed over time, largely as a result of economic restructuring and regulatory reform. Freight transport by trucking and rail have increased their contributions, especially over the past three years. Pipeline income has also exhibited strong growth, although, by including fuel sales in the pipeline GDP counts, the expansion within this sector may be overestimated. Gains in trucking, rail and pipelines have been offset, however, by declines in air, shipping (marine), intercity bus and urban transit.

Table 8.3: Gross Domestic Product (billions of dollars, 1986 constant)

Sector	1988	1989	1990	1991	1992	1993	1994	1995
Air	3.0	2.8	2.5	1.9	2.0	1.9	2.0	2.1
Rail	4.2	4.0	3.9	4.1	4.2	4.3	4.8	4.8
Shipping	1.5	1.3	1.2	1.1	1.0	1.0	1.0	1.1
Transit	1.5	1.5	1.4	1.2	1.1	1.1	1.0	1.0
Trucking	6.4	6.4	6.3	6.1	6.2	6.5	7.0	7.1
Trans. Total	19.2	18.9	18.4	17.2	17.4	17.6	18.6	19.0
Pipeline	2.7	2.8	2.9	3.0	3.4	3.7	3.9	4.1
All Sectors	492.5	505.0	503.6	494.5	497.6	510.6	531.5	542.0

Source: Statistics Canada Catalogue 15-001

Traditionally, the level of transportation activity in Canada has been closely linked to trends within the economy as a whole. Increasingly, however, the transport industry is being influenced by the specialized shipping and travel requirements of businesses and individuals. According to Hoyle (1993, 148) “the intensity of competition has been increased, and the efficiency of movement has been enhanced”. Furthermore, freight carriers are “required to provide cost effective transportation in the correct combination of weights and distances” (Statistics Canada Catalogue 11-509, 1994, 96) and, consequently, these carriers “have had to become more flexible and responsive to shippers” (Statistics Canada Catalogue 53-222, 1994, 7). As a result of these emerging demands, truck transport is rising in prominence for freight transport. Convenience and time savings are also important considerations for passenger transportation as reflected in Canadians’ overwhelming reliance on the automobile for personal travel.

Road Transportation

Road transportation is the dominant mode in Canada, and an extensive road network has been constructed to support this activity. The network has not expanded significantly over the past 20 years (Tables 8.4 and 8.5), except in areas of new residential and commercial development. It has been upgraded, however, such that 35 percent of the road network is now paved. Most travel occurs on paved roads, as indicated in Table 8.6.

Canadian expenditures on infrastructure are higher for roads than for any other mode, amounting to approximately $11 billion in 1993. Responsibility for Canada’s road network is shared among the three levels of government. In 1995, 2 percent of the road network was under federal jurisdiction, 25 percent under provincial or territorial jurisdiction, and the remaining 73 percent under the control of local authorities, including municipalities (Table 8.7). Of the total expenditures in 1993, one-half were by local governments (Nix, 1995).

Table 8.4: Road Network 1975
(two-lane equivalent kilometres)

Road Type	Length
Paved	240,375
Gravel	458,766
Earth	172,253
Total	872,021

Source: Statistics Canada Catalogue 53-201

Table 8.5: Road Network 1995
(two-lane equivalent kilometres)

Road Type	Length
Paved	317,919
Surface-Treated	69,292
Gravel	442,407
Earth	66,829
Winter	4,134
Other	1,321
Total	901,903

Source: Nix, 1995, 9

Table 8.6: Traffic Volumes 1990
(average annual daily traffic)

Road Type	AADT
Freeway	12,000
Paved (urban)	4,000
Paved (rural)	
-busiest 10%	6,000
-medium volume 30%	3,000
-low volume 60%	700
Surface-Treated	350
Gravel	50
Earth	10

Source: Nix *et al.*, 1992, 973

Table 8.7: Road Network, 1995, By Province/Territory And Jurisdictional Responsibility
(hundreds of kilometres)

	Nfld	PEI	NS	NB	Que	Ont	Man	Sask	Alta	BC	Terr.
Federal	2	<1	3	2	5	23	17	32	40	21	5
Provincial/ Territorial	87	51	234	185	293	285	216	262	183	423	90
Local	41	5	23	31	900	1371	645	1725	1592	214	11
Total	131	57	260	219	1199	1679	879	2019	1814	657	106

Source: Nix, 1995, 8-9

The Automobile

There were 17 million registered vehicles operating on Canadian roads in 1995 (Table 8.8), of which 77.3 percent (13.1 million) were passenger automobiles. Automobiles are the dominant mode of passenger transport in Canada, accounting for approximately 93 percent of total passenger movements (Statistics Canada Catalogue 53-215, 1994). Unfortunately, the private nature of automobile ownership, in combination with the relatively high frequency and short distance of auto trips, means that accurate figures detailing personal travel are not available. Estimation procedures are therefore necessary. The Royal Commission on National Passenger Transportation (1992) used historical data on gasoline sales, estimates of the fractions of this fuel used in cars, and estimates of average fuel economy in order to produce annual estimates of vehicle-kilometres. These figures were then multiplied by an index of assumed occupancy rates to provide estimates of automobile passenger-kilometres. Using this method, it was determined that automobiles accounted for 363.1 billion passenger-kilometres in 1994, an increase of more than 12 percent since 1988 (Table 8.8). Other studies have used travel surveys to estimate and characterize automobile travel at either the provincial (e.g., Chipman *et al*., 1991; Brault, 1997) or municipal levels (e.g., Regional Municipality of Waterloo, 1996), but an attempt to piece these together to provide a national profile has not been made.

Table 8.8: Motor Vehicle Data

	1988	1989	1990	1991	1992	1993	1994	1995
Fuel Sales[1]*	32.0	32.0	40.5	40.5	41.2	42.4	44.0	44.9
Vehicle Production[2]**	1.9	1.9	1.7	1.6	1.8	2.0	2.0	2.1
Registered Vehicles[3]**	16.3	16.7	17.0	16.4	16.5	16.7	16.9	17.0
Vehicle Sales[2]**	1.5	1.4	1.3	1.2	1.2	1.1	1.2	1.1
Auto Passenger Kilometres[4]***	322.9	n/a	334.5	329.8	343.8	356.1	363.1	n/a

*billions of litres; **millions of vehicles; ***billions of passenger-kilometres

Sources: Statistics Canada [1]Catalogue 53-218 [2]Catalogue 11-010 [3]Catalogue 53-219 [4]Environment Canada, 1996

Buses and Public Transit

In 1994, 84 urban transit companies, 46 intercity bus companies, more than 600 school bus operators and dozens of other passenger carriers used the road network to provide a vital service for many Canadians (Statistics Canada Catalogue 53-215, 1994). Bus revenues, which total approximately $5 billion annually, have changed very little over the past few years (Table 8.9). School bus operations have experienced growth, while intercity and urban bus services have witnessed a drop in both revenues and passengers (Table 8.10). Buses are the main mode of urban transit in Canada (Table 8.11), except in selected major metropolitan regions.

Table 8.9: Bus Operating Revenues Including Subsidies (billions of dollars)

	1988	1989	1990	1991	1992	1993	1994	1995
Revenue	3.6	4.1	4.3	4.7	5.1	5.1	5.1	n/a

Source: Statistics Canada Catalogue 53-215

Table 8.10: Bus/Transit Passenger Statistics

Sector	1988	1989	1990	1991	1992	1993	1994	1995
Passengers (millions)								
Intercity Bus[1]	18.2	17.2	17.0	15.9	14.9	10.9	11.4	n/a
Transit[1]	1,514.8	1,520.4	1,528.4	1,450.0	1,432.1	1,396.4	1,360.7	1,355.4
Passenger-Kilometres (billions)								
Intercity Bus[2]	14.3	n/a	14.3	14.9	14.5	14.4	14.4	n/a
Transit[2]	10.8	n/a	10.9	10.9	10.5	10.3	10.3	n/a

Sources: [1]Statistics Canada Catalogue 53-215
[2]Environment Canada, 1996

Table 8.11: Transit Fleet

Type	Number
Buses	10,545
Trolley Coaches	305
Light Rail Vehicles	548
Heavy Rail Vehicles	1,381
Commuter Rail Vehicles	359

Source: Canadian Urban Transit Association, 1995

Trucking

Trucking activities, including for-hire, owner-operated and private enterprises, represent the largest sector within the Canadian transport industry in terms of value of goods moved. Data describing owner-operated and private trucking firms are limited, however, and analysis usually concentrates on the largest component of the trucking industry, namely the large, Canadian domiciled for-hire operations.

Table 8.12 provides revenue data for this group of operators. For 1988 and 1989, data pertain to companies with a revenue of at least $100,000. From 1990 onward, the data are for companies with a revenue of at least $1 million. In 1994, this group of carriers generated 85 percent of the total for-hire trucking revenues and operated 80 percent of the total truck fleet (Table 8.13). The change in reporting conventions explains the sudden revenue drop from 1989 to 1990. Revenue growth since 1991 has been strong; this time period coincides with an era of transportation deregulation and trade liberalization.

Table 8.12: Operating Revenues for Large For-Hire Trucking Companies
(billions of dollars)

Year	1988	1989	1990	1991	1992	1993	1994	1995
Revenues	9.6	10.2	8.4	8.4	8.5	9.2	10.9	12.1

Source: Statistics Canada Catalogue 53-222

Regional data for this group of carriers highlights the importance of trucking to Ontario's economy (Table 8.14). Canadian trucking has always been dominated by intra-provincial flows, although longer-distance freight movement, especially trans-border activity, has increased in recent years (Statistics Canada Catalogue 53-222, 1994). This translates into longer average trip lengths, as shown in Table 8.15.

Table 8.13: For-Hire Trucking Fleet, 1994

Type	Number
All For-Hire Carriers	
Straight Trucks	15,897
Road Tractors	42,062
Semi Trailers	126,501
Other	4,579
$1 million + For-Hire Carriers	
Straight Trucks	7,894
Road Tractors	30,894
Semi Trailers	110,996
Other	2,237

Source: Statistics Canada Catalogue 53-222

Table 8.14: For-Hire ($1 million +) Trucking Operating Revenues, By Region, 1995
(billions of dollars)

Region	Atlantic	Québec	Ontario	Prairies	B.C.	Territories	Canada
Revenues	0.88	2.1	4.5	3.2	1.2	0.05	12.1

Source: Statistics Canada Catalogue 53-222, 1994

Table 8.15: Trucking Freight Statistics for Large For-Hire Operators

	1988	1989	1990	1991	1992	1993	1994	1995
Freight Tonnage (millions)	177.1	162.4	174.2	150.6	149.5	173.4	195.6	210.9
Tonne-Kilometres (billions)	57.8	54.5	77.8	70.6	72.9	84.6	101.8	110.0
Average Trip Length (kms)	326	335	447	469	488	488	520	522

Source: Statistics Canada Catalogue 53-222

Air Transportation

Table 8.16: Aircraft, 1993

Type	Fleet Size
All Registered Civil	17,742
-Private	12,716
-State	267
-Commercial	4,759

Source: Nix, 1995, 12

There are 726 certified airports in Canada, providing facilities for the country's fleet of 17,742 registered civil aircraft (Table 8.16). While most are locally owned and operated, 149 airports, including 26 of which handle 94 percent of all air passengers and cargo, are managed by the federal Department of Transportation (Nix, 1995). There are 970 air carriers in Canada, most of which are relatively small. The industry is dominated by two airlines--Air Canada and Canadian Airlines--which combined account for approximately 79 percent of the passenger-generated revenues attained by the larger airlines (Nix, 1995) and which, in 1993, operated 343 aircraft. Airline operations in Canada have continued to serve the population well, despite fears that deregulation, which came in to effect during the late 1980ís, would affect accessibility to hinterland areas. In fact, one study (Furtado, 1995) showed that the air carrier system has expanded into the more remote regions of the country and that the accessibility of smaller places, relative to Toronto, has actually increased.

The economic performance of the airline industry has been variable over the past several years (Table 8.17). Most revenue is attributable to passenger travel. After rapid growth in air traffic during the 1970s and 1980s, the number of passengers carried by Canadian-based operations has declined slightly over the past several years. In 1994, 32.7 million riders travelled by air, compared to 35.9 million in 1988. The number of domestic-only passengers has declined dramatically since deregulation, from 13.6 million in 1988 to 10.3 million in 1994. Air-based passenger transport currently accounts for approximately 3.5 percent of the trips made by residents of Canada (Statistics Canada Catalogue 53-215, 1994). Passenger-kilometres have shown a slight increase, rising from 63.7 billion in 1988 to 65.6 billion in 1994 (Table 8.18), indicating longer trips on average.

Table 8.17: Air Operating Revenues (billions of dollars)

Year	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
Revenues	7.1	7.8	8.2	7.6	7.5	7.5	8.4	9.3

Source: Statistics Canada Catalogue 51-206

Table 8.18: Air Passenger Statistics

	1988	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
Passengers Boarded (millions)								
All[1]	35.9	37.0	36.7	32.2	32.1	31.4	32.7	n/a
Domestic[2]	13.6	13.1	13.0	11.4	11.4	10.2	10.3	11.2
Passenger-Kilometres (billions)								
All[1]	63.7	67.9	69.3	57.7	62.1	61.0	65.6	n/a
Domestic[2]	24.6	24.7	24.9	21.7	22.3	21.3	22.4	n/a

Source: Statistics Canada [1]Catalogue 51-206 [2]Catalogue 51-204

Freight accounts for only a small percentage of the revenue generated by the Canadian air sector and, in comparison to other modes, airlines carry only a small percentage of the cargo. In 1994, air carriers transported only .68 million tonnes of freight (Table 8.19). This cargo typically has high unit value and is time-sensitive.

Table 8.19: Air Freight Statistics

	1988	1989	1990	1991	1992	1993	1994	1995
Freight Tonnage								
(millions)	0.63	0.65	0.63	0.63	0.61	0.65	0.68	n/a
Tonne-Kilometres								
(billions)	1.6	1.7	1.6	1.6	1.4	2.6	1.7	n/a

Source: Statistics Canada Catalogue 51-206

Rail Transportation

At the end of 1995, Canadian railways operated 84,648 kilometres of track consisting of approximately 45 percent mainline (Table 8.20), 25 percent branch line and 30 percent yards, industrial tracks and siding. This trackage is utilized by 29 rail companies, which collectively operate 3,300 locomotives that pull 117,533 freight cars and 570 passenger cars (Table 8.21). Most of the rail infrastructure is owned by either Canadian National (CN) or Canadian Pacific (CP) Railways; they provide freight transport only and account for approximately 90 percent of the total revenues generated by Canada's rail sector (Nix, 1995). Passenger rail service is the responsibility of the crown corporation, VIA Rail.

Table 8.20: Mainline Track (kilometres)

Province	Length
Newfoundland	240
Prince Edward Island	0
Nova Scotia	730
New Brunswick	949
Quebec	4,208
Ontario	13,312
Manitoba	2,874
Saskatchewan	3,717
Alberta	4,445
British Columbia	7,042
Yukon Territory	0
North West Territories	0
Total	37,517

Source: Statistics Canada Catalogue 52-216, 1995

Table 8.21: Rail Equipment

Type	Number
Locomotives	3,300
Freight Cars	117,533
Box	29,311
Hopper	40,227
Gondola	15,946
Refrigerated	206
Flat	26,520
Livestock	28
Caboose	1,099
Other	4,196
Passenger Cars	570

Source: Nix, 1995,11

Over the past several years, Canada's rail industry has experienced a major restructuring period, coincident with changes in government regulations and subsidies. Operating revenues dropped sharply from $8 billion in 1988 to less than $7 billion in the early 1990's (Table 8.22). Revenues have since begun to show signs of improvement, however, and the freight tonnage carried has increased since 1993 (Table 8.23). The privatization of CN in 1995, in combination with unprofitable track abandonment programs, new shorter lines, and increased linkages with the United States, has created an improved environment for rail operations in Canada (Nix, 1995).

Table 8.22: Rail Operating Revenues (billions of dollars)

Year	1988	1989	1990	1991	1992	1993	1994	1995
Revenue	8.0	7.4	7.0	7.1	6.9	6.9	7.5	7.2

Source: Statistics Canada Catalogue 52-216

Table 8.23: Rail Freight Statistics

	1988	1989	1990	1991	1992	1993	1994	1995
Freight Tonnage								
(millions)	293.8	280.7	268.7	274.1	264.5	264.3	295.1	298.6
Tonne-Kilometres								
(billions)	271.0	249.0	248.3	260.5	250.6	256.3	288.4	280.4

Source: Statistics Canada Catalogue 52-216

Rail's primary role is the transportation of bulk or raw materials over long distances for either processing in another part of Canada or export abroad. Iron ore, coal, and wheat have remained the top three commodities over the past several years and, in 1995, comprised 36 percent of the total tonnage carried (Statistics Canada Catalogue 52-216, 1995). Approximately one-quarter of the total freight transported is bound for the United States (Nix, 1995).

Rail passenger transport has fared less well. In 1995, intercity ridership (excluding regional services in Montreal, Toronto and Vancouver) amounted to only 4 million passengers, accounting for .5 percent of the passenger trips made in Canada. Passenger-kilometres have been stagnant, and revenues have declined (Table 8.24) as both services and subsidies have been cut (Statistics Canada Catalogue 52-216, 1995).

Table 8.24: Rail Passenger Statistics

	1988	1989	1990	1991	1992	1993	1994	1995
Passengers								
(millions)	n/a	n/a	n/a	4.2	4.2	4.1	4.1	4.0
Passenger-Kilometres								
(billions)	n/a	n/a	n/a	1.4	1.4	1.4	1.4	1.4

Source: Statistics Canada Catalogue 52-216

Marine Transportation

Water transport, once the dominant mode of freight transport in Canada, is important today primarily for international trade and the regional distribution of bulk commodities. There are 2,400 ports and harbours in the country. Of these, some 350 fall under federal jurisdiction, while the remainder are controlled largely by private interests. The 30 largest ports handle almost 80 percent of all marine-based freight (Nix, 1995), with Vancouver being the busiest port by far. Most of the deep-water ports are located on the east and west coasts and along the Great Lakes-St. Lawrence system, a 3,700-kilometre network of lakes, rivers, canals and locks.

Much of the traffic at coastal ports is foreign-based. In contrast to this, activity in the Great Lakes-St. Lawrence system is dominated by Canadian ships. “Today two-thirds of the entire Canadian fleet, including ocean-going and coastwise ships, operates on the Great Lakes” (McCalla, 1994, 75). Great Lakes shipping is concerned with primarily bulk commodities, and this is reflected in the fleet composition. Over 70 percent of the Canadian fleet’s carrying capacity is in dry bulk ships, an increasing number of which are self unloaders (McCalla, 1994). Although there are many Great Lakes U.S.-flag vessels that are of the ‘super-carrier class’, being 1000 by 105 feet (304.9 x 32.0 metres), most Canadian vessels are built to the dimensions of the locks in the Welland Canal (Millerd, 1996), which connects Lake Erie and Lake Ontario. At present, the maximum size restrictions are 740 by 78 feet (225.5 x 23.8 metres) ; the maximum permissible draft (water levels permitting) is 26 feet, 3 inches (80 decimetres) (St. Lawrence Seaway Authority, 1997).

From an operations perspective, both revenues and freight tonnage have oscillated from year to year (Tables 8.25 and 8.26), fluctuating especially with resource production and markets. In 1995, 360.4 tonnes of cargo were loaded and unloaded at Canadian ports--a record high for international cargo (259.6 million tonnes) and a record low for domestic freight movements (100.6 million tonnes).

Table 8.25: Shipping Operating Revenues (billions of dollars)

Year	1988	1989	1990	1991	1992	1993	1994	1995
Revenues	2.2	2.3	2.6	2.8	2.5	2.7	2.8	n/a

Source: Statistics Canada Catalogue 54-205

Table 8.26: Shipping Freight Tonnage (millions of tonnes)

Year	1988	1989	1990	1991	1992	1993	1994	1995
Tonnage	390.0	363.0	353.1	350.8	327.7	324.0	352.0	360.4

Source: Statistics Canada Catalogue 54-205

Canadian shipping operations are summarized regionally based on the following geographic areas: Atlantic, St. Lawrence, Great Lakes, and Pacific. The Atlantic region includes ports in both Atlantic and Arctic Waters as well as those in the lower portion of the Gulf of St. Lawrence. The Great Lakes region consists of ports located on the Great Lakes, as well as those along the

St. Lawrence river west of the Ontario-Quebec border. Except in the Great Lakes, international traffic is dominant and growing (Table 8.27). In the Great Lakes region, domestic and international freight are of similar importance, and both have declined in recent years. Related to this, cargo volumes through the Montreal to Lake Ontario section of the St. Lawrence Seaway reached a 28-year low in 1991, although there has been some recovery since then. In 1996, the St. Lawrence Seaway recorded its highest overall traffic volume since 1988 (St. Lawrence Seaway Authority, 1996). The decline in Great Lakes shipping is attributed to a variety of factors including reduced grain shipments (more is now exported through west coast ports to Asian markets), increased use of containers (handled mostly at ports outside the Seaway), more ocean-going vessels that are too large for the Seaway locks, limitations on winter navigation, Seaway tolls and competition from railways (Millerd, 1996).

Table 8.27: Total Freight By Region (millions of tonnes loaded and unloaded)

	Atlantic		St. Lawrence		Great Lakes		Pacific	
Year	Domestic	International	Domestic	International	Domestic	International	Domestic	International
1995	11.5	53.2	28.9	80.7	29.0	32.1	31.2	93.5
1994	12.7	47.9	28.8	73.2	31.6	34.7	31.0	91.0
1993	11.3	46.5	24.4	65.4	29.6	29.9	34.5	82.1
1992	11.9	38.4	30.5	66.6	33.8	32.7	28.1	85.2
1991	11.8	42.4	33.3	70.2	38.0	29.7	33.6	91.6
1990	13.3	42.5	33.7	71.6	37.0	32.6	36.5	85.5
1989	12.8	41.8	29.6	74.8	38.4	37.7	43.1	84.9
1988	13.2	42.0	33.8	76.3	40.8	39.4	52.0	92.1

Source: Statistics Canada Catalogue 54-205

Table 8.28 illustrates differences in the regional character of marine operations in Canada. In some instances freight commodities originate in Canada and are transported by more than one mode for processing elsewhere in the country (e.g., some of the iron ore mined in Quebec-Labrador is brought by rail to selected St. Lawrence ports and then loaded onto ships for distribution to steel mills in Ontario; forestry products, such as logs, bolts and pulpwood, are shipped between various Pacific ports). Other times commodities are part of international trade (e.g., Atlantic Canada imports crude petroleum, refines it and then redistributes the products; wheat is transported by rail from the Prairies, loaded at Thunder Bay onto ships destined for trans-shipment points on the lower St. Lawrence River, and finally loaded onto ocean-going vessels for export).

Marine-based operations in Canada are not commonly recognized for their role in passenger transportation, but ferries and other water-borne vessels transported 34.9 million individuals in 1994, ranking these operations second only to air transport in terms of ridership (Table 8.29). The British Columbia Ferry Corporation (BCFC) is the largest of these enterprises. In 1994, the BCFC carried 21 million passengers and 8 million motor vehicles (Nix, 1995). This type of service is essential to many coastal and island communities.

Table 8.28: Shipping - Top Three Freight Commodities In 1994, By Region
(millions of tonnes)

	Atlantic		St. Lawrence		Great Lakes		Pacific	
	Freight	**Tonnes**	**Freight**	**Tonnes**	**Freight**	**Tonnes**	**Freight**	**Tonnes**
Domestic Loaded	Fuel Oil	1.5	Iron Ore	6.6	Wheat	5.8	Pulpwood	7.2
	Salt	1.4	Base Metal	2.3	Non-metals	2.0	Wood	4.4
	Gypsum	1.0	Fuel Oil	2.1	Limestone	1.7	Limestone	0.8
Domestic Unloaded	Fuel Oil	1.8	Wheat	4.7	Iron Ore	5.7	Pulpwood	7.2
	Gasoline	1.1	Base Metal	2.3	Limestone	1.7	Wood	4.4
	Non-metals	0.7	Fuel Oil	1.9	Non-metals	1.6	Limestone	0.8
International Loaded	Gypsum	6.1	Iron Ore	31.4	Salt	2.6	Coal	30.1
	Fuel Oil	4.2	Wheat	5.2	Cement	2.2	Wheat	14.0
	Gasoline	3.2	Base Metal	1.4	Non-metals	1.4	Woodpulp	5.5
International Unloaded	Petroleum	16.8	Petroleum	6.6	Coal	7.9	Sand/Gravel	1.1
	Fuel Oil	1.4	Aluminum	5.6	Iron Ore	5.6	Machinery	1.0
	Machinery	1.0	Chemicals	1.5	Limestone	2.5	Phosphate	0.8

Source: Statistics Canada Catalogue 54-205, 1994

Table 8.29: Marine Passenger Statistics (millions of passengers)

Year	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
Passengers	30.8	31.7	33.7	33.2	32.1	34.0	34.9	n/a

Source: Statistics Canada Catalogue 54-205

Pipeline Transportation

An extensive pipeline infrastructure exists in Canada (Table 8.30). The various pipeline systems allow the transportation of crude oil to refineries and the distribution of natural gas to consumers in both Canada and the United States. The reporting practices of the pipeline sector limit the amount of information documenting transportation-related activities. In 1993, 70 oil pipeline companies were in operation and these generated revenues of approximately $1 billion. The main carrier, Interprovincial Pipe Line (IPL), operates the world's longest crude oil and liquids

Table 8.30: Pipelines, 1993 (kilometres)

Type	**Length**
Oil Pipelines	
Gathering	11,112
Trunk Crude	19,259
Product Lines	5,669
Total	36,040
Gas Pipelines	
Gathering	6,924
Transmission	71,621
Distribution	182,012
Total	260,557

Source: Nix, 1995, 13

pipeline. In 1994, IPL deliveries exceeded 1.5 million barrels per day (Nix, 1995). Of the 100 gas pipeline companies in operation, the largest is TransCanada Pipeline Limited. In 1994, its main pipeline moved 62.9 billion square metres of gas of which 46 percent was exported (Nix, 1995).

Intermodal Operations

Although most of the numerical information on transport activities is mode-specific, it is important to recognize the strong linkages among the three main freight modes (i.e., trucking, rail and marine) through containerization. For marine transport, the proportion of international cargo that is containerized has increased steadily in recent years, reaching 8.7 percent for arriving and 4.9 percent for exported cargo in 1994 (Statistics Canada Catalogue 54-205, 1994). Railway intermodal traffic has also grown, with nearly 16 million units loaded in Canada in 1995, up from 11.2 million in 1992 (Fitzpatrick, 1997).

VULNERABILITIES AND IMPACTS ASSOCIATED WITH CLIMATE CHANGE

Transportation is a complex and dynamic sector that is affected by economic, political, regulatory, technological, demographic and cultural forces. As noted by Jackson (1990), climate change may be only a minor factor compared to these many other forces. Despite this, climate-related costs can be substantial and affect a wide range of businesses, institutions and publics. This section of the report summarizes what is known about the potential impacts of climate change on transportation in Canada. It should be noted that some of the issues that are discussed here could have been included in the section on adaptation. This is because most climate impacts are related to design and operational decisions made by the millions of Canadians involved in transportation activities. In other words, costs are associated primarily with adaptive behaviours such as winter road maintenance.

Key Summary Reports

Over the past decade, several reports have highlighted the implications of climate change for transportation. From an international perspective, the Intergovernmental Panel on Climate Change (IPCC) report (Watson *et al*., 1996) provides the most comprehensive overview of: (a) the state of knowledge on the sensitivity of transport activities to weather conditions or sea level; (b) the potential impacts of climate change on the transport sector; and (c) the broader economic impacts of climate change.

In terms of sensitivities, the report provides a conceptual framework for considering the effects of different climate variables on industry, energy and transportation. The transportation components of this framework have been reproduced in Table 8.31.

In terms of potential impacts, the IPCC notes that “Recent impact studies covering transportation refer only to developed countries such as Canada ... (and)... generally analyze only the direct impacts of climate on infrastructure and operations (Moreno *et al*., 1996, 374). Their discussion of Canadian impacts is based mainly on the review by the IBI Group of Toronto, which is discussed in more detail below. Key impacts that were identified include:

Table 8.31: Sensitivities of Transport Activities to Weather Conditions

	Energy Transport	Transportation Infrastructure	Transportation Operations
Temperature	Pipelines over permafrost vulnerable	Vulnerability if permafrost melts; changed freeze-thaw cycles on roads	Ice and coastal shipping in high latitudes; road maintenance costs; air conditioning in cars
Precipitation		Impact of snow and ice on road and air transport	
Windiness			
Extreme Events		Effects on roads, railways, bridges	Safety and reliability of operations (e.g., airports)
Availability			Inland navigation
Sea-Level Rise		Effects on coastal infrastructure; migration of coastal activity	
Other		Changes in movements of agricultural products; settlement patterns	Effects of fog, snow, rain, and ice on operations and safety

Source: Moreno *et al.*, 1996, 373-374

- a longer season for Arctic shipping, with a greater number of frost-free (should read ice-free) days;
- a longer shipping season but also decreased water depths in the St. Lawrence Seaway; and
- other effects due to changes in snowfall or melting of the permafrost.

As for the broader economic impacts, the IPCC report (Moreno *et al.*, 1996) highlights the strong interrelationships between land use patterns and transportation activities, and argues that transportation impacts should be addressed within the wider framework of human settlement patterns. The authors report that, although there is some recognition of the fact that climate change could produce significant global re-distributions of population and economic activities, detailed geographic predictions of these phenomena are lacking.

The IBI report, referred to above, represents the first overview of the implications of climate change for transportation in Canada. It was commissioned by Transport Canada and completed in 1988. The full report is referred to as Irwin and Johnson (1988), the summary report as IBI Group (1990). The intent of the review was "... to look, in a qualitative way, at the potential implications of climate change on the transportation sector in Canada" (IBI Group, 1990, Preface). The report deals with both direct impacts as well as selected indirect effects, as summarized in Table 8.32. It also identifies both costs and benefits, but on the whole, IBI

Group's assessment of the implications of climate change for transportation is positive, as noted in the study highlights: "Preliminary assessment suggests that, on balance, long-term climate impacts on Canadian transportation may have a net beneficial effect" (IBI Group, 1990, 1). The amount of supportive evidence is often weak, however.

Since 1988, several other reports have summarized the potential impacts of climate change on transportation in Canada. Jackson (1990, 1992), in his report on *Global Warming: Implications for Canadian Policy*, devoted some attention to the transport sector. He summarized and critiqued the IBI Group study referred to above. He also referred to Stokoe *et al.*'s (1988) empirical analysis of marine operations in Atlantic Canada and the Great Lakes Institute's (1986) detailed study of Great Lakes navigation. The two latter reports are discussed later. Overall, Jackson's assessment of transportation impacts is also optimistic. He stated " ... there is little doubt that the present Canadian climate imposes heavy costs on the transportation sector" (Jackson, 1990, 95) and that "... it seems reasonable to anticipate that, overall, global warming would benefit Canada's transportation sector, since so many of the additional costs that the sector incurs, in comparison with other industrialized countries, can be traced directly or indirectly to the severity of the winter."(Jackson, 1990, 100).

Table 8.32: Summary of IBI Group Report

Mode	Transportation Impacts	Geographic Extent	Additional Capital Costs		Change in Unit Operating Cost	Scale of Socio-Economic Implications	Nature of Impact
			To Maintain/Restore System	To Meet Expected Area and/or Demand			
Marine-Ocean and Marine Arctic	Increased Export Trade	Major	N/A	Minor-Significant	Minor Decrease	Significant	Net Benefit
	Increased Coastal Trade	Major	N/A	Significant	Moderate Decrease	Significant	Net Benefit
	Ice-Free Labrador/Hudson Bay	Major	N/A	Moderate	Significant Decrease	Moderate	Net Benefit
	Harbour/Dock (Re)Construction	Limited	Moderate	Moderate	Neutral	Modest	Net Cost
	Increased Coast Guard Activity	Major	N/A	Significant	Significant Increase	Moderate	Net Cost
	Increased Defence Activity	Major	N/A	Significant-Major	Significant Increase	Moderate	Net Cost
Marine-Great Lakes	Increased Export/Import Coastal Trade	Significant	N/A	Moderate	Neutral	Modest	Net Benefit
	11 or 12 Month Operations	Significant	N/A	Modest	Minor Decrease	Moderate	Net Benefit
	Expanded Water Level Control Systems	Significant	Major	N/A	Moderate Increase	Moderate	Net Cost
Roads-South	Decreased Winter Maintenance (Snow Removal)	Major	N/A	N/A	Moderate Decrease	Modest	Net Benefit
	Realignment/Protection from Coastal Flooding	Moderate	Significant	N/A	N/A	Modest	Net Cost
Roads-North	Expanded System to Serve Northern Areas	Major	N/A	Major	Modest Increase	Major	Net Benefit
	Realignment/Protection from Coastal Flooding	Modest	Moderate	N/A	N/A	Minor	Net Cost
	Shorter but Heavier Snow Removal Season	Major	N/A	N/A	Modest Increase	Modest	Neutral
	Shorter Season for Winter Roads	Significant	Modest	N/A	N/A	Modest	Net Cost
Railways	Expanded System to Serve Northern Areas	Major	N/A	Major	Modest Increase	Major	Net Benefit
	Realignment/Protection from Coastal Flooding	Modest	Moderate	N/A	N/A	Modest	Net Cost
	Reduced Winter Traffic due to Ice-Free Great Lakes	Significant	N/A	N/A	Neutral	Modest	Neutral
	Improved Operations on Northern Lines	Moderate	Moderate	N/A	Moderate Decrease	Modest	Net Benefit
	Net Decrease in Winter Maintenance	Major	N/A	N/A	Modest Decrease	Modest	Net Benefit
Air	Expanded System to Serve Northern Areas	Major	N/A	Significant	Modest Increase	Major	Net Benefit
	Expanded Navigation Aids (or Down Time)	Major	Moderate	Moderate	Modest Increase	Modest	Net Cost
	Lower Lift and Engine Efficiency	Major	N/A	N/A	Modest Increase	Minor	Net Cost
	Shorter Season for Winter Airstrips	Significant	Modest	N/A	Moderate Increase	Modest	Net Cost
	Increased Coast Guard and S&R Activity	Major	N/A	Significant	Significant Increase	Moderate	Net Cost
	Increased Defence Activity	Major	N/A	Significant-Major	Significant Increase	Moderate	Net Cost

Legend: Five Point Impact Scale in Declining Order: Major, Significant, Moderate, Modest, Minor
Net Benefit = Transportation revenues may increase relative to costs, possibly in the context of an overall increased transportation role
Neutral = Costs and Benefits offset each other
Net Cost = Transportation costs may increase relative to revenues
N/A = Not applicable

Source: Irwin and Johnson, 1988, Exhibit 3-3 as reproduced in Jackson, 1990

Despite the overall positive tone of both of the these and other summaries (e.g., Canadian Climate Program Board, 1991; IJC, 1993; Environment Canada, 1994) available evidence suggest that the expected impacts vary considerably by mode and region. The remainder of this section is dedicated to a more detailed discussion of climatic vulnerabilities and impacts. It is organized by transport mode. For each mode, various types of impacts on transport infrastructure and operations are identified and references are made to place- or region-specific vulnerabilities

Roads

Because of the importance of roads for both passenger and freight transport in Canada, the implications of climate change for road infrastructure and travel are fundamental to an assessment of the socio-economic impacts of climate change.

Infrastructure - Paved Roads

Paved roads are the economic arteries of the nation. The principal pavement type used in Canada is a flexible pavement consisting of granular base and sub-base courses along with a surface course of asphaltic concrete (Nix *et al.*, 1992). It is widely acknowledged that climate, especially the harshness of the winter, affects both the initial construction design as well as the maintenance costs of these roads. The primary concern is over low-temperature cracking related to freeze-thaw cycles and frost action. As part of the 1992 Royal Commission on National Passenger Transportation, Nix *et al*. (1992), reviewed various models of road deterioration in order to identify the relative contribution to pavement deterioration of traffic loads and environment. They concluded that, "... according to the best evidence available in Canada, for flexible pavements and particularly for roads where the total annual axle loadings are relatively modest, environmental factors account, by far, for the largest portion of pavement deterioration ... (O)n a very high-volume road ... environmental factors may account for as much as 50 percent of the pavement deterioration. On low-volume roads, environmental factors may account for 80 percent or more of the deterioration." (Nix *et al.*, 1992, 1014). The authors do not consider the potential effects of climate change on Canada's road infrastructure, but their analysis would suggest that a warmer climate would have beneficial effects on pavement life.

Some studies have suggested that some of the benefits of milder winters could be offset by heat stress causing pavement damage/buckling in southern Canada, as has been observed during selected events in the United States (e.g., Miller, 1988). According to one of Canada's experts on pavements (Haas, 1997), this is not a serious concern, however, because few roads in Canada are made of jointed concrete pavements, and those that are have had their joints reconstructed. There is the possibility that periods of extreme, prolonged heat combined with heavy traffic could cause some pavement rutting, but even this could be handled in the design stage.

Infrastructure - Coastal Regions

There is broad-based consensus that global warming would affect sea levels due to a combination of thermal expansion and increased melting of glaciers. This has implications for coastal infrastructure and operations of all types, including transportation.

Studies by Martec Ltd. (1987), Lane and Associates (1988) and Stokoe *et al* (1988, also summarized in Stokoe 1988), provide insight into the implications of climate change for coastal infrastructure, including roads, bridges and causeways, in the Atlantic Provinces. All three studies used a one-metre rise in sea level as the starting point for their analyses.

Both the Martec Ltd. (1987) and Lane and Associates (1988) studies were based on statistical modeling to predict the height and geographic extent of the 1 in 20 and 1 in 100 year storms, assuming a one-metre rise in sea level. The Martec Ltd. (1987) study focused on Saint John, N.B. and concluded that road infrastructure would be heavily affected. The authors predict that Courtenay Bay Causeway would have to be rebuilt, increased flooding in the Jemseg-Maugerville section of the Trans-Canada Highway would severely disrupt road transportation between Atlantic and Central Canada, and road and other infrastructure damage would occur along the Bay of Fundy shoreline, particularly in the City of Saint John. Lane and Associates (1988) focused on Charlottetown, P.E.I. and concluded that sections of several streets in Charlottetown would be below high tide or subject to flooding during storms. They indicated that three small causeways on the North River Road, Beach Grove Road and Riverside Drive would have to be rebuilt to a higher elevation, and that the North River Causeway would have to be raised.

Stokoe *et al*. (1988), whose study was broader in scope, also suggested that a one-metre rise in sea level would have serious consequences: 14 causeways in the Maritime Provinces and 17 in Newfoundland would need to be upgraded, at a cost in the order of $100 million; 200 bridges in each of Nova Scotia, New Brunswick and Newfoundland and 33 in Prince Edward Island would have to be reconstructed at a cost approaching $1 billion; and finally road reconstruction costing in the hundreds of millions of dollars would be required.

These inventories of vulnerable sites and structures are a useful starting point for adaptive planning, but should not be taken as predictions of what will occur in the next century, since roads and bridges have a typical lifespan of 20-50 years. As noted in Jackson (1990, 98), "... the sea-level rise due to global warming that is anticipated is substantially less than one metre, even by the year 2070. Over that length of time, all or most of the structures will probably require replacement or major maintenance for other reasons, and appropriate provision for sea-level rise can be incorporated into such improvements." It is important, however, that infrastructure design take climate change into account. At this point, there is little evidence that this is occurring.

Less attention has been given to the potential effects of sea level rise on other coastal regions of Canada. Clague (1989, 32) examined the Pacific coast and noted that "Shorelines formed on Pleistocene sediments may be severely eroded as the sea rises. In addition, low-lying delta plains and some roads and buildings may be inundated during storm surges." Richmond, located on the Fraser delta just south of Vancouver, is one such vulnerable area (Beckmann *et al*., 1997).

Infrastructure - Northern Roads and Forest Roads

There are several issues associated with road infrastructure and access in the North and other remote regions. There are concerns over the viability of non-permanent roads such as winter and forest roads, and over the usability and maintenance of all-season roads, especially those that have been constructed over permafrost.

One type of road that has been studied in detail is ‘winter roads on ice’. Winter roads constitute an important part of the transportation network in parts of the North. For example, about 10-15 percent of the total annual volume of flow of goods in the Mackenzie Valley moves over winter roads, some of which cross major rivers including the Mackenzie, the Liard and the Great Bear (Woo and Lonergan, 1990). As the name implies, winter road are functional in the winter only, being made of snow, ice or a mixture of mineral soil and snow/ice. ‘Winter roads on ice’, or ice roads as they are commonly called, include those winter roads that are created on the frozen surface of lakes and rivers.

The definitive piece of research on the implications of climate change for ice roads in Canada was done as part of the Mackenzie Basin Impact Study (Cohen, 1997) by a team of researchers at the Universities of Victoria and Toronto (Woo and Lonergan, 1990; 1992; Woo, 1992; Lonergan *et al.*, 1993). “A scenario approach, based on three global circulation models (GCMs), was used, with an emphasis on modelling climate variability, river ice conditions and economic impacts” (Lonergan *et al.*, 1993, 331). Stochastic simulation models of air temperature and precipitation were developed in order to produce synthetic time series data that reflect the effects of climate change. These data were then used to simulate river ice growth and decay, which, combined with empirical formulae, were used to indicate the duration when vehicles exceeding certain weights would be safe to cross the Mackenzie River at Norman Wells.

Table 8.33: Ice Road Season for Crossing the Mackenzie River at Norman Wells

Scenario	Mean Duration	Standard Deviation
Current	178 days	15.1 days
OSU GCM, 2xCO_2	148 days	14.7 days
GISS GCM, 2xCO_2	138 days	20.6 days
GFDL GCM, 2xCO_2	132 days	20.8 days

Source: Lonergan *et al.*, 1993, 341

Three GCM scenarios were considered and all were associated with a substantial reduction in the length of the ice road season, as shown in Table 8.33. The authors noted, however, that the reduced opportunity for over-ice traffic would be compensated by a longer open-water season for barge transport of anywhere from 6 to 9 weeks. Given the lower cost of barge transport relative to roads in general, especially winter roads, it was estimated that the net effect on the economy could be positive if the cost savings were passed on to consumers. Because of the monopolistic competition in the transport industry of the region, however, the authors anticipate that the cost savings arising from an extended ice-free season would not benefit consumers (Woo and Lonergan, 1992). In fact, there is a possibility that the net effect could be negative if companies decide to lay off employees (Woo and Lonergan 1992) or if some of the traffic is diverted from ice roads to a more expensive mode, such as air (Bone *et al.*, 1994).

In the North, many of the all-season roads are also vulnerable to climate change because they have been built over permafrost. The Arctic regional report of the Canada Country Study provides a concise summary of the characteristics and spatial extent of permafrost in Canada, as well as the likely response of permafrost to climate warming. Based on this, is appears that increased permafrost instability would increase the costs of building and maintaining all-weather roads in the Yukon and Northwest Territories. It would be possible to estimate the geographic extent and financial implications of permafrost thaw by combining climate-change scenarios with current heat transfer models, but no examples of this type of analysis were found.

Other roads that may be affected by changes in climate, especially precipitation, are the thousands of kilometres of forest roads, many of which are privately owned. These roads are crucial to the harvesting and subsequent management of forest resources in Canada.

Infrastructure - Extreme Geophysical Events

Changes in precipitation regimes are expected to affect the frequency and magnitude of natural processes such as debris flows, avalanches and rockfalls. In the past, there have been many examples of damage to transportation infrastructure and disruption to service in mountainous regions of Western Canada, due to rainfall-induced landslides, and it is evident that the integrity of some transportation corridors in this region would be negatively affected by increased rainfall-induced events of this type (Evans and Clague, 1997). Slope instability is also a risk in parts of eastern Ontario and Quebec.

Operations - Winter Maintenance

The Canadian winter has a significant impact on road maintenance costs. Winter maintenance programs exist to minimize economic losses, prevent accidents and facilitate handling of emergencies. These programs involve snow plowing, snow removal and disposal, the application of de-icing chemicals and/or abrasives, and other activities such as snow fencing (e.g., Perchanok *et al*., 1991). Although programs differ from place to place (see for example various issues of *Civic Public Works*), largely as a function of temperature and snowfall, they represent a significant expense for every provincial and local government in the country. To give an indication of the magnitude of related expenses, consider de-icing chemicals. Four million tonnes of de-icing salt are spread each year by provincial and municipal road crews across Canada (Samuels, 1989); road salt typically costs $35-$40 per tonne.

Annual expenditures do vary, depending on the weather. For example, the Ontario Ministry of Transportation winter road maintenance costs dropped by $14 million (8 percent) from 1993-94 to 1994-95. This was attributed to unseasonably warm December and January temperatures, above average rainfall and low snowfall amounts in 1994-95 (Mortsch, 1995). Various studies have developed regression equations to summarize the empirical relationship between winter road maintenance activities/costs and key weather variables (e.g., Cohen, 1981; McCoy 1993; McCabe, 1995; Cornford and Thornes, 1996). Results vary due, in part, to differences in the temperature and precipitation variables used and also the temporal-spatial scale of analysis, but it is clear that ‘less harsh’ winters are associated with lower costs.

It is not surprising, therefore, that the IBI Group (1990) suggested that one of the major impacts of global warming would be substantially reduced winter maintenance activities and expenses in southern Canada where the shorter winter season would likely be combined with less snowfall. They also noted that in central Canada the benefits of a shorter winter season could be offset by increased snowfall. The report does not provide any quantitative estimates, but two recent undergraduate theses provide some indication as to the magnitude of the potential savings for two locations in Ontario. McCabe (1995) examined salt use on roads under the jurisdiction of Metropolitan Toronto. Using sensitivity analysis guided by output from two GCMs, he estimated that climate change would reduce salt use (tonnage) by between 17 and 71 percent. McCoy (1993) studied selected Ontario provincial highways in Bruce and Grey Counties and estimated that at 3.5 degrees C. warming would reduce salt use by approximately 35 percent and sand use by 55 percent. These studies are not definitive but are among the first attempts to quantify the potential savings of climate change on winter road maintenance activities.

Mobility and Other Operational Effects

Transportation systems exist to facilitate mobility; thus, there has been a long-standing interest in weather-related disruptions to transportation operations. Both research papers and media coverage tend to focus on extreme events. A couple of recent examples include the winter storms that paralyzed the south coast of British Columbia from December 22 to January 3, 1997 and resulted in economic losses in the range of $200 million (Pan Pacific Communications, 1997) and the April, 1997 blizzard that cost trucking companies in southern Manitoba millions of dollars. Of course, Canadians' mobility is negatively affected by many weather events, which, in effect, define a hierarchy of disruption (de Freitas, 1975); unfortunately, quantitative estimates of the associated costs tend to be available only for the most serious of these.

Fuel consumption is also weather-sensitive. Temperature affects both the time required for a vehicle to warm up and the overall fuel efficiency, although a few degrees warming is not likely to have major effects (Moreno *et al.*, 1996). On the other hand, warmer temperatures could lead to more air conditioning in vehicles, which could lead to a substantial increase in fuel consumption, as demonstrated in the American study by Titus (1992).

Safety

Transportation accidents are a serious concern in Canada and most other countries. Road accidents are the number one cause of lost life expectancy in North America (Evans, 1991); total related costs in Canada are in the billions of dollars (e.g., MTO 1994). Although it is difficult to compare accident rates from one mode to another, road travel is the mode of greatest concern because of the absolute magnitude of the problem (Table 8.34).

For any given road collision, it is difficult to separate out the effect of weather (e.g., rain/snow, wind, fog, glare, heat stress) from other contributing factors. Still, aggregate numbers make it clear that weather is an important risk factor. In Canada in 1995, approximately 20 percent of all the personal injury collisions occurred while precipitation was occurring (Table 8.35), yet in many parts of Canada, precipitation occurs only 10 to 15 percent of the time. This suggests that

Table 8.34: Transportation Accidents, 10-Year Averages

Mode (latest year)	Accidents	Fatalities
Road (1993)[a]	183,667	3,986
Rail (1994)[b]	1,028	120
Air (1994)[c]	522	167
Marine (1994p)[d]	958	51
Pipeline (1994p)[e]	10	<0.5

p preliminary
a Collisions that were reported and resulted in a fatality or injury
b Federally-regulated rail carriers only
c All Canadian-registered civil (non-military) aircraft operating anywhere in the world and foreign aircraft operating in Canada
d All vessels operating in Canadian waters and all Canadian-registered or licensed vessels operating anywhere in the world (excludes pleasure craft)
e Federally regulated oil and gas pipelines only.
Source: Nix, 1995, 20. Based on data from Transportation Safety Board of Canada and Transport Canada.

accident rates are elevated during rainfall and snowfall, and, indeed, this has been confirmed in detailed studies by Mende (1982) for Metropolitan Toronto and Andrey (1989; Andrey and Olley, 1990; Andrey and Yagar, 1993) for several Alberta cities. The results of these studies indicate that accident rates increase from 40 to more than 300 percent during precipitation, with increases being greatest for property damage collisions and least for fatal crashes. The results of these studies are not amenable to making projections about the likely effects of changed precipitation patterns on safety, however. The reason is that is some instances risks are higher for snowfall than rainfall, and other times the pattern is reversed. Andrey (1989) attempted to build a logit model to explain the relative risk of collision based on different storm characteristics, but the results were not encouraging. It appears that many variables, in addition to weather, affect accident patterns; these include time, place, driver and vehicle characteristics, and roadway environment. More work needs to be done to understand weather-related risk patterns and drivers' adaptations to weather hazards.

To date, transportation safety has not been seriously considered in the climate change literature. This is serious gap (Andrey, 1990), as climate change would alter the driving environment in various ways.

Table 8.35: Number of Road Traffic Collisions, 1995, by Weather Condition

Weather Condition	Fatal Collisions	Personal Injury Collisions
Clear (sunny or cloudy)	2,302	127,306
Fog/Mist/Smog/Dust/Smoke	48	1,582
Rain	232	19,433
Snow/Freezing Rain/Hail/Sleet	221	13,396
Other/Not Stated	48	2,382,
Total	2,851	164,099

Source: Transport Canada, TP3322, 1995 Canadian Motor Vehicle Traffic Collision Statistics

Rail

Rail is the workhorse of overland transportation in Canada, being responsible for moving between 250 and 300 billion tonne-kilometres of freight each year. In terms of climate change, rail infrastructure is vulnerable to some of the same risks as are roads. For example, Ross and Wellisch (1997) noted that increased precipitation could lead to increased flooding and washouts in western Canada and that this could disrupt coal transport by rail. Indeed, there have been several examples of rain-induced landslides in the past, including the 1997 mudslide in the Fraser Canyon that washed out a section of CN track near Lytton, derailing a freight train and killing two crewmen (Vancouver Sun, March 21 and 26, 1997). Also, in selected coastal areas of Atlantic Canada, there is reasonable evidence that sea level rise could cause serious disruption to rail systems (Martec Ltd., 1987). Apart from papers outlining the potential direct effects of climate-induced geophysical extremes on rail infrastructure, however, there has been virtually no serious research on the implications of climate change for Canadian rail operations. This is a serious gap in the climate change literature since rail operations in Canada are very much affected by climate, especially by the harsh Canadian winter. In particular, low temperatures increase the incidence of rail defects/breaks and switch freeze-ups, heavy snowfalls increase the costs of track maintenance, and frost can cause signal failure. In addition, winter conditions increase wheel wear and necessitate shorter train lengths and temporary slow downs. In short, winter increases both operating costs and the probability of delay and/or derailment.

Not surprisingly, rail companies have formulated plans and procedures for dealing with winter weather. The following information provided by CN Rail (Darby, 1997) illustrates the nature of their winter operating plan as well as some related costs:

- Track inspection including ultrasonic rail testing is done in order to identify and repair rail defects.
- Efforts are made to improve equipment design (e.g., front plows of brooms to clean out the flangeways better) and optimize equipment usage (e.g., hot versus cold snow jets).
- Snow removal programs (approximately $5.5 million in winter of 96-97) and sanding and salting operations are implemented.
- Wheel wear is monitored and damaged wheels replaced, e.g., 9000 pairs of wheels were changed out in February, 1997.
- Temporary slow orders (travel speeds reduced by up to one-third) are given when temperature drops below -20 degrees Celsius.
- There are procedures to minimize disruption during snow storms, with different levels of response for storms of different severities.
- The winter operating plan is constantly being improved, e.g., practice workshops are held, personnel are trained, the location and readiness of snow-fighting equipment are reviewed, and winter and storm post-audits are conducted.

Given the negative impact of the current climate on rail operations in Canada, it is not surprising that the IBI Group (1990) suggested that one of the major beneficial effects of climate change would be decreased winter maintenance costs for rail operators. While there is insufficient information to provide a quantitative estimate as to the potential savings, the direction of the impact is reasonably well established.

The IBI Group (1990) report also identified several other potential impacts of climate change on the rail sector, but closer scrutiny suggests that these are not serious issues. First, they noted that warmer temperatures would decrease engine efficiency. Discussions with the industry, however, suggest that this effect would be minor and that improved engine technology will have a greater impact on fuel efficiency than climate change (Darby, 1997). A second potential impact identified by IBI Group pertains to the northward retreat of permafrost. The IBI Group suggested that this would change railbed requirements, which could result in either lower or higher infrastructure costs. At present, there is very little trackage over permafrost terrain; the only CN line is the Churchill line that extends to Hudson Bay. Furthermore, the long term fate of these remote lines will have more to do with transport demand and intermodal transport opportunities and than with climate or terrain. Thus, it is unlikely that changes to the permafrost would have significant effects on rail operations in Canada. Finally, the IBI Group indicated that climate-induced changes in grain production, settlement patterns, and other transport operations would affect rail operations. Such indirect impacts, which are highly speculative, are dealt with later in this section.

Marine

Great Lakes-St. Lawrence

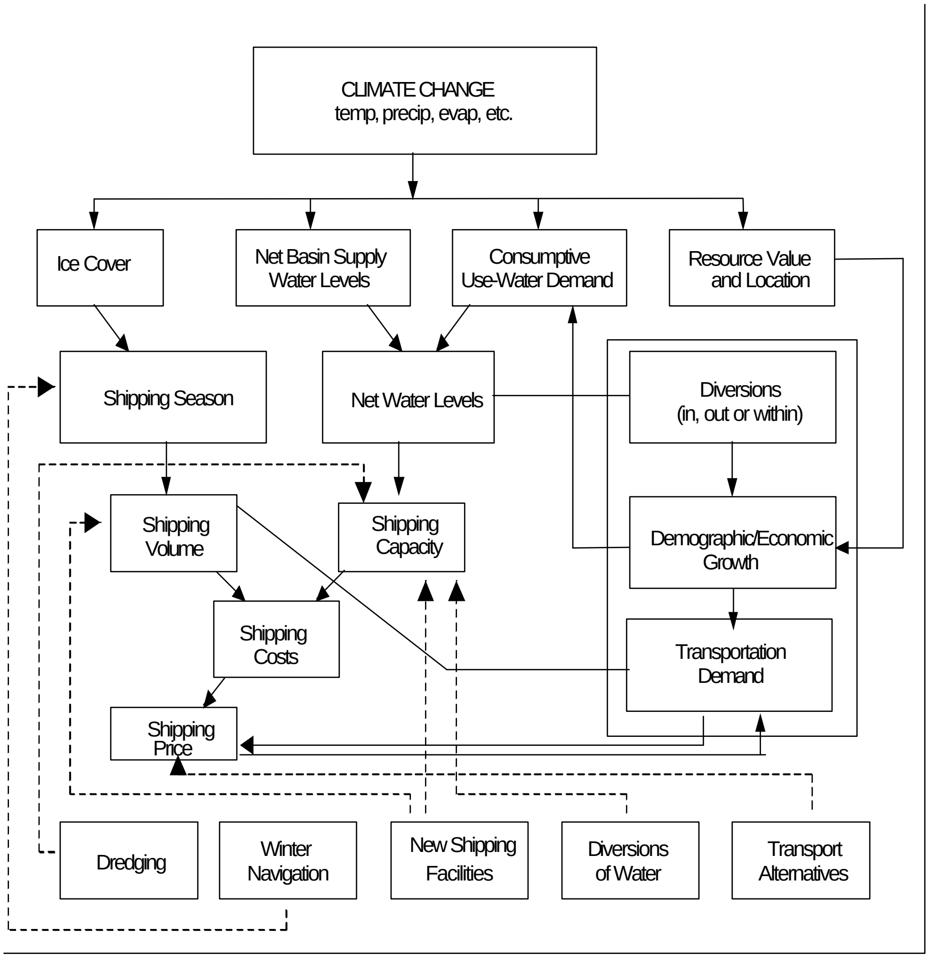
As noted in section 3, shipping in the Great Lakes-St. Lawrence system accounts for a significant proportion of the marine activity in Canada, and as an inland waterway is very much affected by water depths. The Water Resources chapter of the Canada Country Study summarizes the potential effects of climate change on the hydrology of the Great Lakes-St. Lawrence system. Although estimates do vary from study to study, there is consensus that climate change, as projected by GCMs, would decrease net basin supply substantially, thus reducing water levels and flows. Less attention has been devoted to the effects of future warming on ice cover, but there is some empirical evidence that a changed climate would also reduce the spatial and temporal extent of lake ice (e.g., Assel, 1991; Marchand *et al.*, 1988). These physical changes have implications for navigation, as is illustrated in the conceptual model in Figure 8.1.

In terms of climate change impacts, the first serious investigation focusing on Great Lakes navigation was conducted by the Great Lakes Institute of the University of Windsor (1986). Summaries of this work are published as Marchand *et al.* (1988) and Sanderson (1987). References to this work appear in virtually all summaries of the implications of climate change for water resources and navigation in Canada.

This study combined the output of several models--climatic, hydrologic , and socio-economic--in order to estimate the possible impacts of one climate change scenario on Great Lakes shipping. A complex economic model (modified form of ILER, 1981) was used to "... determine for each month the allowable draft for shipping along each of the trade routes in the system, based on available water depths under a given regime of lake levels. These drafts are converted into ship loading capabilities from which the number of trips required to move the various cargoes is calculated. These compilations incorporate the knowledge of fleet composition, vessel characteristics, operating speeds, unloading time, load line limits and other operational characteristics of the system" (Marchand *et al.*, 1988, 123).

Five scenarios of shipping costs were considered: one for the mid 1970s (basis of comparison), one for no climate change but with a forecasted economy to the year 2035, and three using the GISS 2xCO_2 climate scenario (includes one with a static economy; one with the forecasted economy; and a third with the forecasted economy, increased consumptive use of water and an extended shipping season due to reduced ice cover). The simulation results, as summarized in Table 8.36, suggest that average annual shipping costs to Canadian Great Lakes shipping companies for the four principal commodities (iron ore, grain, coal and limestone) would increase by 5 to 30 percent (depending on the scenario) and shipping costs, typically, would equal or exceed those of the period of record low water levels of 1963-65.

Figure 8.1: Theoretical Framework of the Impacts of Climatic Change on Great Lakes Commercial Navigation



Source: Marchand *et al.*, 1988, 114

Table 8.36: Average Annual Navigation Costs - Canadian Fleet ($1979 US millions)

Scenario	Iron Ore	Grain	Coal	Limestone	Total	% Years at or above 1963-65
Basis of Comparison	78.75	77.25	31.38	9.60	196.97	10
Forecasted Economy	76.29	68.03	50.34 - 82.44	7.58	202.25 - 234.34	10
Climate Change, Static Economy	83.98	80.08	33.15	9.67	206.88	69
Climate Change, Forecasted Economy	82.84	72.83	53.61 - 87.78	8.04	217.32 - 251.49	66
Climate Change + + +	86.55	75.56 - 75.68	55.93 - 91.58	8.34	226.38 - 262.16	97

Source: Marchand *et al*., 1988, 126-127.

A more recent study by Millerd (1996) provides another estimate of the impacts of global warming on navigation in the Great Lakes-St. Lawrence system. The hydrological impacts of a doubling of CO_2 were simulated by coupling the Canadian GCM results with a runoff model and other techniques developed at the Great Lakes Environmental Research Laboratory. The analysis was based on cargo activity by the Canadian Great Lakes fleet, including shipments between Canadian ports as well as those between Canadian and American ports. The focus was on major bulk commodities, such as grains, iron ore, coal, limestone and others. Individual shipments were traced to ascertain if simulated water levels would restrict the amount of cargo that could be loaded and shipped. The results showed that the climate change scenario had a significant, negative impact on commercial navigation, with an annual average impact of over $2 million, 90 percent of which was associated with the shipping of grains and coal.

Various other studies have produced simulations of water levels and flows under various climate scenarios (e.g., Hartmann, 1990a), but these physical-process models have not been integrated with socio-economic models of transport activities and costs. There have also been attempts to understand the impacts of past low-water levels on navigation in the Great Lakes-St. Lawrence regions (e.g., Bergeron (1995) focused on the port of Montreal, which is a key container port; Koshida and Brotton, (1997) considered the causes and impacts of 1960s low water levels in the Great Lakes), but it is difficult to extend these in order to come up with an estimate of the system-wide effect of climate change. Still, these and other studies (e.g., Slivitzky 1993) do highlight some of vulnerabilities and potential impacts of climate change on navigation. Discussion has focused on the economic costs of more trips to ship the same amount of cargo due to reduced drafts; the potential for backups at bottlenecks in the system (e.g., the Welland Canal); the non-viability of selected ports; and the likelihood of increased dredging, which has both economic and environmental consequences. There is general optimism that an extension of the navigation season (potentially to 11 from 8.5 months) (Marchand *et al*., 1988) would contribute to better vessel utilization and less stockpiling (Hartmann, 1990b), but evidence to date suggests that this is unlikely to offset the negative effects of lower water levels.

Coastal Regions and the North

Little research has been conducted on the implications of climate change for coastal navigation. This may be due to the fact that serious, negative effects are not expected. As noted in Stokoe's (1988, 4) report on Atlantic Canada, "In comparison with other factors affecting the volume of shipping and port activities, the direct impacts of climate change would be minor". In fact, as Stokoe (1988) suggests, a rise in sea level would help to accommodate the trend toward larger ships with greater drafts, and an ice-free Gulf of St. Lawrence and Atlantic coast would reduce costs associated with ice-related damages to vessels and ice-breaking operations by the Canadian Coast Guard, both of which cost in the order of tens of millions of dollars each year.

In the North, climate change would almost certainly improve the potential for coastal navigation. This is illustrated in studies of the Beaufort Sea area. McGillivray *et al*. (1993) used GCMs and an historical analog to examine the impacts of climate change on the Beaufort Sea ice regime and its implications for the Arctic petroleum industry. Their results indicate that a greater extent of open water in the summer, coupled with a longer open-water season and thinner first-year sea ice, would extend the Arctic shipping season. This could make tanker operations economically attractive for the oil industry (Goos and Wall, 1994). In a similar vein, Anderson *et al*. (1994) suggested that a longer summer would mean more ice-free days, not only for the Beaufort Sea but also for the Mackenzie River, which is vital transportation artery connecting the Great Slave region with the Mackenzie Delta.

In addition to these potential benefits, however, sea level rise could cause damage to marine-related infrastructure, as has been suggested in studies of the Atlantic region, e.g., at the Saint John shipbuilding and dry dock facilities at Courtenay Bay, New Brunswick (Martec Ltd. 1987) and the main marine terminal and the Coast Guard docks at Charlottetown, P.E.I. (Lane and Associates Ltd., 1988). There are also many uncertainties about the implications of climate change for icebergs (e.g., Brown 1993) and storm activity as they may affect marine operations and safety.

Air

Of all the transport modes, aviation requires the most complex and far-reaching application of climatology. In fact, during the first half of the twentieth century, the sensitivity of air travel to weather was a major impetus to the development of meteorology, especially forecasting (Critchfield, 1983). Despite improved forecasting ability and major technological improvements in aviation, it is clear that weather continues to play a major role in air transportation operations, costs and incidents (Thornes, 1992). It is therefore not surprising that Perry (1993) suggests that aviation would be more sensitive to climate change than any of the other transport modes.

Despite this, there is a paucity of literature on the implications of climate change for aviation, both generally and more specifically for Canada. Two issues that have been raised in the climate change literature (e.g., IBI Group, 1990; Perry, 1993) pertain to the possibility that pay loads would have to be reduced on warm days because of lower air density and concern that some runways in the North would be damaged by changes in permafrost (see Arctic regional report).

It is possible to gain other insights into the implications of climate change for air transport by examining current vulnerabilities. In terms of operations, it is clear that inclement weather can and does cause delays. Based on Statistics Canada data, Barron (1983, 2) reported that "Canadian airlines lost more than $8 million in 1981 in disrupted trips, largely due to weather". A recent example is the winter storm that paralyzed sea, air and land transportation throughout the Vancouver-Victoria region over the Christmas weekend in 1996 (Vancouver Sun, December 30, 1996).

Safety is also a serious concern. Weather-related risk factors that affect air safety include, for example, runway surface friction (e.g., Biggs *et al.*, 1991), wing icing problems, atmospheric visibility and air turbulence. Indeed, there are many examples of crashes that were, at least in part, attributable to weather factors, (e.g., fatal Cessna crash near Flin Flon in January, 1996; Owen, 1996).

Pipelines

As noted in both the Arctic regional report and the Energy sectoral chapter, pipelines in Canada are vulnerable to changes in temperature and precipitation as they affect permafrost, river flows and landslide incidence. No detailed inventories of potentially affected lines were found, however.

Indirect Impacts

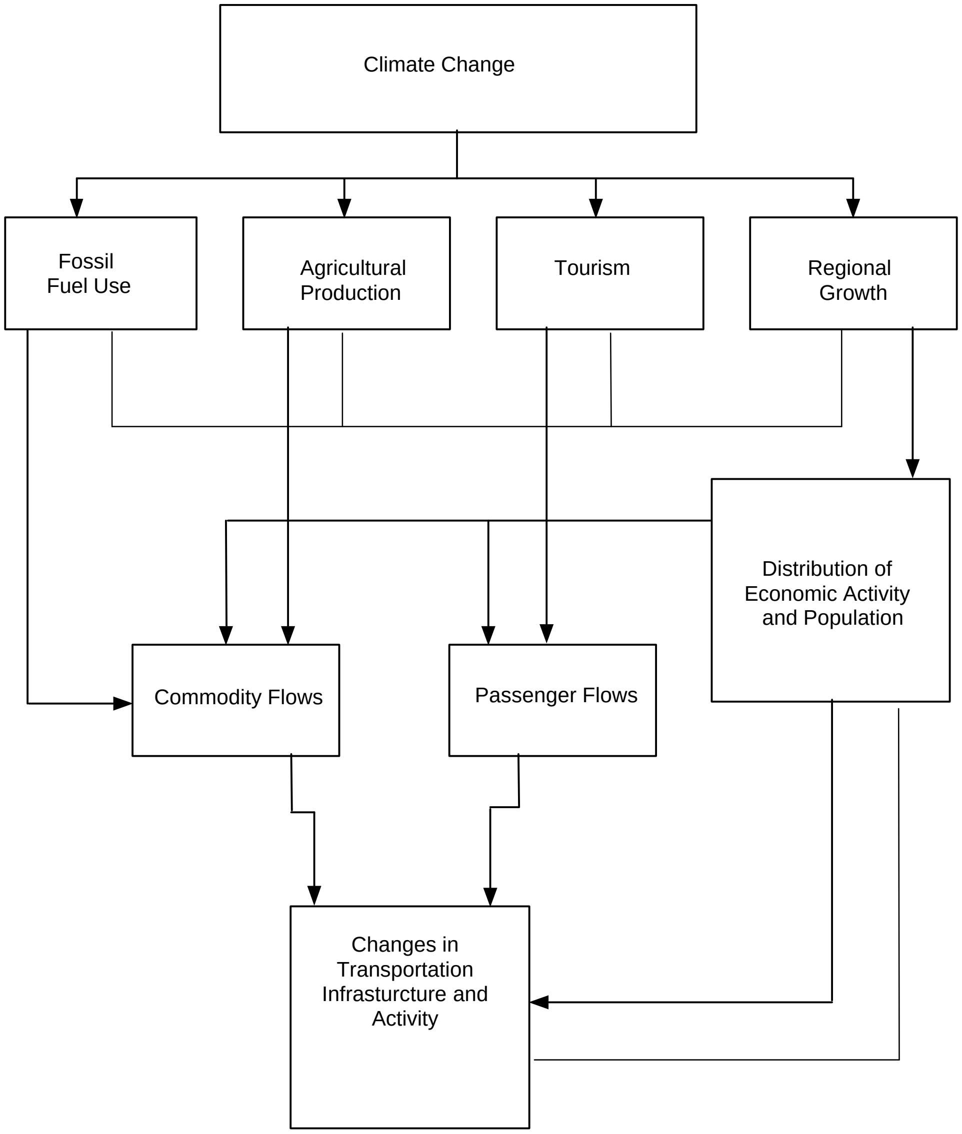
Because of the many factors that affect transport demand and supply, it is impossible to predict with any confidence the future state of this sector in fifty or even twenty years time. In terms of the climate change issue, there is general agreement that mitigation efforts are likely to evoke greater changes in transportation, especially in modal split and vehicle design, than the combined direct and indirect impacts of a changed climate.

Having said this, it is worth considering the types of indirect impacts that an altered climate might have on transportation activities. The IPCC report (Moreno *et al.*, 1996) provides a framework for considering the indirect impacts of climate change on transportation (Figure 8.2). One way in which climate can affect transportation is through changes in production patterns, especially of climate-sensitive resource commodities, like agricultural and forestry products. While there is a significant amount of research on the biophysical impacts of climate on crop yields and forest productivity, there is little basis for translating these first-order impacts into changes in transportation supply and demand in Canada.

Despite the lack of research on this topic, there is widespread speculation that climatic change would alter Canadian transportation activities in a significant way (e.g., Black, 1990; Moreno *et al.*, 1996). This speculation seems to be based, at least in part, on the comments of the IBI Group study (1990, 5):

The most significant change in transportation demand would arise from a northward expansion of agricultural, forestry and mining activities, resulting in increased population and intensified settlement patterns in Canada's central and even Arctic areas. The marine, road, rail and air modes would have to expand their facilities and service coverage accordingly; while this would entail substantial capital and operating costs, it could represent on balance an economic opportunity, since revenues from the increased northern traffic may be expected to more than offset the increased costs.

Figure 8.2: Indirect effects of climate change on transportation



Source: Moreno *et al*., 1996, 380

While it is reasonable to anticipate that there would be some climate-induced redistributions of people on a global scale because of coastal flooding, food shortages and other stresses, it seems overly simplistic to think that ecotone migration in Canada would cause settlement patterns to be altered in a substantial way. This type of environmental determinism is inconsistent with the settlement and transportation history of the nation. Indeed the past three decades have witnessed increased concentrations of people and infrastructure in southern urban regions. As noted by Jackson (1990, 99-100) "It seems difficult to regard this (change in settlement pattern) as anything more than wishful speculation ... It seems more probable that the main effects of global warming on transportation systems and individual mobility will be experienced where the population is already concentrated, especially in those major cities that are now accustomed to heavy winter snowfall during a long winter season". Put simply, the effects of a modified physical landscape on future settlement patterns in Canada will depend on many factors (Bone *et al.*, 1994b), and we are not in a position to make informed projections. Our knowledge of the effects of climate change on human activity patterns, even of tourists and other temporary residents, is very limited (Moreno *et al*., 1996). There is a real need for more research on both the indirect effects of climate change and the effects of climate-change mitigation measures, such as transportation control measures (TCMs), on transportation demand. This is a priority area for future work.

ADAPTATIONS TO WEATHER AND CLIMATE

Transport industries, government agencies and the Canadian public expend considerable effort and spend substantial sums of money to reduce the risk of delay or incident due to inclement weather (Herbert and Burton, 1995). Detailed information on these many adaptations may be found in journals, conference proceedings, technical reports, standards manuals, operating guidelines, transcripts of inquests and other hearings, and media reports. There have been some attempts to summarize meteorological influences on transportation infrastructure and operations (e.g., Perry and Symons, 1991; Thornes, 1992), but there is no comprehensive inventory of adaptations and their associated costs and benefits for Canadians.

Weather sensitivities are reflected in the design, construction and maintenance of roads, railway lines, runways, harbours and pipelines. For example, precipitation affects roadway decisions about drainage and surface texture and roughness; and wind and fog conditions directly influence airport site selection and runway orientation. Weather considerations are also evident in vehicle design and standards. For example, the Motor Vehicle Safety Act specifies a variety of standards that affect the design and performance of all motor vehicles sold in Canada (Myers, 1997). Perhaps the best example of a weather-related standard is CMVSS 103: Windshield Defrosting and Defogging.

Transportation operations, i.e., the when, where and how of transport activities, are also weather-sensitive. Rail operating guidelines in the form of 'cold tables' and driver training curricula for operators of motor vehicles are two examples of adaptations to current climates. Other examples include weather forecasts and road advisories that allow those responsible for maintaining or operating transport systems to make informed decisions. Indeed the list of actual and potential adaptive measures is very extensive.

Little is known, however, about the effectiveness of many of these adaptive measures, especially in terms of individual responses to weather conditions or forecasts. There are a few Canadian studies that illustrate the range of adjustments for owners/operators of motor vehicles. For example, Guerriero (1995) notes that modal choice can be affected by winter weather, with people tending to drive rather than walk during snowstorms in order to stay out of the elements. This study is consistent with the findings of Changnon for rainy weather in Chicago (1996). Also, Andrey and Knapper (1993) and Doherty *et al*. (1993) found that drivers sometimes cancel trips and frequently adjust operating speed during inclement weather, but the magnitude of the adjustments are difficult to measure and their role in reducing accident risk is poorly understood. More research on human response to weather hazards and information is needed.

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CHAPTER NINE

CANADA COUNTRY STUDY: CLIMATE IMPACTS AND ADAPTATION

BUILT ENVIRONMENT SECTOR

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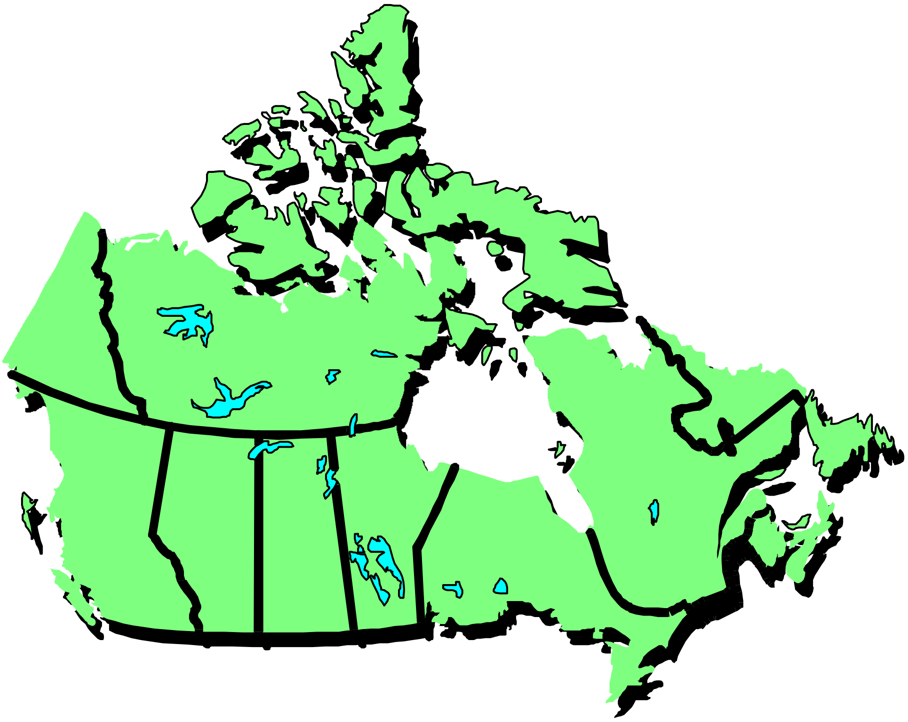

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EXECUTIVE SUMMARY

The built environment reflects the impacts and adaptations to climate variability and change in all sectors except unmanaged ecosystems and wetlands. The construction industry contributed 15% of Canada's 1993 GDP of $618B, and employed nearly 900,000, making it the largest of the 12 sectors. Statistics Canada reports capital expenditures on construction and renovation by type of asset, broken down into groups, some of which indicate level of activity in the other sectors as follows: non-industrial engineering (agriculture, forestry); mining, oil and gas, electric power (energy); marine (fisheries); institutional (health); commercial (recreation and tourism); communication, transportation (transportation); sewage, waterworks (water resources). In terms of construction expenditures in the six regions, (excluding machinery and repairs) the breakdown was: Arctic $0.3B=0.4%, Atlantic $5.8B=7.7%, Québec $15.9B=21.1%, Ontario $23.6B=31.3%, Prairies $16.9B=22.4%, BC & Yukon $13.1B=17.4% for a total of $75.5B. Although construction expenditures are by no means all directly related to adaptation to climate variability and change, it is helpful to know the relative investments in the different regions and sectors.

As for the insurance sector, the largest payouts on claims arise from coverage of various elements of the built environment, usually as a result of extreme weather events. A goodly portion of these payments end up as construction expenditures. The insurance sector's response to escalating claims, both from more frequent and severe storms and from larger insured inventories of buildings in the path of those storms, is to call for avoidance of high-risk areas, improved resistance in structures, and lower expectations of coverage. Some construction is done explicitly to mitigate natural disasters, such as coastal defenses, altering landforms where mud and debris slides are likely, and dikes and levees to cope with flooding.

Decisions by builders are primarily driven by the need to build both safely and economically rather than by concern over potential effects of climate change. Climate data, particularly those defining extreme weather events, do nevertheless govern many aspects and costs of construction. This is done through compliance with regulations and bylaws, usually based on national model codes and standards. The appropriate balance between strength (safety) and serviceability over the useful life of a construction on the one hand, and overall economy (initial cost plus maintenance) on the other depends on realistic predictions of wind and snow loads, temperature, rainfall, foundation conditions (e.g., permafrost, slope stability), and also risk of flooding or earthquake activity. Service lives range from less than 10 to more than 100 years, so predictions of climatic extremes may require explicit adjustment for trends, some of which may be due to global warming.

Adaptation to global warming

The most obvious way in which humans adapt to climate variability is by surrounding themselves and their social and economic activities by environmental separators, i.e., building envelopes. Other parts of the built environment constitute the supporting infrastructure for both buildings and activities. Adaptation of the construction process specifically to the threat of global warming occurs in three areas: structural safety during extreme weather events, energy conservation, and minimization of life cycle costs of buildings and structures.

The first concern for designers and builders is that structures be strong enough to resist foreseeable forces during the life of the structure. Although some extreme weather events, such as tornados, can deliver forces in excess of design loads, adherence to building code requirements should prevent serious damage to all but a few structures, those in the direct path of a tornado. Similarly, earthquake design can not forestall damage to buildings at the epicentre, but is required and usually effective in restricting damage in surrounding areas. Mitigation of damage from natural disasters is the mission of the UN program, International Decade of Natural Disaster Reduction (IDNDR), in which Canada participates.

Energy conservation can be considered an important response to climate change because the optimum level of insulation in buildings varies with climate averages for any particular locale. Energy conservation became an issue in 1973/1974 with the oil price shock. For ten years, research and technology in alternate fuel sources and energy efficient buildings blossomed. Then oil prices dropped, and much of the research and concern over energy conservation faded. We still have that legacy of preparation and research, now that public concern is reviving interest in “no regrets” initiatives, i.e., those which increase the GDP whether or not anthropogenic global warming turns out to be detectable. Two new model codes for energy-efficient construction are due to be published in 1997; the trick now is, to get builders and owners to use them.

Measures to reduce heat loss (or gain) in buildings require care if two unpleasant side effects are to be avoided. One is the effect on air quality and health of occupants of tighter buildings, and the other is the effect on the fabric of the buildings themselves if moisture buildup in the envelope is not explicitly avoided. Life cycle cost analysis, including maintenance procedures, has to be implemented to safeguard the gains of lower fuel costs.

The groundwork has been laid for achieving energy efficiency through tighter, yet durable buildings through research in Canada, the United States, and elsewhere. Climate data to serve the construction industry is more important than ever, but government cutbacks leave Environment Canada with little room to enhance that service. If we expect greater variability and severity of extremes, climate design data and advanced methods of processing them will be needed to improve and justify predictions that will require added expenditure to keep structures safe and economical.

Gaps and weaknesses

Canadians are not adequately prepared to deal with extreme weather events that result in major disasters, such as the flooding in Québec in 1996, or the potential for a strong earthquake on the west coast. Canada’s participation in IDNDR has been limited by lack of funding to date; warning systems and investigative teams that can react quickly are needed. Even more desirable are measures to reduce damage through more resistant design and avoidance of high-risk regions.

More complete climate data collection, both in items recorded and in geographical coverage, is required to properly serve the construction sector. Recent changes in wind and snow loads for many Canadian locations have significantly altered the predicted safety and service lives of many structures that were designed in accordance with the old numbers, and will alter the costs and resistances to extreme weather events of structures designed with the new numbers. Performance of structures during extreme weather events should be monitored to confirm and further fine-tune climate design data.

SECTORAL CHARACTERISTICS

Introduction

The built environment comprises habitations and shelter for humans and their possessions; office buildings, factories and plant complexes for commercial and industrial enterprises; structures for supply, generation and distribution of water and electrical power and other energy sources (e.g., pipelines for gas and oil, coal handling facilities); facilities for collection and treatment of waste; networks of roads and waterways including bridges, canals, locks, wharves, airport runways, hangars; air and sea traffic control towers; communications towers; and miscellaneous other facilities needed in human society (e.g., hospitals, amusement parks, penitentiaries).

Transportation networks are viable only so long as they connect centres of habitation, commerce, industry, and markets. The insurance sector (this volume) is even more closely allied to the built environment than the transportation sector (this volume). The response of the built environment to climate variation and change, and in particular, to extreme weather events, triggers the demand for insurance protection. The year-to-year experience of the insurance industry monitors the adaptation of the built environment to climate variation and change. The worrisome increase in the size and frequency of claims in recent years may reflect not only increased population and insured inventory intersecting extreme climatic events, but also increased size and severity of those events.

Accurate information on climate variability and change is essential if we are to design, build, operate and maintain structures in the built environment, and to ensure their survival for their required service lives. Energy requirements are closely related to the functioning of buildings and the variations of climate in which they operate. The siting of buildings, whether in cities or in the field operations of primary industries and agriculture, is influenced to a considerable degree by climatic conditions. Both extreme weather events and average climatic conditions also play a direct role in the construction process. Winter construction may require temporary enclosures and heating, thawing of foundation material, and use of ice bridges or access over frozen ground. Spring construction is often delayed or undone by heavy rains and flooding. Strong winds can halt construction and even destroy work in progress if temporary bracing is inadequate. Even if the measures for coping with such events remain the same, the extent of use and the places where these measures are needed will respond to climate variability and change.

The primary function for most structures that enclose space is to establish and maintain an indoor environment suitable for the use of the enclosed space, often at nearly constant conditions of temperature and humidity. All constructions making up the built environment, whether enclosing space or not, must be durable. Like the structures of Nature, man-made structures are subject to erosion by wind and water, splitting and spalling by freeze-thaw cycles, chemical breakdown in the presence of water, oxygen, and assorted pollutants, and catastrophic damage from lightning, hail, windstorms, landslides or avalanches, flooding, and earthquakes or volcanic eruptions. Any process that curtails the service life of a structure must be considered in designing for durability, but it is useful to deal with extreme climatic events primarily in the provision of safe structures, and to take account of climatic averages in coping with gradual deterioration of components and assemblies.

Size and Nature of the Construction Industry

The construction industry peaked in 1990, producing a total of $102.4 billion (B) in repairs and new construction, (15% of Canada's GNP) and employing 985,000 workers (Statistics Canada, 1993b). The industry was fragmented into about 380,000 employers, 32% of them very small with less than $250,000 in business; only 10,000 (3%) of these firms were grossing more than $1 million /year. With a work force that is very fluid, a large seasonal component, and narrow profit margins, it is not surprising that the private sector makes very little investment into improving building technology through research and development (less than 0.1% of construction volume, to add to another 0.1% from government sources). In spite of these handicaps, the Canadian construction industry is recognized for its strengths in several areas, and in 1990, won 1% of the world market of $US 120 B in construction contracts, behind Japan (14%), US (36%), Europe (43%), and all other countries (6%). Exports of building materials were $9 B, and imports were $13 B (Daniel, 1992). Figures for 1993 are somewhat lower, with 861,000 employed, but total construction ($75.5 B for new and renovated construction plus $15.6 B for repairs) was still nearly 15% of GDP (Statistics Canada 1993b).

The built environment is the domestic output of the construction industry. Built assets now total $1.5 to $2 trillion dollars or about 15 times the yearly amount spent in construction. Though Canada is a relatively young nation, most of its built assets are showing their age (average service life a startlingly low 15 or 16 years!) (Statistics Canada 1990a;b), and command an increasing share of the construction dollar for maintenance, repair, and renovation. As the main provider of infrastructure for most of Canada's social and economic activity, the construction industry is really Canada's largest, even though exports of services and building materials are only about half the positive balance of its nearest competitor, forestry.

Built Environment - Serving other Sectors and all Regions

The built environment underpins virtually all of Canada's economic and social activities, providing the infrastructure and the modified environments required in our north temperate climate. Statistics Canada supplies a breakdown of expenditures for construction, as well as for machinery and equipment (Statistics Canada, 1993a), for each of the six regions, but assigning expenditures by sector turned out to be rather unsatisfactory. Insurance, ecosystems, and wetlands could not be singled out, and items not obviously belonging to another sector are listed as "rest of built environment". Forestry and water resources in particular seem poorly represented. Despite these shortcomings, tables 9.1 and 9.2 help to describe shares of the infrastructure for each region and sector.

Table 9.1: Regional distribution of Capital Expenditures in Canada, 1993

	Construction Expenditures		**Machinery and Equipment**		**Construction and Equipment**	
B.C. and Yukon	13,068.3	17.3	5,127.9	11.2	18,196.2	15.0
Prairies	16,900.9	22.4	8,591.7	18.8	25,492.6	21.0
Ontario	23,587.1	31.2	19,740.0	43.2	43,327.1	35.7
Quebec	15,912.5	21.1	9,779.2	21.4	25,691.7	21.2
Atlantic	5,784.8	7.7	2,365.2	5.2	8,150.0	6.8
Arctic	287.6	0.4	108.7	0.2	396.3	0.3
TOTALS	**75,541.2**	**100.0**	**45,712.7**	**100.0**	**121,253.9**	**100.0**

Source: Statistics Canada, 1993b - Table 2 and Table 3

Table 9.2: Sectoral distribution of Capital Expenditures in Canada, 1993

	Construction Expenditures		**Machinery and Equipment**		**Construction and Equipment**	
SECTOR	**$ millions**	**percent**	**$ millions**	**percent**	**$ millions**	**percent**
Agriculture	1,440.7	1.9	2,374.9	5.2	3,815.6	3.2
Energy	15,862.4	21.0	918.6	2.0	16,781.0	13.8
Forestry			66.4	0.2	66.4	0.1
Fisheries	242.8	0.3	77.5	0.2	320.3	0.3
Health	1,166.4	1.5	778.0	1.7	1,944.4	1.6
Recreation & Tourism	3,885.2	5.1	596.7	1.3	4,481.9	3.7
Transportation	5,765.6	7.6	2,249.5	4.9	8,015.1	6.6
Water Resources	2,095.6	2.8			2,095.6	1.7
Rest of Built Env	45,082.5	59.7	38,651.1	84.5	83,733.6	69.1
TOTALS	**75,541.2**	**100.0**	**45,712.7**	**100.0**	**121,253.9**	**100.0**

Source: Statistics Canada, 1993b - Table 5 and Table 6

Insurance and Extreme weather events

In a northern country like Canada, heating is a major requirement for many months of the year, which exposes buildings to the risk of fire. While insurance against fire losses may be the primary concern for building owners and insurance companies alike, these large risks seem to be relatively predictable. The same may not be true of policy “riders” covering damage caused by wind, snow, hail, and rain. Often the coverage bears no relation to degree of risk or of precautions taken to prepare for extreme weather events. Premiums may be lower if the occupants do not smoke, but in the case of a windstorm a more relevant concern is whether or not the roof has been adequately anchored to the walls, and the walls to the foundation.

When tornadoes happen in built-up areas, insurance payouts are typically in the millions of dollars. The risk is not limited to trees and buildings; major losses are often suffered by power utilities when power lines and transmission towers are brought down. Another major threat to the built environment is flooding, with significant losses occurring yearly. Those who persist in rebuilding within flood plains find it impossible to get insurance coverage, but if the situation is sufficiently unusual, governments at some level will supply funds to cope with the disaster. On a more personal level, architects, engineers and builders carry insurance in the event that structures fail through lack of “due diligence” in providing for extreme weather events (Pym, 1989).

Insurers against natural disasters lay off some of their liability with international reinsurance companies, and those in Canada must concern themselves about the health of the reinsurance companies when they are hit by massive claims, whether in Canada or elsewhere in the world. There has been a disturbing escalation in the number and size of claims in recent years, with several insurance companies forced into bankruptcy in spite of reinsurance. Some have indicated that they believe global warming is playing a role through increased frequency and severity of such extreme weather events as tropical cyclones, hail storms, and flooding by storm surges and tsunamis. Human populations are at risk, and so is the built environment. With the growth of populations and the generation of wealth, people and the built environment are spreading ever more into the paths of extreme disasters even if their frequencies and magnitudes were constant (Berz, 1990).

Concern over global warming is focusing attention on climatic variability and extremes, and the experiences of the insurance industry world-wide display, in dramatic fashion, the impact of extreme weather events on the built environment. Those experiences are generating recommendations for major shifts in our handling of the risks posed by extreme weather events. Anecdotal evidence in the Canadian context shows why we can not afford to be complacent despite our distance from tropical storms, volcanoes, and massive earthquakes. In a recent speech, Jim Harries said that disaster losses in Canada for 1992-1996 rose 65% over the previous five years, mostly caused by severe weather. The two most costly Canadian disasters occurred in this decade: the Calgary hailstorm of September 1991 ($343 million) and the flood in the Saguenay region in July 1996 (more than $350 million) (Harries, 1997). Harries goes on to quote the IPCC Second Assessment Report: “Within the construction sector it is essential to identify the standards required and adhere to these. Often incorrect construction is to blame for damage and indeed, one of the great future issues will be how to ‘retrofit’ substandard buildings.” Another important observation concerns the overtaxing of municipal facilities, in particular, sewer systems. In Ottawa and Winnipeg, periods of heavy rainfall caused losses of about $200 million through sewer backup and related flooding.

Energy

Canada contributes about 2% of the world’s total CO_2 emissions from human sources (House of Commons Standing Committee on the Environment, 1989-1993). Buildings account for one-third of energy use, for space and water heating, lighting, cooling, ventilation and equipment (Barakat, 1995). But the built environment accounts for even more than that, considering the energy inherent in the manufacture of building materials. The issue for buildings is to assist in the reduction of greenhouse gases by becoming more energy-efficient. This is one of the “no-regrets” policies that the federal government continues to pursue, started originally when the price of oil suddenly rose in 1973, creating waves of concern around the world.

Oil Price Shock - 1973

Canadian government research expenditures into alternative energy sources and methods for energy conservation rose steadily, from about $US 300 M (1988 dollars) in 1977 to a peak of $US 550 M in 1984 (1988 dollars) (Organization for Economic Cooperation and Development, 1989). The oil price shock of 1973 triggered a drive for greater self-sufficiency in the supply of energy, and the search for efficient space heating and cooling led to extensive research to improve the control of heat flow through the building envelope. Alternative sources of energy, and other ways of heating houses and replacing part of the demand for fossil fuels were explored, for the next decade. When prices subsided, government research expenditures fell quickly, back to the $US 300 M level by 1988. However, public support may develop for a renewed push to stop wasting energy if a consensus forms that human contributions to greenhouse gases pose a significant threat.

Indoor Environment and the Building Envelope

Of all the built environment located above-ground, structures that enclose space are most intimately dependent on climate and its variability. The building shell, or envelope, separates the indoor environment from the constant changes of the natural one outside. In so doing, the envelope bears the brunt of all Nature’s forces, including wind-driven rain, snow, hail, grit, roof gravel, loose construction materials, and debris from failed envelopes upwind. And that is only the extreme weather events. Day-to-day, for the entire useful existence of the building, the building envelope experiences constant variations in the gradient of solar radiation, temperature, moisture, and pressure across its cladding, insulation, and air and vapour barriers. Unless radiation, moisture and pollutants are properly controlled, premature failure of the wall or roof can result.

Canada has an enviable reputation in North America for research and expertise in building envelope technology. Although the major world-wide suppliers of curtain walls for high-rise buildings are in the United States, an international survey revealed that these suppliers considered Canada to be their prime source for advanced technology (Ledbetter, 1990). The building envelope really includes basement walls and foundations, but for now, consider roofs and walls only: together, they account for 20 to 25% of total building cost, less for commercial, government and institutional, and more for industrial and residential (Hanscomb Consultants Inc., 1993).

Durability

As the built environment ages, and the pace of change in the work place increases, durability and the extension of service life become more important. This puts more stress on the need for accurate and detailed climate information. Whereas the prediction of extreme weather events is needed to design for structural resistance to wind, hail, snow and ice loads, there is a growing awareness that more common occurrences, say, of wind and driving rain, are important contributors to a difficult local environment for building envelope components. Heating and cooling requirements depend on predictions of degree-days and hours of sunshine.

Construction waste management is another area that shows the maturing nature of Canada’s built environment. According to one source, the construction industry accounts for 30 - 40 % of the material going into landfill (Science Council of British Columbia, 1991), but another estimate (14%) is much lower, though still considerable (CMHC, 1991). There have been some moves to “reduce, reuse, and recycle” building materials, both from new construction and from renovation. This was partly the result of rising fees for landfill disposal, and prohibitions against some construction materials, as landfill sites became scarce. Buildings with longer service lives make better use of materials, and indirectly save on the energy required to manufacture such products as dry wall, concrete, and steel.

IMPACTS OF CLIMATE VARIABILITY AND CHANGE

Introduction

The constructions that make up the built environment must function for their service lives within Nature’s environment, and all stages of their lives (design, construction, operation, maintenance, demolition or renovation) require a knowledge of climate variability. If predictions of extreme weather events become increasingly difficult to make accurately, and if those predictions change markedly, then some structures that were built on the basis of newly outmoded predictions will be at risk. If extreme weather events become more frequent and also more severe, there will be an increasing number of structures exposed to damage; only the most recently built structures will be built to the more realistic standards. As structures age, they inevitably suffer some loss of function through deterioration of components, and unless this is foreseen and countered with appropriate maintenance, the older buildings are again at increased risk. The impact of climate variability on the built environment increases as the stock of built assets increases with the growth of population and economic activity. Climate change, added to other social and economic determinants, could result in relocation of facilities.

Permafrost

With increasing temperatures, foundation conditions will gradually change in the North. Permafrost will thaw despite precautions now taken to keep it frozen under structures, roadbeds, or around underground pipelines. There will be a transition period requiring other measures while the permafrost thaws, affecting both existing and new construction. Older structures will have to be monitored, sometimes at considerable cost as in the case of a Northwest Territories building on wooden piles ($120,000 over two years). Increased seepage will occur under dams on permafrost. A major problem is differential settlement, leading to jamming of doors and windows, or even collapse of buildings. Utility lines, and pipelines could rupture. Mining operations might become easier, but waste dumps, tailings dams, and water diversion channels would require increased and expensive maintenance as permafrost retreats. There are 2,000 km of all season roads, 2,000 km of winter roads, and plans for another 2,000 km of all season roads in the

Northwest Territories, at costs ranging from $200,000 to $600,000/km. Those costs will double if the projected climate warming takes place (McG. Tegart *et al.*, 1990).

Climate Data for the Design of Buildings and Structures

Traditionally, climate information in Canada has been tailored more to the operational needs of transportation and agriculture than construction. Nevertheless, climate data is essential for the design, construction, and maintenance of all our built works, from dams, transmission towers, and roads to sewer and water systems, factories and office buildings, and residences. Climate variability is, in a sense, the very reason for the existence of much of the built environment. This close relationship tends to obscure the fact that climate change will have a direct impact on construction activities, because we already expect design data to anticipate the variability of climate parameters.

Extreme Weather Events

Predictions of extreme weather events are affected by variability more than by changes in the mean. Although it is difficult to distinguish between changes in variability induced by global warming and by other agents of change, there is the practical evidence of change in the new estimates for design wind and snow loads to accompany the 1995 edition of Canada’s model National Building Code (NBC) (National Research Council, 1995a). Climate data are supplied in Appendix C of the NBC for over 600 municipalities, and it appears that more than half of them have different wind loads, or snow loads, or both, from their counterparts in previous editions. This is the first major reassignment of values since 1965, and indeed the analysis of the data goes back further, to about 1958.

Some part of the changes are due to new and better analysis techniques, but the addition over 40 years of new observations, changes in instrumentation, addition and deletion of observation sites all contributed to the changed predictions. For those designers relying solely on the data in Appendix C of the NBC, or its equivalent in previous codes, converting to the new information has an immediate impact. Some newly designed structures will become significantly more resistant to extreme weather events, others less so, than if the older design data were used. To the degree that the new data presents a more accurate assessment of current climate variability, the risk of loss in a future extreme event is better managed, and funds to cover life-cycle costs are better deployed.

Questions as to what to expect in the way of differing climate variability, and differing predictions of extreme weather events, and whether global warming plays a discernible role, will not be dealt with here. But the point must be made that it is the built environment that will show the impact of such change, with or without the informed adaptation by designers, builders, using climate data collected over the years, and analyzed, by their advisors in Environment Canada. Clearly it is in all our interests to achieve close cooperation between the various players.

Impact of Extreme weather events

Natural hazards become national disasters when extreme weather events collide with significant portions of the built environment, and where lives and livelihoods are suddenly threatened, emergency measures and relief funds must be deployed rapidly. As in the Insurance industry, natural hazards are now very much a global affair, requiring cooperation world-wide. Technology and resources, including monitoring and warning networks, are being developed among nations under the coordination of the UN-sponsored International Decade for Natural Disaster Reduction (IDNDR) (1990 - 2000) (Canadian National Committee for IDNDR, 1994).

The great concern expressed in the Canadian National Report for the IDNDR's mid-term review in Yokohama is for the escalating vulnerability of humanity to natural disasters as observed over the last 20 years. As the reinsurance industry defines them, catastrophes have increased nearly four-fold, and losses to smaller nations often are greater than their GNP. Catastrophes in underdeveloped countries impact all nations, and in the past five years, the proportion of aid funds that had to be spent on disaster recovery increased from 2% to nearly 7%.

Canada has exceptionally long power transmission lines, and a design balance has to be maintained between economy and reliability. They are vulnerable to wind loading combined with ice buildup. Bridge piers and dams face extreme flood levels and ice jams, and offshore drilling platforms in the Atlantic are threatened by icebergs. Permafrost is a foundation material found throughout the North, and special construction procedures are used to prevent thawing under buildings or around pipelines. Sometimes services and buildings are placed well above ground on piles. Heating and air-conditioning systems must handle extreme ranges of heat, cold, and wind. These are some of the special conditions found in a northern country like Canada, outlined in a task force report to the Canadian Climate Program (Smit, 1993).

Howe Sound, British Columbia has steep slopes (up to 17 degrees) subject to severe landslide hazard during heavy rainstorms. Floods containing glacial debris with boulders up to several metres in diameter have been carried from the upper reaches right to the shore and into the fjord, destroying rail and highway bridges, damaging buildings, even sweeping them into the Sound, with major loss of life. Total annual rainfall is 1900-2100 mm, with as much as 100-140 mm in 24 hours. An October 1982 rainstorm caused direct damages over $1 million. To date, the British Columbia Ministry of Highways has spent more than $20 million building defenses (Smit, 1993).

Costs of Premature Failures of Walls and Roofs

In contrast to extreme weather events, in which the damage is done in seconds (tornadoes), hours (snow storms), or days (floods), premature failures caused by deterioration usually take months or years to become evident. The most common factor in most cases of premature deterioration is moisture that is transported into the wall or roof assembly. Moisture penetration from a warm and relatively humid interior can be driven by vapour pressure through building materials or by air leakage under an air pressure differential. Rain or snow can be driven into wall and ceiling cavities by wind. Ultraviolet radiation is another failure mechanism that attacks sealants and paints. With proper design, correct choice of materials, and the necessary periodic maintenance, any reasonable design service life can be achieved, but this does not always happen (Public Works Canada, 1990).

The Institute for Research in Construction of the National Research Council (IRC), Canada Mortgage and Housing Corporation (CMHC), and Public Works and Government Services Canada (PWGSC) have all taken premature deterioration seriously and in various ways have provided information to help reduce this climate-driven problem. In an effort to estimate the scale of the problem in Canada, IRC commissioned a study to determine how much money might be saved if better building practices had been used in the design and construction of walls and roofs (Hanscomb Consultants Inc., 1993). As noted earlier, walls and roofs account for roughly 25% of the cost of a building. The study further showed that on average, $CDN 28 B (1993 dollars) was spent yearly on renovation of buildings, and of that, $7 B went for walls and roofs. Using the hypothesis that renovations taking place before the service life had ended showed premature deterioration, the consultants proposed that these renovations demonstrated a premature failure rate of 3 to 5%. This means that premature failures may be costing us $200 M to $350 M per year.

Climate-related deterioration is most likely to be limited to the envelope of buildings, but roads, transmission towers, bridges and dams all experience gradual loss of function through interaction with wind and wind-borne rain, pollutants, abrasive materials, and also the action of solar radiation. Service lives of these other structures could in some cases be usefully extended through a better appreciation of the effects of environmental agents. Climate variability and change have a bearing on the severity of these effects (e.g., hours of sunshine, temperature extremes, frequency of combined wind and rain, etc.).

Increasing Density of Population and Possessions

The impact of climate change is being steadily enhanced by the growth of target areas for extreme weather events. For that matter, the impact increases even if the climate does not change. The combination of increasing population and of built assets, puts both people and property at risk, with a proportionately larger price tag for a given event that hits an occupied target. There is a good deal more certainty of this effect, than of climate change. A similar observation was made in assessing the impact of climate change on water in the Grand River Basin of Ontario (Sanderson, 1993).

Functional Obsolescence and Location of Facilities

Another issue concerns the location of buildings and infrastructure facilities. Economic and social enterprises will tend to migrate to the most favourable locations in terms of weather, supplies of water, energy, (skilled) labour, and access to markets. Difficult as it is to reposition built assets, this will have to be done. Not only physical deterioration, but also functional obsolescence threatens the viability of buildings and other structures. The search for extended service lives as a means for reducing life cycle costs will require predictions of climate changes leading to migrations of people and jobs, perhaps to increasingly hospitable northern regions, and away from established centres that may see water shortages, desertification, or greater exposure to pests and infections.

Such upheavals occur on a regular basis, and not just because of climate change. Rail lines become uneconomic, and are sometimes abandoned, unless new uses can be found. There is a down side to providing ever longer service lives for built assets, unless thought is also given to flexibility of function in the event that the asset outlives its original use.

ADAPTATION APPROACHES AND OPTIONS

Introduction

Most of the following examples address one of two issues: efficient use of energy, with one effect being the modification of events; and design of structures to resist extreme weather events, or preventing effects. These adaptation measures are, or were, mainly driven by concerns other than the perception of global warming as a threat. As in other developed countries, Canada's programs to promote energy efficiency and to discover alternative energy sources were originally driven by the 1973 hike in oil prices, and efforts tapered off when oil prices fell in the 1980's. The federal government sponsored research into energy conservation measures, and construction techniques that can keep the indoor environment within acceptable bounds without increasing the rate of deterioration of the building envelope. Some of that research faded away when oil prices fell back to pre-shock levels, but there is still a respectable foundation to build on.

The construction industry has always had to pay attention to climate and has developed coping mechanisms for balancing economy and risk. To the extent that they serve also as adaptive strategies in the case of climate change, whether driven by global warming or not, these methods and policies certainly fit the category of "no regrets".

As in many areas of economic activity, the public is turning more and more to higher quality, and the assurance of quality, in the products that they buy and use. It makes sense to spend more initially, making up the difference in extended and trouble-free operation later on. The pursuit of quality is an important behavioural trait favouring the conservation techniques and attitudes needed to respond to global warming.

Codes and Standards for Design and Durability of Buildings

Canada has standards and national model codes for the design and regulation of most structures in the built environment. They are regularly revised to reflect new information on climatic extremes and how to cope with them in design. In terms of the adaptation template, codes and standards are active applications for preventing unwanted effects of climate variability. A recent addition is the new model energy code for housing, which has potential for modifying events (i.e., the reduction of CO_2 emissions).

National Building Code

Engineered structures are subject to design requirements laid out in Part 4 of the National Building Code (NBC) whenever this model code is adopted by a municipality. This covers over 80% of the Canadian population, in every province and territory, and specific climate design values are provided for over 600 municipalities in Appendix C (National Research Council, 1995). Part 9 of the NBC covers housing, and other buildings less than 600 m^2 and under three storeys in height. Climate information is supplied mainly by Environment Canada, based on the analysis of weather station records taken at over 800 sites, for periods ranging from 10 to 80 years.

Part 5 of the NBC deals with protection of the indoor environment against wind and moisture in its various forms. This part has been greatly expanded in the 1995 edition, and alludes to the need for durability.

CSA S478 - Guideline for Durability in Buildings

Public Works and Government Services Canada (PWGSC) manage perhaps the largest portfolio of built assets in the country. Like many other owners and operators, PWGSC are faced with mounting costs of maintaining their buildings. Experience with parking structures, which failed prematurely in large numbers in the 1980's, resulted in the first Canadian standard with clear requirements for ensuring durability in design (Canadian Standards Association, 1994). PWGSC monitored their buildings, and developed a range of in-house manuals on durability, primarily concerned with the building envelope. PWGSC still had difficulty getting the message across to consultants and contractors, and so they requested and provided the major funding for S478, Guideline on Durability of Buildings (Canadian Standards Association, 1995).

CSA S478, a first in North America, stresses quality assurance, a team approach to achieving and maintaining durable structures, a clear statement of intended service life and the maintenance program required, and suggests three avenues for predicting service lives of structures and their components: use of documented records of successful performance, modeling of the deterioration process, and testing of assemblies in simulated environments. Appendices provide general information on the mechanisms of deterioration.

Maintenance, Monitoring, and Life Cycle Assessment

CSA S478 stresses record keeping, maintenance schedules, and life cycle assessment as a strong inducement to consider trade-offs between higher first cost with less maintenance and lower first cost, requiring higher or more frequent maintenance. This standard has great potential, if followed, for reducing life cycle costs and providing extended service lives for buildings. One area only touched on briefly, is the matter of functional obsolescence.

An option for adaptation in the change of use or location category might be to turn to moveable built assets (i.e., more of a nomadic existence). Functional obsolescence comes in many forms, ranging from a building being on the wrong site to changes in architectural preferences, or changes in the type of jobs available. There is a move away from manufacturing towards service jobs, and knowledge-intensive jobs in which the output can be sent electronically almost instantaneously around the globe. Instead of making structures sturdier and longer-lived, in some instances it might be better to make them lighter, more flexible in terms of use. The adaptation here is aimed at a more rapid change in function, but the same approach might aid in coping with climate changes that dictate a move to another locale.

Life cycle assessment specifically for built assets is being developed jointly by PWGSC and IRC (Vanier, 1996a;b; Brown, 1996), and the methods should prove useful for the assessment of costs of adapting to climate change.

Avoiding the "Sick Building Syndrome" - Indoor Air Quality

Measures to reduce energy use through tighter building envelopes can lead to unacceptable degradation of air quality if ventilation requirements are not met. Extensive research is underway on monitoring methods (Reardon, 1993; Strauss, 1995; Swinton, 1993a; Veitch, 1993,1994; Shaw, 1997), concurrent with investigations of energy conservation measures (Swinton, 1993b; Shaw, 1993).

Coping With Natural Hazards - IDNDR

As already mentioned, Canada participates in the UN's IDNDR, which shares many of the concerns for climate change. The program addresses risk assessment, mitigation activities, research, the development of warning networks, and international cooperation. Climate change is implicated in three of the four natural hazards cited: meteorological, hydrological, and biological.

The reinsurance companies take a keen interest because several of their client insurance companies have been bankrupted by individual events, such as Hurricane Andrew in Florida, 1992. Over the last 10 years, major natural hazards in Canada have cost insurance companies $1 billion for thunderstorms, hailstorms, windstorms and flooding. These companies warn that a geological hazard, a major earthquake in the Vancouver area might require payments of $14 to $32 billion and have called for tax breaks to permit the building up of a fund for that eventuality. If insurance cannot cover major losses, it is generally up to governments to chip in, and either way, an economic shock wave ripples out, disrupting other plans needing funding (Canadian National Committee for IDNDR, 1994).

A prototype natural and technological hazard information sharing network is under development on the Internet, based at Simon Fraser University in Vancouver, BC, (http://hoshi.cic.sfu.ca/hazard/index.html). The goal of HazardNet is "to enhance the timeliness, quality, quantity, specificity and accessibility of information for persons and organizations world-wide concerned with preventing, mitigating or preparing for large-scale natural and technological emergencies". There is clearly an overlap here with the concerns of climate change.

Research units for hazard mitigation and/or disaster preparedness are in place at the Université du Québec à Rimouski, the University of Manitoba, and the University of British Columbia. They are important components of IDNDR's Framework for Action (Canadian National Committee for IDNDR, 1997). Risk assessment, hazards, vulnerabilities, and mitigation for floods and windstorms, among others, put IDNDR's interests directly in the service of adaptation to climate change (Davenport and Charlwood, 1995). Among CNC-IDNDR's ongoing activities are twice yearly workshops since 1988, called Project Tornado, to increase understanding of severe weather by municipal officials. Flood forecasting centres monitor provincial streamflow in several provinces: New Brunswick (Saint John River), Ontario, Manitoba, and Alberta. The recent flooding in Manitoba of the Red River has been called the "Flood of the Century", displacing 28,000 people despite the efforts for weeks of thousands of volunteers, and the existence of a permanent floodway around Winnipeg. Records just go on being broken.

A new project sponsored by the Centre for Studies in Construction at the University of Western Ontario will capitalize on Canadian expertise in advanced construction technologies. Project "Storm Shelter" will assess the vulnerability of standard and low cost housing, identify impacts of disasters on family members, and develop construction methods to reduce vulnerability to natural hazards. This project has primarily to do with Third World countries. Export possibilities for Canadian house builders are foreseen in Pacific Rim Asian, and Caribbean countries, and international cooperation will be sought, in developing training programs and disaster-resistance ratings as well as construction methods.

Adaptation through energy efficiency

Though originally prompted by concerns over access to international oil supplies, programs aimed at conservation launched by several federal government agencies serve as good examples of adaptation to perceived risks in the built environment, and in fact are precisely in line with recommendations for reducing CO_2 emissions. The following lists and references are far from complete, but they indicate the scale of research and technological resources already in place.

Canada

The House of Commons Standing Committee on Environment held many sessions from 1989 to 1993, first hearing testimony from expert witnesses and interested parties from virtually every sector of the economy, then preparing a series of reports. Some of the remarks noted in the voluminous record give an interesting insight into the adaptation approaches discussed or recommended, some of which turned into recommendations for government policy.

- Brian Foody reported that oil companies design North Sea drilling platforms take into account a one-metre rise in sea level, anticipated to result from the effects of greenhouse gases (House of Commons Standing Committee on Environment, 1989 - pages 27-8).
- Bert Metz, from the Royal Netherlands Embassy remarked that sea level rise would not be a problem *per se*, even though 25% of the Netherlands is below sea level and 65% of the land area is at risk from flooding when the sea is high. Dike building is their business, and a good one world-wide. Raising dikes in Holland by one metre would cost them about $CDN 6.7 billion. They are, however, concerned about the intrusion of salt water into ground water supplies, and also about the increasing frequency and severity of winter storms. The European Community intends to phase out CFC's by 1998 and reduce CO_2 to 1989-90 levels

by the year 2000. They will do this by greater efficiency in residential heating, strengthening building codes, encouraging public transit, and taxing energy (the dreaded carbon tax). The Netherlands, with a population of about 15 million, produces about one percent of the fossil-fuel generated CO_2.

- Jim Bruce, *ex officio* Chair, Scientific and Technical Committee of IDNDR (Canada) had the following recommendation for the Environment Committee: Strengthen National Building codes for energy conservation in both housing and commercial buildings, with incentives for energy efficient appliances; incentives for solar and wind energy; small and medium-sized hydro sites.
- Mr. Skinner, a director of the International Energy Agency (IEA), said that the former West Germany (FRG) increased their GNP while decreasing energy consumption, by an aggressive energy efficiency program and government grants. One of those grants targeted the double glazing of windows (House of Commons Standing Committee on Environment, 1990).

Federal Government Buildings

- Starting in 1975, the Canadian Federal Government reduced energy use in government buildings by about 24.3% from a base year of 1976, everything from housekeeping to building retrofits, and off-oil switches to wood, natural gas, and propane.
- Landfill from Parliament Hill buildings was reduced by 78%
- In 3 years, 2,200 tonnes of paper were recycled, for a saving of $700,000.
- In one building alone, energy-efficient lighting saved $27,200.
- Vehicles converted to natural gas are saving 20 cents/km (House of Commons Standing Committee on Environment, 1993).

R-2000: Natural Resources Canada's Super Energy Efficient House Program

Natural Resources Canada (NRCan) promotes energy-efficient homes with high levels of insulation, a tight building envelope, a mandatory continuously operating ventilation system, and environmentally friendly materials and equipment. They must be built by specially trained builders whose work is periodically tested, and certificates are issued for R-2000 homes. R-2000 fact sheets suggest that even though the purchase price may be 2 to 6% above a comparable "conventional" house, energy savings alone should provide a payback within only a few years. Some banks offer lower mortgages as an incentive, and in some cases the total cash flow could actually be lower for the R-2000 home (Natural Resources Canada 1994).

Energy costs are generally lower with an R-2000 house, but the payback period depends on other factors as well, such as the climate and the cost of fuel. An independent assessment using test homes in the three prairie provinces compared R-2000 with similar conventional houses, giving mixed results (Innovative Housing Grants Program - Alta., 1989).

- Averaged energy savings varied by as much as 40% in a particular city.

- Different heating equipment was used in some R-2000 houses (electrical instead of gas, even though it cost 2.5 times more in Manitoba, and 5 times more in Alberta and Saskatchewan).
- In Saskatoon a conventional house would be built to an equal or higher level than an optimized R-2000 house in Regina.
- The R-2000 program has changed the way conventional housing is now built, and some of the advanced features formerly found only in R-2000 are now considered almost standard equipment.
- In Alberta, the study found the entire R-2000 package not cost-effective; payback periods were 15 to more than 25 years. However, using a) R-20 insulation on basement walls;, and b) air-sealing plus ventilation and a heat recovery ventilator gave payback periods of 4-10 years and 6 - 10 years.
- In Saskatchewan, with higher gas prices ($3.40/GigaJoules (GJ) vs. $270/GJ), the comparable payback periods were 2 - 9 years, 3 - 7 years, and for the entire R-2000 package, 5 to 20 years.
- In Manitoba (gas $5.30/GJ), the simple payback periods for the total package ranged from 4 to 13 years.

C-2000: Natural Resources Canada’s Program for Advanced Commercial Buildings

The CANMET Energy Technology Centre (CETC) of NRCan developed this demonstration of high-performance office buildings and launched it in late 1993. Two of seven buildings designed are now built and being monitored (April 1997; for further information contact C-2000, CETC , Fax: (613) 996-9416). High performance covers several requirements:

- projected energy consumption no more than 50% of that required by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) 90.1 (ASHRAE, 1989)
- minimal environmental impact
- high quality indoor environment
- adaptability
- long-lived building components
- facilitation of future maintenance

The incremental cost over conventional construction for each of the two buildings completed so far was about 8%; one met, and one improved on the annual energy performance requirement. The demonstration program has two more years of monitoring to go, but interim conclusions suggest that the keys to success are a) teamwork in design, including specialists (energy engineer, cost consultant, environmental specialist), and b) a clear and comprehensive guide. The added design effort, including energy simulations, would likely cost an extra $50-70 thousand, and commissioning of all major systems including the building envelope is another essential feature.

The C-2000 guidelines will be revised to make the Canadian Energy Code for Buildings (NECB) the new energy performance reference instead of ASHRAE 90.1, retrofit issues will be addressed, and supporting information will be updated and expanded. The program criteria were applied to a CMHC program called Ideas Challenge, for multi-unit residential buildings, and following the success of the C-2000 projects in BritishColumbia, two major utilities have started a Design Facilitation program to take advantage of the lessons learned. In a related development, the Federal Government announced in February 1997 that $20 million per year over three years would be used to promote investments in both energy efficiency and renewable energy for new and existing commercial buildings (RAIC, 1997).

Canada's National Model Energy Code for Buildings

In 1976 work started on a prescriptive code based on the then recently published ASHRAE 90.1 Standard. It was published in 1978 as "Measures for Energy Conservation in New Buildings", revised and updated in 1983 with a new section on "Houses". Subsequent development focused on the difficult challenge of making it into a performance code, but meanwhile, despite earlier provincial support, only CMHC (in 1978) and Québec (in 1983) adopted the "Measures". By this time, oil prices were back to pre-oil price shock levels, and priorities had changed. Limited use of the "Measures", and loss of technical support because of Federal cutbacks on energy research nearly terminated further development of the code in 1989, but a last-minute rescue by NRCan, the Canadian Electrical Association, and all provincial ministries, including funding of $1.5 million, allowed a 1995 edition to be completed (National Research Council, 1995b;c. Note that these references are reprints of drafts for public comment. The final versions should be available early in 1997).

The two new energy codes improve on the "Measures", and also on the ASHRAE 90.1 standard in several ways. First, regional variations in energy and construction costs are explicitly dealt with. Second, splitting the document into two makes its application to houses much simpler. Third, although the prescriptive approach had to be retained as the default requirement, alternatives are allowed if computer simulations can show that energy performance is not lessened. How the computer simulations are to be done, including control on input data, will be spelled out in ancillary documents (Haysom, 1993).

Energy efficient cooling

Air-conditioning (AC) of buildings consume close to 10% of the world's total energy, and this percentage is likely to increase with global warming, partially off-setting any savings in energy for heating. In commercial buildings, as much as half of AC is required just to remove waste heat from electric lighting (Lord, 1994). Environmental and health benefits are claimed for the use of heat-driven absorption coolers to provide space cooling for a group of buildings (Hart and Rosen, 1996). The elimination of CFCs in refrigerants requires alternatives, one of which is desiccant cooling technology (Painchaud, 1993; Shelpuk, 1993).

Buildings Energy Technology Transfer Program

Energy, Mines and Resources (now NRCan) started the off-oil federal energy management plan in 1975, for all departments, agencies, and crown corporations, with the goal of reducing spending by 1985/1986 to 10% below that of 1975/1976. Accumulated benefits at the end of the program were said to be $872 million with capital outlays of $200 million, and the target was more than met: 24.3% below the base year. This was done through retrofitting buildings, as well as no-cost housekeeping improvements (EMR, 1985). EMR also issued a series of at least 20 research reports, 1984-1986, for the general public, entitled Buildings Energy Technology Transfer Program (BETT 1984-86).

CMHC Publications

Canada Mortgage and Housing Corporation (CMHC) commissions research into many aspects of housing, some of which are of interest here. The first is a book of passive solar house designs for Canada, with a list of articles and other resources on energy efficiency and passive solar technology (CMHC 1989). Each of the designs comes with an energy analysis, showing costs for several Canadian cities. Other publications of interest deal mainly with durability problems and their causes, case studies across Canada, “best practice guides” to help builders and designers to apply the lessons learned. In addition, cross-Canada seminars are frequently held , such as the most recent, on water penetration control (CMHC 1996).

IRC/NRCC Publications and Research

One of the most popular series ever produced is the Canadian Building Digest series, for architects and engineers in particular, giving an overview of various building science topics. Of the 250 published, over 100 deal with some aspect of durable design. A few can be mentioned, dealing with wood (CBD 111, 112, 1969), concrete (CBD 116, 1971), metals (CBD 170, 1975) and parking garages (CBD 224, 225, 1982). Two other useful series are the Building Research Notes, and Building Practice Notes. A partial list of 110 research papers, handbook chapters, and seminar presentations concerned with energy conservation research spans the years from 1975-1992. That covers the period of peak federal funding for research on alternative energy sources and energy conservation measures.

Current research and publications deal with infrastructure assessment and renewal, restoration and renovation of existing buildings, and optimization of the indoor environment for occupant health, safety, comfort and productivity. Occupant salaries over the 40-year life of an office building are estimated to be nearly ten times that of its initial cost (Barakat, 1995). Public access to IRC reports and also other sources has been made easy by the production of 2 to 8 page lists of publications, organizations, bibliographic databases, and other material relevant to a given subject area. These “Pathfinders” are available by IRC AutoFax at (613) 990-4101 and also via the Internet (http://www.nrc.ca/irc/library/guide.html). Here are a few topics of particular interest here: Ground Source Heat Pumps, Concrete Deterioration in Parking Garages, Healthy Buildings, Insulated Backfill (Ganguli, 1994a;b;c;d).

United States

An assessment by Nordhaus of the impacts of climate change in the United States gave little cause for concern (Nordhaus paper in Dornbusch and Poterba, 1993). The main effect seen for construction was the benefit of having a longer construction season. This optimism seems to be based on confidence in adapting to a warmer climate, although unexpected and unwelcome phenomena might occur more frequently. As far as taking measures for mitigation and adaptation, the recommendations were:

- improve knowledge
- develop new technologies
- do the no-regret policies
- and only if we must, impose a carbon tax.

Building Envelope Research Centre, ORNL

Energy conservation research and policies in response to the oil price shock of 1973 were not confined to Canada. In fact, the early versions of Canada's energy conservation code were adapted from an American Society for Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) standard (ASHRAE, 1989). Like Canada, concern about oil supplies faded as the prices came down, and like Canada, research facilities turned their attention to energy efficient buildings. An interesting development at United States Oak Ridge National Laboratory's Building Envelope Research Center is a proposed data-base accessible via the Internet for comparing the thermal performance of whole wall systems of innovative design (Christian and Kosny, 1996).

The idea is to perform laboratory tests on full wall sections of both conventional design and new ones, to analyze thermal performance using complex three-dimensional computer models, and then to supply equivalent one-dimensional wall ratings for use by builders and designers. The rationale for this data-base is that current ways of comparing wall systems, particularly when manufacturers' literature is the main source, do not accurately represent the effects of thermal bridges like studs, air leaks, etc. As traditional materials like dimensioned lumber become scarce, expensive, and of poorer quality as timber supplies are used up, it becomes important to be able to rate alternatives, and to develop systems of equal or better thermal performance. For most of the United States, climate change is likely to increase air conditioning costs rather than heating costs, but in both cases there is energy to be saved with high performance walls.

KNOWLEDGE GAPS

Introduction

The built environment is more than just another economic sector. "As Canadians, our built environment is our shelter from the elements (survival), our homes (refuge), our means to generate wealth (e.g., transportation, communication, energy, offices, factories, water, etc.), our energy, water, and waste treatment systems (survival, wealth and health), our means for well-being (hospitals, schools) and our human habitat. It is as important to us as the natural environment is to the other inhabitants (creatures) of this planet." (Auld, 1997).

The built environment embodies most of the ways in which Canadians adapt to the rigors and extremes of a northern climate. This adaptation includes variability and trends, whether these climate changes are caused by anthropogenic contributions to global warming, or some other forces. Consumption of fossil fuels plays a central role in our adaptation to climate, as well as in transportation of goods and people across the vast distances of our sparsely populated land. Thus, energy efficiency becomes a two-edged weapon for attacking the effects of global warming: there is potential for both mitigation and improved adaptation.

Canadians also save energy by better management of the service lives of built assets, since construction materials require energy for their manufacture, and for their eventual disposal. In some cases, we should plan for re-usability of resources rather than simply looking for longer service lives, given the rapid pace of change in both the type and the location for various economic activities. Where construction in the North is concerned, the rate and extent of change in the permafrost limits is another major concern for the built environment.

Wise management of the built environment requires adequate and appropriate climate design data. This means not only accurate prediction of extremes for the initial design, but also measures of year-by-year exposure to agents of deterioration (e.g. wind-driven rain and solar radiation). As we come to appreciate the benefits of life-cycle cost assessment, we will call for increased monitoring of these environmental agents on existing and innovative structures, to determine what building practices and materials work best.

Canada covers a lot of territory and several climate types. It takes years to collect enough information to spot trends, evaluate variability, and predict extremes. Recording stations must not be too far apart, nor too far away from building sites. There are obvious difficulties when site locations or characteristics change. The details of data collection and analysis requirements are better identified by the professionals in Environment Canada. The points must be made, however, that knowledge gaps in the data network (in time and space) will probably always exist, and certainly do exist now. The construction industry itself seems only vaguely aware of the urgent need to have the most accurate information possible, and has so far not actively lobbied for improvements. Perhaps this lack of awareness is the key knowledge gap to address first!

The preceding sections are sprinkled with comments, observations, and recommendations as to the need for climate data or specific building practices to cope with climate variability and change. About 30 such remarks have been repeated below, in support of summary statements on knowledge needs of the built environment.

Climate Design Data

The safety, serviceability, and economy of the built environment depend heavily on accurate and realistic predictions of climatic variables, particularly extremes. Even without taking account of potential trends caused by global warming, long-standing knowledge gaps and deficiencies prevent optimum decisions from being made. Observing and recording methods respond more to the needs of transportation, agriculture, and recreation, and change is slow to come, possibly because the construction industry has been too fragmented to either perceive the needs or to demand improvements. Geographic coverage is lacking in some areas, and this will grow worse if one result of global warming is the relocation of industrial and agricultural activities to previously unpopulated regions.

- Service lives of buildings range from less than 10 to more than 100 years, so predictions of climatic extremes may require explicit adjustment for trends, some of which may be due to global warming. [Executive Summary]

- More complete climate data collection, both in items recorded and in geographical coverage, are required to properly serve the construction sector. Recent changes in wind and snow loads for many Canadian locations have significantly altered the predicted safety and service lives of many structures that were designed in accordance with the old numbers, and will alter the costs and resistances to extreme weather events of structures designed with the new numbers. [Executive Summary]

- Climate data to serve the construction industry is more important than ever, but government cutbacks leave Environment Canada with little room to enhance that service. If we expect greater variability and severity of extremes, climate design data and advanced methods of processing them will be needed to improve and justify predictions that will require added expenditure to keep structures safe and economical. [Executive Summary]

- If predictions of extreme weather events become increasingly difficult to make accurately, and if those predictions change markedly, then some structures that were built on the basis of newly outmoded predictions will be at risk. If extreme weather events become more frequent and also more severe, there will be an increasing number of structures exposed to damage; only the most recently built structures will be built to the more realistic standards. [Impacts of Climate Variability and Change]

- Traditionally, climate information in Canada has been tailored more to the operational needs of transportation and agriculture than construction. Nevertheless, climate data is essential for the design, construction, and maintenance of all our built works, from dams, transmission towers, and roads to sewer and water systems, factories and office buildings, and residences. [Impacts of Climate Variability and Change]

- To the degree that the new data presents a more accurate assessment of current climate variability, the risk of loss in a future extreme event is better managed, and funds to cover life-cycle costs are better deployed. . [Impacts of Climate Variability and Change]

- The point must be made that it is the built environment that will show the impact of such change, with or without the informed adaptation by designers, builders, using climate data collected over the years, and analyzed, by their advisors in Environment Canada. Clearly it is in all our interests to achieve close cooperation between the various players. [Impacts of Climate Variability and Change]

Energy Efficiency

One way to demonstrate the value of accurately tailoring structural capacity and insulation levels to the climate of a region or site is to model the effects of design decisions on the life-cycle costs of typical structures. A useful beginning in this direction involved a warehouse design, with a comparison of simulated annual heating and cooling requirements for seven locations in Canada (Yazici, 1996). This study could serve as a prototype for modeling that explores the costs associated with global warming trends modifying climate design data.

- Energy conservation can be considered an important response to climate change because the optimum level of insulation in buildings varies with climate averages for any particular locale. [Executive Summary]

- Two new model codes for energy-efficient construction are due to be published in 1997; the trick now is, to get builders and owners to use them. [Executive Summary]

- Measures to reduce heat loss (or gain) in buildings require care if two unpleasant side effects are to be avoided. One is the effect on air quality and health of occupants of tighter buildings, and the other is the effect on the fabric of the buildings themselves if moisture buildup in the envelope is not explicitly avoided. Life cycle cost analysis, including maintenance procedures, has to be implemented to safeguard the gains of lower fuel costs. [Executive Summary]

- Energy requirements are closely related to the functioning of buildings and the variations of climate in which they operate. The siting of buildings, whether in cities or in the field operations of primary industries and agriculture, is influenced to a considerable degree by climatic conditions. [Sectoral Characteristics]

- Jim Bruce, ex officio Chair, Scientific and Technical Committee of IDNDR (Canada) had the following recommendation for the Environment Committee: Strengthen National Building codes for energy conservation in both housing and commercial buildings, with incentives for energy efficient appliances; incentives for solar and wind energy; small and medium-sized hydro sites. [Adaptation Approaches and Options]

- Air-conditioning (AC) of buildings consume close to 10% of the world’s total energy, and this percentage is likely to increase with global warming, partially off-setting any savings in energy for heating. In commercial buildings, as much as half of AC is required just to remove waste heat from electric lighting (Lord, 1994). Environmental and health benefits are claimed for the use of heat-driven absorption coolers to provide space cooling for a group of buildings (Hart and Rosen, 1996). The elimination of CFCs in refrigerants requires alternatives, one of which is desiccant cooling technology (Painchaud, 1993; Shelpuk, 1993). [Adaptation Approaches and Options]

- Buildings account for one-third of energy use, for space and water heating, lighting, cooling, ventilation and equipment (Barakat, 1995). But the built environment accounts for even more than that, considering the energy inherent in the manufacture of building materials. The issue for buildings is to assist in the reduction of greenhouse gases by becoming more energy-efficient. [Sectoral Characteristics]

- ... public support may develop for a renewed push to stop wasting energy if a consensus forms that human contributions to greenhouse gases pose a significant threat. [Sectoral Characteristics]

Construction Practices

- Both extreme weather events and average climatic conditions also play a direct role in the construction process. Winter construction may require temporary enclosures and heating, thawing of foundation material, and use of ice bridges or access over frozen ground. Spring construction is often delayed or undone by heavy rains and flooding. Strong winds can halt construction and even destroy work in progress if temporary bracing is inadequate. Even if the measures for coping with such events remain the same, the extent of use and the places where these measures are needed will respond to climate variability and change. [Sectoral Characteristics]

- Any process that curtails the service life of a structure must be considered in designing for durability, but it is useful to deal with extreme climatic events primarily in the provision of safe structures, and to take account of climatic averages in coping with gradual deterioration of components and assemblies. [Sectoral Characteristics]

- “Within the construction sector it is essential to identify the standards required and adhere to these. Often incorrect construction is to blame for damage and indeed, one of the great future issues will be how to ‘retrofit’ substandard buildings.” [Sectoral Characteristics]

- Unless radiation, moisture and pollutants are properly controlled, premature failure of the wall or roof can result. ... As the built environment ages, and the pace of change in the work place increases, durability and the extension of service life become more important. This puts more stress on the need for accurate and detailed climate information. [Sectoral Characteristics]

- Construction waste management is another area that shows the maturing nature of Canada’s built environment. ... Buildings with longer service lives make better use of materials, and indirectly save on the energy required to manufacture such products as dry wall, concrete, and steel. [Sectoral Characteristics]

- The Institute for Research in Construction of the National Research Council (IRC), Canada Mortgage and Housing Corporation (CMHC), and Public Works and Government Services Canada (PWGSC) have all taken premature deterioration seriously and in various ways have provided information to help reduce this climate-driven problem. In an effort to estimate the scale of the problem in Canada, IRC commissioned a study to determine how much money might be saved if better building practices had been used in the design and construction of walls and roofs [Impacts of Climate Variability and Change]

- As in many areas of economic activity, the public is turning more and more to higher quality, and the assurance of quality, in the products that they buy and use. It makes sense to spend more initially, making up the difference in extended and trouble-free operation later on. The pursuit of quality is an important behavioural trait favouring the conservation techniques and attitudes needed to respond to global warming. [Adaptation Approaches and Options]

- In terms of the adaptation template, codes and standards are active applications for preventing unwanted effects of climate variability. A recent addition is the new model energy code for housing, which has potential for modifying events (i.e., the reduction of CO_2 emissions). [Adaptation Approaches and Options]

Building Sites

Permafrost studies, formerly a strength of Canadian construction research, should once more be given priority, so that adjustments in the existing northern built environment and in methods for new construction can accommodate deepening of the active layer, and eventual retreat of permafrost limits.

- With increasing temperatures, foundation conditions will gradually change in the North. Permafrost will thaw despite precautions now taken to keep it frozen under structures, roadbeds, or around underground pipelines. There will be a transition period requiring other measures while the permafrost thaws, affecting both existing and new construction. [Impacts of Climate Variability and Change]

- An option for adaptation in the change of use or location category might be to turn to moveable built assets, more of a nomadic existence perhaps. ... The adaptation here is aimed at a more rapid change in function, but the same approach might aid in coping with climate changes that dictate a move to another locale. [Adaptation Approaches and Options]

Longer Term Planning and Monitoring Innovation

The pursuit of energy efficiency, whether driven mainly or in part by the desire to reduce greenhouse gas emissions, requires increased attention to the development of durable and healthful building enclosures. This requires the commissioning of new buildings and the long-term monitoring of untried building products and methods. Considering the embodied energy of the materials themselves, owners need to extend the useful life of structures by providing for change of use at some later stage. Research may be required on how to incorporate flexibility in design, allowing economical rearrangement and reuse of components and assemblies.

- Performance of structures during extreme weather events should be monitored to confirm and further fine-tune climate design data. [Executive Summary]

- Measures to reduce energy use through tighter building envelopes can lead to unacceptable degradation of air quality if ventilation requirements are not met. Extensive research is underway on monitoring methods ... [Adaptation Approaches and Options]

- CSA S478 stresses record keeping, maintenance schedules, and life cycle assessment as a strong inducement to consider trade-offs between higher first cost with less maintenance and lower first cost, requiring higher or more frequent maintenance. This standard has great potential, if followed, for reducing life cycle costs and providing extended service lives for buildings. One area only touched on briefly, is the matter of functional obsolescence. [Adaptation Approaches and Options]

- Life cycle assessment specifically for built assets is being developed jointly by PWGSC and IRC (Vanier, 1996a;b; Brown, 1996), and the methods should prove useful for the assessment of costs of adapting to climate change. [Adaptation Approaches and Options]

- Climate-related deterioration is most likely to be limited to the envelope of buildings, but roads, transmission towers, bridges and dams all experience gradual loss of function through interaction with wind and wind-borne rain, pollutants, abrasive materials, and also the action of solar radiation. Service lives of these other structures could in some cases be usefully extended through a better appreciation of the effects of environmental agents. Climate variability and change have a bearing on the severity of these effects (e.g., hours of sunshine, temperature extremes, frequency of combined wind and rain, etc.). [Impacts of Climate Variability and Change]

- The search for extended service lives as a means for reducing life cycle costs will require predictions of climate changes leading to migrations of people and jobs, perhaps to increasingly hospitable northern regions, and away from established centres that may see water shortages, desertification, or greater exposure to pests and infections. [Impacts of Climate Variability and Change]

Coping with Extreme weather events

Additional funding is needed for the development of a network for the investigation of natural disasters. Increased severity and frequency of extreme weather events are two potential results of global warming, and even though the evidence for Canada is unclear as yet, the alarming trends of insurance claims leave little doubt of the value of such studies. Disaster investigations pay dividends in mitigation measures for future events, and to make sure that expensive lessons get maximum exposure, the work of the Canadian National Committee of IDNDR should receive additional support for the development of information and warning networks.

- Canadians are not adequately prepared to deal with extreme weather events that result in major disasters, such as the flooding in Quebec in 1996, or the potential for a strong earthquake on the west coast. Canada’s participation in IDNDR has been limited by lack of funding to date; warning systems and investigative teams that can react quickly are needed. Even more desirable are measures to reduce damage through more resistant design and avoidance of high-risk regions. [Executive Summary]

- Concern over global warming is focusing attention on climatic variability and extremes, and the experiences of the Insurance industry world-wide display, in dramatic fashion, the impact of extreme weather events on the built environment. Those experiences are generating recommendations for major shifts in our handling of the risks posed by extreme weather events. [Sectoral Characteristics]

- Natural hazards become national disasters when extreme weather events collide with significant portions of the built environment, and where lives and livelihoods are suddenly threatened, emergency measures and relief funds must be deployed rapidly. [Impacts of Climate Variability and Change]

- Research units for hazard mitigation and/or disaster preparedness are in place at the Université du Québec à Rimouski, the University of Manitoba, and the University of British Columbia. They are important components of IDNDR’s Framework for Action (Canadian National Committee for IDNDR, 1997). Risk assessment, hazards, vulnerabilities, and mitigation for floods and windstorms, among others, put IDNDR’s interests directly in the service of adaptation to climate change (Davenport and Charlwood, 1995). [Adaptation Approaches and Options]

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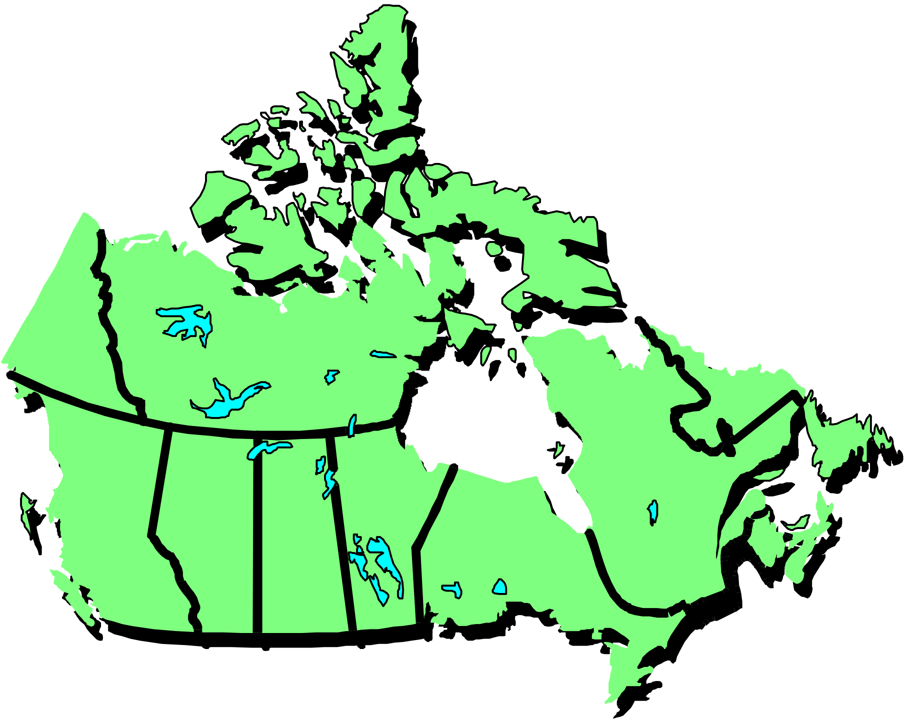
CHAPTER TEN

CANADA COUNTRY STUDY: CLIMATE IMPACTS AND ADAPTATION

INSURANCE SECTOR

Mark W. Baker[1]



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EXECUTIVE SUMMARY

Insurance is a diverse decentralized sector of the Canadian economy. It is of great importance as it affects both the business and personal aspects of all Canadians.

Climate change could have a severe effect upon the insurance industry and therefore the economy as a whole. Presently, most work done is of a general nature, much of it, especially that done by reinsurers, on a global rather than a Canadian basis. Most research is concentrated in the property and casualty sector of the industry and deals with potential effects of climate change on catastrophic events such as hurricanes, tornadoes and other severe weather events. Many authorities, especially those associated with reinsurance, feel that climate change could have devastating implications for the industry, or at least, increase the frequency and severity of some types of events. Others feel that changes in the frequency and severity of catastrophic events are due to regular climatic variability as well as other socio-economic factors.

Further research is needed in the areas that connect climate change and severe weather events to the amount and type of damage done and, therefore, the money and actions needed to mitigate and/or repair that damage. Such research has to be specific and practical in order to be of any use to the industry.

The insurance industry is at a crossroads of sorts, being very vulnerable to catastrophic events and therefore concerned with anything that would increase its losses. It is difficult to prove conclusively that what is being experienced presently is due to climate change and therefore difficult to take action, especially on anything to do with rating and premiums. On the other hand if action is not taken until conclusive proof is obtained it may be too late.

INTRODUCTION

Purpose

The purpose of this paper is to provide a literature review of the awareness, knowledge and opinions of the insurance industry in Canada towards the possible effects of climate change on the industry itself. An attempt has been made to summarise the viewpoints from various sources. As this is a review of the insurance sector’s attitude toward climate change, the paper has concentrated on insurance publications and journals as well as public statements by spokespersons of industry. It is hoped that in this way a balanced and comprehensive viewpoint of the sector has been presented. The property and casualty segment of the insurance industry has produced by far the most literature dealing with climate change as it feels that it may be severely affected by it. The paper has therefore concentrated on this literature.

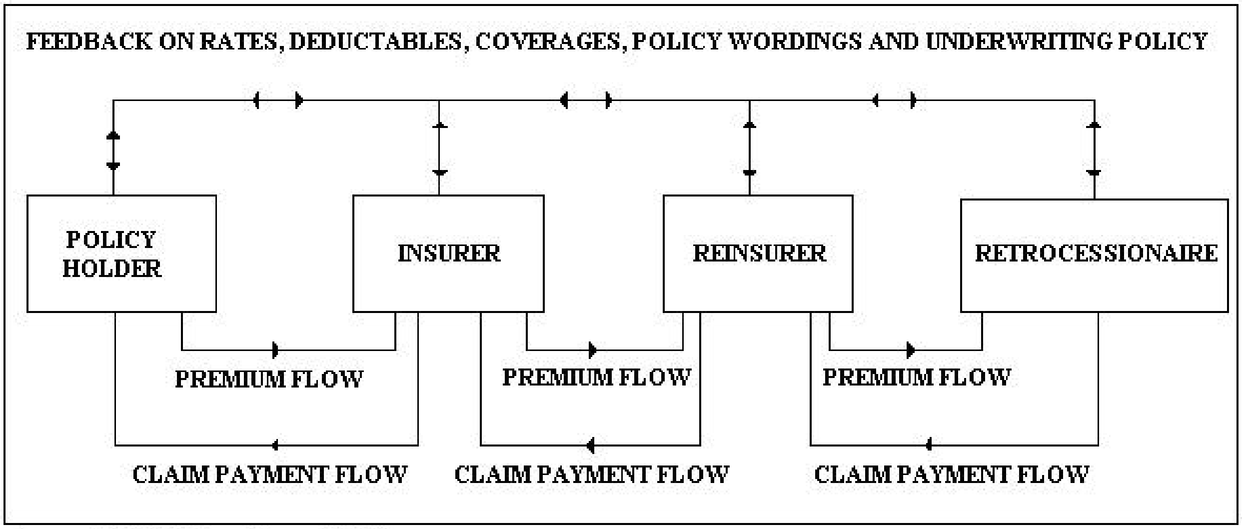
The Characteristics of the Insurance Industry Sector

Insurance in Canada is a very diverse, decentralised sector of the economy with many players of various sizes. In addition, it is also one of the most important parts of the economy as no business can operate without it. Many parts of an individual person’s life (e.g., driving a car) are intertwined with insurance and thus, this sector touches all Canadians in one way or another.

"Insurance is the method of sharing the losses of the few individuals who suffer them among the many in the group who do not" (Insurance Institute of Canada, 1987). The losses of the few are paid for by the premiums of the many. The frequency and severity of claims are therefore of great interest as it is at the heart of the setting of rates and the amount paid out. The possible influence of climate change upon catastrophic events, which produce large numbers of often very costly claims, is the area that has caught the attention of the property and casualty sector of the insurance industry and is, in fact, the focus of most of the insurance thinking on the influence of climate change. In general not only the Canadian but the world insurance industry feels that it is very vulnerable to extreme weather events that produce large numbers of claims. In fact the industry feels that they may be dealt a crippling blow at any time by erratic weather induced by global warming. Gerhard Berz, head of Geoscience research at Germany's Munich Re is quoted as saying "Disaster losses will continue to rise drastically in dimension and frequency" and that computer simulations indicate that already a US $50 billion insured loss is possible in the US from a single hurricane (The Financial Post, 1997).

The general structure of the property and casualty insurance sector can be seen in the following model (Figure 10.1).

Figure 10.1 Simple Model of the Property and Causality Insurance Sector



Source: Modified from Meyer (1997)

Premiums are paid by the policy holder. Insurers who wish to spread the risk further beyond themselves, purchase reinsurance from a reinsurer. Reinsurers again may further spread the risk by again reinsuring themselves. In this way reinsurance can spread risks internationally, balancing losses across nations.

Claims are paid from the insurer to the policy holder. The insurer then claims from the reinsurer (Note: there is no direct legal relationship between the reinsurer and the policy holder). Interaction between all parties produces feedback that alters rates, deductibles, policy wordings, coverages, underwriting and all aspects of the policy contracts involved.

Insurers in Canada are both Canadian and foreign-owned, while reinsurers are primarily foreign-held. Not only are there a large number of insurers, but there are also many different types. These can range from mutual corporations, joint stock companies to various different types of pools. In addition, the industry has seen the entrance of banks into the insurance market (Insurance Bureau of Canada, 1996). There are over 230 companies actively competing in the property and casualty industry, with about 40 reinsurers. Table 10.1 shows how decentralised the industry is as it can be seen that the top 10 insurers control less than 50% of the market.

Table 10.1: Top Ten Insurers

COMPANY	DIRECT PREMIUMS
General Accident	$1,304,388,000
Zurich	$1,001,731,000
Co-operators	$899,259,000
Axa	$885,664,000
Royal	$822,078,000
Ing	$692,957,000
Fairfax	$660,939,000
Economical	$618,629,000
State Farm	$583,051,000
Dominion of Canada	$542,164,000
Wawanesa	$522,627,000

The Canadian property and causality market takes in approximately $16 billion (approximately 2.24% of GDP) (Colombo, 1997). Of this, approximately $1.3 billion of this is reinsured. The surplus (net worth) is approximately $11 billion. Of the $16 billion total, approximately $6.49 billion is exposed to catastrophe (all dollar amounts are as of 1993). The industry's profitability was $800 million after taxes or 7% in 1993. (Ross, 1994).

In general, the industry is simply a capital pool. Capital in the world today is very mobile. In this way risk can by spread by both reinsurers and insurers world wide. The fact that much of the insurance industry is foreign owned (about 60 percent) means that the opinions of the rest of the world on climate change are very important to the Canadian insurance industry. From a positive side this means that any costs experienced by Canada from climate change will be spread around the world. However, this fact cuts both ways and the Canadian insurance industry would be affected not only by the changes within its own borders but by changes throughout the world. Unfortunately, the balance tends to lean toward the negative as Canada is not perceived as a catastrophe-prone area, (catastrophe is the area in climate change that the industry is most concerned about), especially when compared with the United States. Even the recent losses in Québec and Manitoba pale with those produced by Hurricane Andrew in Florida. Most research done on climate change and the insurance industry leads back to catastrophic weather events and their effects.

It should be noted that pressure to look at climate change may come not only from within the insurance industry, but also from its investors who might be concerned about the safety of their investment capital (Citizens Trust, 1997).

IMPACTS OF CLIMATE VARIABILITY AND CHANGE ON THE INSURANCE INDUSTRY

As previously stated, most research has been done in the property and casualty area of insurance and concentrates on the business, property, and to a lesser extent, automobile lines of insurance. The insurance industry also has a tendency to lump all catastrophic events together (e.g., earthquakes are often talked about in the same chapter as storm events in the industry literature), although they are recognised as different and unique hazards (Insurance Bureau of Canada 1995).

Insurance and reinsurance companies are concerned about and keep track of catastrophes on a year-by-year and an event-by-event basis. This is done not only in Canada but world-wide and shows amounts paid out on natural catastrophes can change greatly year by year (Sigma, 1994; 1996). However, there seems to be a consensus that severe weather events are becoming more common and the amount paid is going up. In addition, at least part of this has been attributed to climate change.

It should be noted that a major catastrophe can do large amounts of damage (i.e., Hurricane Andrew was estimated to do $US 30 billion in damage) (Ross, 1994). It is therefore possible to use up a significant amount of surplus in a single event. Thus the main vulnerability of the insurance industry, in relation to climate change, is to severe weather, especially a single catastrophic event. Such events are not as common in Canada as in the United States or Europe. Canadian storms, although costly, do not normally have the industry-destroying potential of American hurricanes or earthquakes (Ross, 1994). However, an increase in smaller events can also lead to the “death of 1000 cuts”. Climate change can lead to both an increase in high frequency/low severity (i.e., hail storms) and low frequency/high severity (i.e., hurricanes) events (Ross, 1994). An insurance company can be caught by both situations, often at the same time.

It should also be noted that due to the international nature of the insurance industry, increasing catastrophic events due to climate change elsewhere in the world would diminish capacity to write risks in Canada and increase rates. This is especially true of reinsurance. As previously stated, the industry perceives that Canada is not very catastrophe prone (as compared with the American east coast for example), and seems to feel that in Canada, climate change would produce more “high frequency/low severity” events.

The feeling of being “not cat(astrophe) prone” may not be correct as Canada can suffer severe weather events. The recent floods in the Saguenay region costing $350 million dollars and major hailstorms hitting Calgary and Winnipeg for $140 million and $120 million, respectively, have occurred in the last few years. In addition, the 1997 flooding of the Red River, while not producing a large amount of payout in claims, was still a very severe event. The fact remains that although it may not seem so, Canadians may have been lucky so far.

Catastrophe dominates the industry’s thoughts with regard to climate change, as it is difficult to cope with using the traditional methods of rating. If the changes associated with climate change come gradually over 20 to 30 years, the industry would cope with it via a slow change in coverages or rates over, for example, 5-year periods using traditional actuarial methods.

However, if climate change occurs as a set of thresholds producing significantly more high cost events very quickly, the industry's traditional slow and steady approach may not work. Rates develop to take into account atmospheric disturbances (Kovacs, 1994) but this takes time, time the industry may not have.

George Anderson, the President of the Insurance Bureau of Canada, has noted that the insurance industry has presented data noting an increase in the frequency and severity of severe weather. Using inflation adjusted figures, the cost of the 40 most severe catastrophic losses world-wide for insurers over the period of 1970 to 1996 was just over $US 100 billion. However, only 8 % of the cost was incurred in the 1970's, 22% of the cost came in the 1980's and 70% of the insured losses from catastrophes over the last quarter century came in the 1990's. Insured losses from catastrophes in the 1990's were 9 times greater that in the 1970s. There are still 3 more years to go in this decade so this figure can only go up (Anderson, 1997).

Anderson feels that there are three trends that affect the increasing losses from natural catastrophes. The first is population growth, the second is that there is more valuable infrastructure located in more vulnerable places. The third factor is a recognition that climate change is occurring and one result appears to be more frequently occurring severe weather events. Anderson has stated that the industry's attitude to climate change is that insurance companies are not sure that human-induced climate changes have caused the more frequent and intense storms. He does not feel that the details of the scientific debate are not of great interest to the industry. What does matter is the survival and sustainability of affordable widely available insurance coverages on which modern society has come to depend. The increase in the number and unpredictability of storm and weather surprises means that coverage may no longer be taken for granted (Anderson, 1997).

Other members of the Insurance Bureau echo these thoughts. Jim Harries, the Manager of Policy Development of the Insurance Bureau of Canada, has stated that climate change is having an effect on insurance. Insurance policies have gradually become more comprehensive, providing coverage for a wider range of risks, and on the other hand, specifying more clearly what is excluded. In addition to physical damage, property insurance will often respond to economic costs, including alternative accommodation or business interruption. He notes that the two most costly disasters to hit Canada both occurred during this decade. The first is Calgary hailstorm in September 1991, resulting in insured losses of $CDN 343 million. The second was the severe flooding in July 1996 in the Quebec Saguenay Region, causing insured losses in excess of $CDN 350 million and total economic damage expected to exceed $CDN 1 billion. Even with this, we have not been hit with a mega-catastrophe of the severity seen in the United States, Europe or Japan (Harries, 1996).

Harries cites Dlugolecki (1996) stating that there are 5 broad categories of extreme events that could be affected by climate change, some of which are interconnected:

A. River Basin and Coastal Floods

B. Droughts

C. Windstorms - Hurricanes and typhoons are considered the main risks, the damage depending on their strength, duration and whether or not population centres are in their path.

D. Other convective event extremes - These include hailstorms, thunderstorms and tornadoes.

E. Temperature extremes - The main risk for property insurance is extreme cold, which can burst pipes and cause significant water damage.

All of these events cost the industry money in claim payments and all can be affected by climate change.

The official publications of the reinsurance industry show even more concern. Dr. Berz of Munich Re feels that the “greenhouse effect” will aggravate the present problems with catastrophic loss (Berz, 1993). He believes that the increasing intensity of all convective processes in the atmosphere will force up the frequency and severity of tropical and extra-tropical cyclones, tornadoes, hailstorms, floods and storm surges in many parts of the world. He feels that reinsurers are paying a disproportionate amount of these costs (Berz, 1995). Berz further states that the decisive question is not whether this long list of evidence is conclusive but whether the climate data and computer climate models can provide enough information to allow sufficient time to assess future changes and develop the appropriate adjustment and preventative strategies. The strategies to deal with climate change have to be adjustable and not lead down any blind alleys. In addition, the most successful strategies are those that from the very outset are the so-called “no regret” strategies such as the reduction of fuel consumption of cars or reduction of energy consumption in general. (Berz, 1995).

In another paper (Berz et al., 1995), it was pointed out that, the number of major natural catastrophes in the last 10 years was 4 times as high as compared with 1960's, economic losses were 6 times as high and insured losses 14 times as high as compared with the 1960's (taking inflation into account). Berz et al. (1995) considered that there were several causes due for this:

A. Sharp increase in losses due to ever increasing concentrations of populations and their property, especially in regions seriously exposed to natural catastrophes, such as coastal areas.

B. Climate changes and other environmental damages are exerting an increasing influence on the frequency and intensity of natural catastrophes.

C. It is no coincidence that natural catastrophe losses have increased so dramatically since the early 1980's, i.e., in the very period which has been marked by exceptional increase in average global temperatures.

D. The increasing temperature of the atmosphere and the oceans reinforces many atmospheric processes and increases the probability of windstorms, storm surges, tempests, floods and other extreme events.

They feel that the phenomenon of climate change is therefore likely to first make its presence felt as natural catastrophes that have very damaging long term effects. They further state that for this reason comprehensive steps have to be take as soon as possible to prevent a further increase in the man-made “greenhouse effect” (Berz et al., 1995).

The Swiss Reinsurance company also has made strong statements on climate change. They feel that a definitive answer of how climate change will affect society is impossible due to a lack of knowledge and the fact that human reaction to weather manifestations is mainly a question of adjustment and adaptation (Swiss Re, 1994).

These different types of trends makes predictions of climate change difficult. A clear climatic signal is unlikely to emerge from the mass of statistics until the current value of the trend has become so prominent that it can no longer be confused with periodic and episodic processes obscuring it (Swiss Re, 1994).

The Swiss Re paper was prepared using the Intergovernmental Panel on Climate Change (IPCC) findings. Interestingly, they found it difficult to get fine differences due to the lack of data. The “greenhouse effect” could mean that weather patterns have not felt the full impact of the effect of climate change due to other processes. However, the uncertainty and variability of climate means that a rude awakening is possible at any time, not just decades in the future. The Swiss Re group feels that there might be sea level rises in the future and that it is highly probable that short periods of extremely heavy precipitation will increase. They do not feel that there will be an increase in tropical cyclones.

The Swiss Re group has stated that climate is not constant, but variable. It therefore follows that all plans based on the constancy of climate are inaccurate insofar as future climate events deviate from previous ones. Importantly, the Swiss Re paper points out that the past will no longer be the key to the future. It is totally impossible to predict probabilities in a variable climate in which future weather patterns can be as different from past ones as a cold winter is to a hot summer. As long as there is no way of forecasting how the future climate will evolve and as long as it can be justifiably assumed that within the space of two human generations higher values will be achieved than at any time in the proceeding 10,000 years, the occurrence anywhere on Earth of sudden storms of unprecedented, and perhaps even inconceivable, ferocity and duration cannot be ruled out. Thus any attempt to calculate the probability of extreme weather situations could potentially cause more harm than good and calculations imply a false sense of security (Swiss Re, 1994).

The Swiss Re group also pointed out that there is the concept of prosperity damage consisting of a more or less pronounced worsening of the development possibilities. It is a gauge of the extent to which an affected system can be set back in its development. In essence it is a loss of potential. With adequate insurance, prosperity damage can be reduced considerably, however this assumes the availability of affordable insurance coverage. It should be noted that this paper went considerably further than analysing the insurance situation and also made statements about the potential for wars and other social disturbances due to global warming, stating that they would increase dramatically (Swiss Re, 1994). While this may be useful, it would seem to be straying from the realms of insurance into that of political science.

The previous remarks of the reinsurance industry are globally oriented rather than directed specifically at Canada and the statements of the Insurance Bureau of Canada are somewhat general in nature. Unfortunately, this seems to be the best that can be done at this time. A Canadian paper by Etkin and Brun (1997) looks at the situation somewhat less apocalyptically and as is specific as possible with the level of today's science. They have concluded that:

A. Using the results of most numerical climate models over the next half century a doubling in CO_2 will lead to an average overall warming of the earth's global climate by between 1.5° and 4.5°C, a proportional increase in global average precipitation and an increase in extreme events in general.

B. That there was no strong evidence to support the hypotheses that hurricanes will become more frequent or severe, though there are some experts that support this theory.

C. It is unclear how extra-tropical storms (mid-latitude cyclones) frequencies will change in the future, though there is some evidence that in some areas will receive more frequent or more intense storms.

D. Evidence supports the hypothesis of more frequent and severe thunderstorms in the future.

E. Rare heat wave events will become more common before the middle of the next century and cold waves less frequent.

F. In the future more local flooding is likely, due to more intense and more frequent thunderstorms.

G. More frequent drought is a likely consequence of climate warming.

Etkin and Brun (1997) feel that the conclusions on how climate change will affect the frequencies and intensities of extreme events in Canada are mixed. A warmer climate would produce more thunderstorms with extreme rainfall, tornadoes, hail and drought, while the frequencies of cold waves will become rarer.

It should be noted that flood is a concern of the insurance industry, but not as much or in the way as might be thought as first glance by the layperson. Most policies, especially those providing coverage for homeowners, do not cover flood. Often each company's concern is based on what specific coverage's they offer and which are affected by flood. A company that offers sewer backup widely would be more concerned with flood than one that does not. Nevertheless it often seems that many professionals in the insurance industry often prematurely dismiss flood as a potential catastrophe as they only initially think of personal lines property policies and do not take into account business property polices, loss of use endorsements, business interruption or other polices and endorsements that do cover flood.

It must be noted that there are many other factors that may have been causing an increase in catastrophic loss. Factors that may be causing an increase in storm damage are summarised here and include:

A. Growth of cities - There has been substantial increase in population and size of cities over the last 20 years. In addition, populations in general have moving into Catastrophe prone areas, especially recreation or retirement communities.

B. Insufficiency of infrastructure - Often the above increase in size does not include an increase in needed improvements in infrastructure. An example is inadequate increase in sewer and storm sewer capacity. This can lead to greater sewer back up claims.

C. Poor Planning - i.e., allowing construction in flood plains. This generally does not happen in Canada presently.

D. Inadequate or poorly enforced building codes. This is a concern as it is estimated that 25% of the losses of Hurricane Andrew could have been prevented through better compliance with the local building code (Kunreuther, 1996).

E. Post Loss gouging - Unwarranted increases in costs of building materials and labour in the wake of a major catastrophe

F. Fraud - Unfortunately, some people will try to take advantage of an extreme event situation. For example not repairing hail damage paid for on an automobile claim and then putting in a subsequent claim after a second hail storm.

G. The susceptibility of structures to damage. The widespread use of aluminium siding in hail-prone areas is an example.

H. Insurance payment of maintenance losses.

I. The ability of insurers to respond - i.e., smaller insurers may not have the ability to transfer claim personnel in to a disaster site to settle claims (Ross, 1994). There is always the temptation under these circumstances for insurance adjusters to spend their way out of a claim, thus driving the total settlement up.

J. The broadening of coverages available in the last 20 years. With more coverage comes more claims and more payouts.

It should be noted that these factors may be as or even more important than climate change. A the very least they provide a "noise" factor in any financial calculations that make it more difficult to detect a pattern.

It should be noted that there is a school of thought that feels that catastrophes are not increasing. Pielke and Landsea (1997) feel that hurricane impacts in the United States and effects of climate change upon them have been refuted. They state that if the loss data for the last three decades is normalised, taking into account inflation, wealth and population change, normalised damages actually decreased in the 1970's and 1980's. The losses for the 1990's are not unprecedented and in fact resemble those of the 1940's for both frequency and severity (Pielke and Landsea, 1997). Hurricane losses are therefore more indicative of changes in society, e.g., the 9 factors mentioned above. Thus the increase in hurricane activity is part of the natural variability of climate and not that of climate change. Given that other sources state that there is not much evidence for increase in hurricanes due to climate change (Etkin, 1997), Pielke and Landsea (1997) may have some telling points. However this is cold comfort to an industry vulnerable to a Hurricane Andrew style event. In addition, Pielke and Landsea (1997) did not address the other types of climate events that cause serious property damage and to which Canada is more likely to experience.

Individual insurance companies in Canada appear to be doing little research on their own. They participate in forums when invited and work through their industry-wide organisations such as the Insurance Bureau of Canada or the Insurers' Advisory Organisation. This is an effective means of pooling resources, accomplishing research disseminating the results and getting the most value for the dollar.

Reinsurers are doing some research on their own but it is on a world-wide basis, with any Canada-specific information being produced in the same manner as the insurers. The government and academic community are actually producing much of this research, the results being presented to the insurance industry through the various forums. There have been few attempts to actually quantify the results for climate change and the insurance industry. An example of one was done by Friedmann 1988. The financial results dealt with the eastern United States and are as follows:

Estimated change in the annual damage-producing potential of insurance industry coded catastrophes caused by the insured perils of wind and hail between the present climatic regime and an undefined time during the transitional climate period (1990-2110) when a projected warming due to the “greenhouse effect” might be attained (table 10.2). Damage potential is expressed in 1989 US dollars (table 10.3).

Table 10.2: Change in Annual Damage Potential

STORM TYPE	ANNUAL DAMAGE BASED ON PRESENT CLIMATIC CONDITIONS	CHANGE IN ANNUAL DAMAGE POTENTIAL	ANNUAL DAMAGE BASED ON TRANSITIONAL CLIMATE CONDITIONS
Winter Storm	$ 230,000,000	- $ 20,000,000	$ 210,000,000
Hurricane	$ 680,000,000	+ $ 270,000,000	$ 950,000,000
Severe Local Storm	$ 780,000,000	+ $ 25,000,000	$ 805,000,000
Total	$1,690,000,000	+ $ 275,000,000	$1,965,000,000

After Friedman, 1988

Table 10.3: Total damage projections

Time Interval Year	Increase in Annual Damage Potential of Weather-Caused Catastrophes over that of Present Climatic Regime	Approximate Percentage increase Over Present Climatic Regime
1995-1999	+ $150,000,000	10%
2000-2004	+ $300,000,000	20%
2005-2010	+ $500,000,000	30%

After Friedman, 1988

The attempt of the paper is laudable and in fact is one of the few attempts to put dollars to a prediction. However, Friedman does not cite the actual climate warming model that the calculations are based on. In fact his conclusion states that at that time it was based on the "meagre amount of pertinent information that is currently available. Results are subject to major modifications as more credible data is developed". Thus its results are suspect for predictability and in fact Friedman states that much more work needs to be done (Friedman, 1988).

Other that property and causality insurance, mention has been made in the literature of the potential effects of climate change on mortality rates and life insurance. There are statements that the ageing population complicates the picture. As the population ages, it is less able to cope with natural disasters. In addition and unfortunately, seniors often congregate in danger zones. It is also stated that droughts, floods and heat waves can increase mortality and morbidity. In addition, there is the extension of vector-borne diseases that are tropical in nature, an example given is that of malaria (Lecomte, 1994). However, it does not seem to be thought that this would severely affect actuarial tables, at least not on the level the AIDS crisis or other areas that have affected the life insurance industry. The life insurance industry does not seem to be taking much of an interest in the issue (Dlugolecki *et al.*, 1996).

Crop insurance may also have to deal with climate change. In terms of catastrophic events it is in the same boat as the rest of the property and casualty industry especially with regards to hail. However, it has the added problems of drought, frost and excessive moisture to deal with (Wallace, 1997). These added factors would probably not present a great problem if the climate were to change slowly over a period of years. However, natural systems usually work in thresholds and any large jump in these events over a short period of time may not give the industry time to adjust.

Interestingly, there seems to be little produced by the marine insurance industry. However climate change with its possible effects on shorelines, pack ice, amount and time of ice break up and other oceanic effects would appear to affect the merchant fleets of the ocean and the insurance companies that services them.

Insurance companies can handle slow methodical change. However, as previously stated, climate does not change slowly and methodically, but rather often in thresholds. While an incremental increase in severe weather events could be handled by present methods, it does not appear that nature will co-operate. Therefore much of the industry feels that they cannot take a wait-and-see attitude toward climate change. While there is still uncertainty, the least likely scenario is considered to be no climate change. Any assessment of risk, such as done by the insurance industry for natural hazards based upon the assumption that climate is constant, is likely to be in error, perhaps seriously so. In fact this seems to be the major message for the industry, that the past is no longer the key to the future and that the old way of doing business is no longer adequate. If nothing else, the debate on climate change has helped to generate a better understanding of climate and its relationship to insurance.

MITIGATION STRATEGIES

There are several mitigation strategies open to the industry. These must be effective as insurance is one of society's major methods in dealing with the severe weather and therefore many of the aspects of climate change. The insurance industry is by nature practical and needs practical methods for mitigation (Lecomte, 1994).

Dlugolecki (1996) states that the insurance industry has adopted 4 strategies to cope with changes in risk. These are limiting the risk, physical risk management, transferring the risk and technical pricing. He feels that a more fundamental approach is required to deal with climate change and catastrophic risks, featuring communication and co-operation between policy holders, the insurance industry and government. He also stresses the need for the funding of reserves through tax relief (Dlugolecki, 1996).

A more comprehensive list of all options cited from all sources follows, they include:

A. Attempting to alter the climate

   1. Political involvement in reducing greenhouse producing gases. This has often been suggested by the European Reinsurance companies such and Munich Reinsurance and Swiss Reinsurance.
   2. Funding weather changing activities. An example of this is the cloud seeding in the prairies. This has been a successful Canadian approach. However, it should be noted that there has been some legal concerns hail in one area being forced to fall in another potentially causing damage there.

B. Attempting to alter the social infrastructure

   1. Funding research into improved building materials, methods as well as lobbying for improved building codes. This is a popular risk management style approach for the insurance industry as it has had much experience doing this sort of activity in concert with other industries and sectors of the economy.

C. Limiting exposure. As this only limits the exposure of individual insurance company, it is not really a mitigation strategy for society as a whole. In fact insurers are always reluctant to limit coverages. Market withdrawal is only a last ditch resort. Reinsurance does further spread the risk, but again without other strategies does not really mitigate the risk for all of society.

   1. Limiting the numbers of policies written dollar coverage provided in a specific geographic area.
   2. Reducing policy limits
   3. Increasing deductibles
   4. Changing payment terms (i.e., paying on an Actual Cost Value (ACV) vs. Replacement Cost).

5. Changing underwriting (U/W) rules as to what risks can be written.
6. Market withdrawal
7. Re-insurance, further spreading the risk.

D. Financial mitigation

1. Tax relief for reserves earmarked for catastrophic payment. This creates a pool of capital that protects the company's policy holders (Insurance Bureau of Canada, 1995).
2. Rate increases to generate further premiums. Again, this is not a method that the industry likes to employ.

It should be noted that the Canadian tax situation makes it difficult to set up reserves, sometimes money is transferred out of the country to allow the creation of reserves (Ross, 1994). There many mechanisms to do this, often involving the setting up of captive companies. This option is open not only to insurers but also to any company wishing to deal with a risk via a captive or a pool (Head *et al.*, 1993).

The pool concept is very popular at the moment and in fact is being looked at around the world, even at the international level with groups of small nations looking to set up their own insurance pools for catastrophe due to climate change (UNEP, 1997).

Finally, almost every paper cited stresses the need for co-operation between all levels of government, the insurance industry and policy holders in all areas involving severe weather events, catastrophic risk, climate change and insurance. Not only must there be practical, sustainable attempts at mitigation, but education of all parties of the various aspects of the problem. This is a problem that affects all of society and will require all society's resources to solve.

GAPS AND AREAS FOR FURTHER RESEARCH

Serious research to this point seems to be limited to an overview of the potential effects of climate change with respect to the property and casualty industry. Such research is usually of a very general nature. It should be noted that there is a fair amount of basic information on catastrophes and severe weather in Canada. For example, hurricanes are dealt with by the weather and environmental services division of Atmospheric Environment Service and risk analysis of tornadoes is done by the risk assessment group of the Natural Hazards division. (Davenport and Charlwood, 1995). In short there is a lot of initial work on risk assessment that is directly applicable to insurance, specifically with reference to catastrophic events. However, even with all of this and the various climatic and global warming models available, it has not been possible to develop specific detailed regional predictions giving hard and fast numbers on the increase or decrease of catastrophic events.

Thus there is a considerable gap at the "bottom line" with little work done that could place a hard dollar value on climate change. What is needed by the industry is specific information such as "A 2x increase in CO_2 will produce a X degree Celsius increase in Southern Ontario. This will produce approx. Y number of hailstorms doing Z dollars amount of damage." Such information would allow the industry to see what changes in its business practices would be needed to deal with such a situation. There is a need for better models for climate vs. damage (Ross, 1994) not just climate change (White and Ross, 1995). For life insurance work needs to be done to see how increasing temperature and severe weather would affect mortality tables. All "models" should also have a high rate of confidence. It is difficult to raise rates or reduce coverages on a possibility or even a vague probability.

In the case of severe weather the question of climate change may not even be the major issue. The property and casualty industry has to deal with the issue of industry damaging events, such as hurricanes, as well as populations and infrastructure in harms way, now. These situations may or may not be attributable to climate change. What can or cannot be done for the future therefore becomes second priority compared to what has to be done in the present.

The industry would seem to be at a cross roads. There is not complete consensus in the scientific community about climate change and there is also considerable controversy about what the right actions to counter climate change might be. Once the scientific community comes to an agreement, the insurance industry will have to come to a conclusion about what actions it will take and this may be sometime in the future. Whatever the solution will be, it will have to be part of a total societal response as mitigation efforts through insurance alone are insufficient (Wallace, 1997). In short a total "risk management" concept would have to be adopted. It should be recognised that Canada is vulnerable to climatic events and therefore to any forces, man-made or natural that may change them.

The greatest change may in fact be in the insurance industry's way of thinking. If the past is no longer the key to the future than many of actuarial methods used to predict losses and therefore rates may have to change. Leaving this tried and true method for the world of modelling would be a huge step for many companies, a step that many would not want to take

In the end, if nothing is done, by the time everything is proven beyond a shadow of a doubt, the insurance and reinsurance companies may have taken very large, even industry damaging losses. Right now, it is not what we know, but what we don't know that may hurt us.

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CHAPTER ELEVEN

CANADA COUNTRY STUDY: IMPACTS AND ADAPTATION

HEALTH SECTOR

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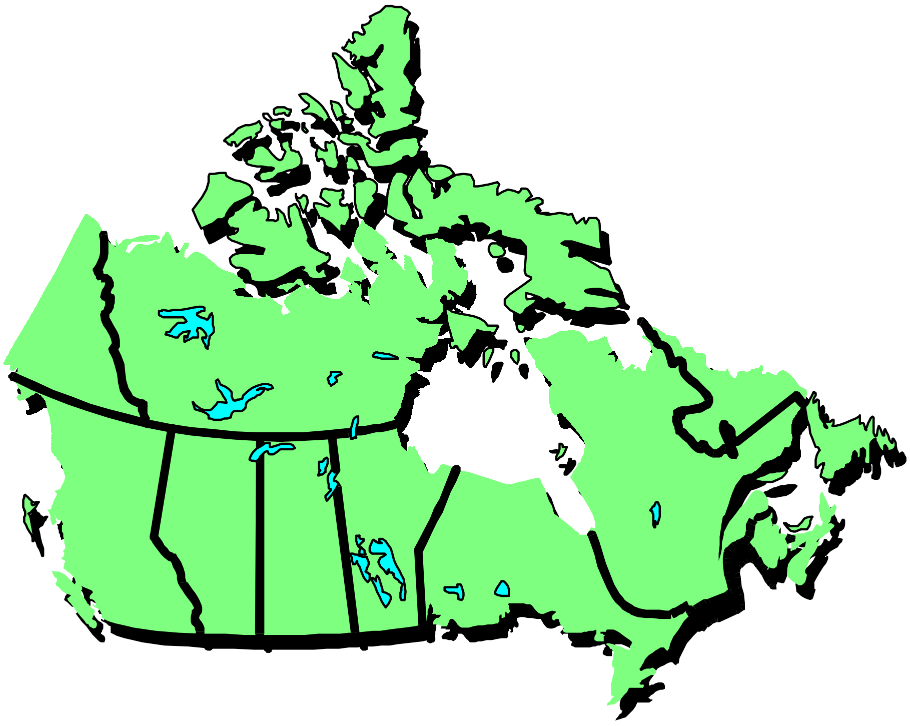

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EXECUTIVE SUMMARY

Human health is intimately linked to the environment. "The sustained health of human populations requires the continued integrity of the Earth's natural systems (IPCC, 1996). "Human health ultimately depends on society's capacity to manage the interaction between human activities and the physical and biological environments in ways that safeguard and promote health but do not threaten the integrity of the natural systems upon which the physical and biological environment depends. This includes maintaining a stable climate" (WHO, 1992a).

Human activities are altering the Earth's climate and changing the chemistry of the Earth's atmosphere. As a result, six air issues are receiving much attention in Canada. These issues include: on a global scale, (1) climate change (global warming) and (2) stratospheric ozone depletion (and increased ultraviolet radiation). On a regional scale, these issues include: (1) air toxics, (2) acid precipitation, (3) smog and (4) particulate matter.

In light of the current awareness of (1) the intimate relationship between the environment and human health, and (2) the six Canadian air issues, this report reviews: (1) the Canadian human health impacts of the six air issues; (2) adaptation approaches and options; and (3) knowledge gaps and research needs.

It is important to note that the six air issues are inter-related. As a result, the issues may interact to cause negative/positive effects on the atmosphere, the ecology of the Earth and the human population. Unfortunately, the six air issues have been assessed largely as individual issues. Moreover, the health impacts of each of the six air issues have been largely examined in relation to only one air issue--a notable exception is the health impacts of weather and air pollution.

Health Impacts of Climate Change (Global Warming)

Global climate change would disturb the Earth's physical systems (e.g., weather patterns) and ecosystems (e.g., disease-vector habitats); the disturbances would, in turn, pose direct and indirect risks to human health. Direct risks involve climatic factors which impinge directly on human biology. Indirect risks do not entail direct causal connections between climatic factors and human biology.

Potential Direct Health Impacts of Climate Change *(*Global Warming)

(1) Health Impacts of Thermal Extremes

It has been suggested that an increased frequency and severity of heat waves may lead to an increase in illness and death, particularly among the young, the elderly, the frail and the ill, especially in large urban areas. Heat waves affect existing medical problems and all causes of death, not just those related to problems of the respiratory or cardiovascular systems. Finally, heat waves have been linked with outbreaks of violent and other antisocial behaviour.

Acclimatization of populations may, however, reduce the predicted heat-related morbidity and mortality in the future. It is important to note that acclimatization to increasing temperatures occurs gradually, particularly among the elderly, and may be slower than the rate of ambient temperature change. Higher body core temperatures have been linked to elevated perinatal deaths, pre-term births, and an increased incidence of renal calculi.

A comprehensive empirical study, which examined the potential impacts of climate change on human heat-related mortality for ten cities in Canada, found that if temperatures warm as expected, under 2xCO_2 conditions, urbanized areas in southeastern Ontario and southern Quebec could be impacted very negatively. An "average" summer in 2050 could result in a range of 240 to 1140 additional heat-related deaths per year in Montreal, 230 to 1220 in Toronto, and 80 to 500 in Ottawa, assuming no acclimatization.

(2) Health Impacts of Extreme Weather Events

It has been suggested that increased frequency and severity of extreme events may increase: (1) deaths, injuries, infectious diseases and stress-related disorders; and (2) other adverse health effects associated with social disruption, environmentally-forced migration and settlement in urban slums.

Potential Indirect Health Impacts of Climate Change (Global Warming)

Vector-borne Diseases

It has been suggested that western equine encephalitis, eastern equine encephalitis, St. Louis encephalitis and the snowshoe hare virus would expand their ranges in Canada in response to atmospheric warming. It has also been suggested that malaria may extend northward into Canada with climate change. One study noted that in temperate countries, continued and increased application of control measures, such as disease surveillance and prompt treatment of cases, would probably counteract any increase in vectorial capacity. Other mosquito-borne diseases that may extend northward into Canada with climate change include dengue and yellow fever.

Tick-borne diseases, such as Lyme disease and Rocky Mountain Spotted Fever, may also extend their geographic distribution with climate change. Finally, changes in the incidence of hantavirus pulmonary syndrome are expected with global warming.

Environmental and/or Water Contamination

Illness, related to environmental contamination (e.g., by *Bacillus anthracis*), water contamination (e.g., by *Giardia, Cryptosporidium*, *Leptospira* and sea-food toxins) and water quality (e.g., by parasites), is likely to be increasingly favoured.

Water Quantity

Possible impacts of sea level rise include: salt water intrusion from the ocean into ground water supplies; inundation of water systems from a rising water table, with possible contamination by chemicals and pathogenic organisms; and flooded treatment plants with concomitant contaminated receiving waters. Lowered water levels in the Great Lakes and decreased flow of the St. Lawrence River could cause a deterioration in water quality. Finally, increases in the variation of precipitation, and changes in the timing of spring run-off events, are likely to result in more forced evacuations from communities near rivers.

Foodborne Diseases and Nutritional Health

Any effects of global warming on Canadian nutrition are likely to be associated with the effects (of global warming) on the foods brought in from other countries. Food imports are likely to be associated with increases in outbreaks of some viral, parasitic and bacterial diseases: for example, imports leading to outbreaks of hepatitis A.

Respiratory Disorders

Global warming may affect the seasonality of certain respiratory disorders. Increased air temperature may exacerbate air pollution in both urban and rural areas, and thus exacerbate respiratory disorders. Increased air temperature may also increase the number of smog days and, in turn, lead to a greater number of hospital admissions.

Migration

There are likely to be an increased number of environmental refugees. Refugees may bring with them disease agents into an increasingly hospitable environment. Internal refugees may migrate because of flash floods, contaminated water supplies, and flooded low-lying coastal areas.

Public Health Infrastructure

Currently, the public health infrastructure is not organized to cope with the interconnections among fiscal, agricultural, transportation and energy policies, their effects on climate, and subsequent climatic effects on health.

Health Impacts of Ultraviolet Radiation

Exposure to ultraviolet radiation from the sun is associated with a number of human health effects; these include cancers of the skin, cataracts of the eye lens and effects of the immunologic system.

Skin Cancer

There are three types of skin cancer--melanoma, basal cell carcinoma (a non-melanoma skin cancer) and squamous cell carcinoma (a non-melanoma skin cancer).

Melanoma

The incidence of melanoma has increased significantly in recent decades. Although melanoma overall is less common than non-melanotic skin cancers, it has a greater tendency to be invasive, and therefore results in a higher mortality rate. The following factors have been examined in relation to melanoma: constitutional factors/skin sensitivity; exposure in early adulthood; occupational/cumulative exposure; and intermittent exposure.

A tendency to burn rather than to tan, and intermittent exposure to bursts of sun during a susceptible period in an individual's life appear to be significant risk factors for melanoma. A history of sunburns may actually be a marker for the risk factor of sun sensitivity. Tanning may be protective for those without any sun sensitivity.

Non-Melanoma

Non-melanoma skin cancers are the most commonly diagnosed of all cancers. Basal cell carcinoma is the most common of the two types, but squamous cell carcinoma has a greater tendency to be aggressive. The incidence of non-melanoma skin cancers has been increasing in recent decades. Between 1973-1987, the incidence of non-melanoma skin cancers rose by 60% in the Province of British Columbia for each tumour type.

Recent studies have confirmed and questioned the relationship between cumulative sunlight and risk of non-melanoma skin cancer. Intermittent exposure to sunlight, particularly in childhood, has also been found to play a role in the development of non-melanoma skin cancer, particularly basal cell carcinoma.

Eye

A number of epidemiological investigations have studied the question of whether the risk of cataract is increased with long-term exposure to UVR. A positive correlation between cataract prevalence and sunlight hours was found for a large study in Nepal. A study in Italy found that persons with job locations, or with significant amounts of recreation, in sunlight had an increased risk of cortical and mixed cataracts, but not nuclear cataracts. A study of 838 Chesapeake watermen found that watermen with high cumulative levels of ultraviolet B exposure had the greatest risk of cortical cataract. However, a final study found no association between cumulative sunlight exposure and risk of cataract. But average lifetime use of head coverings in summer was associated with a lower risk of developing cataract.

Immune System

The skin is considered to be the front line defence in the body's immune system. Non-ionizing radiation in the ultraviolet radiation spectrum has been suspected to alter the skin's defence function. The evidence for the effects of ultraviolet radiation on the immunologic system, and subsequently on carcinogenesis, infectious disease and autoimmune reactions is still incomplete, but some preliminary results are available. It has been suggested that: (1) the immune system is involved in the development of skin cancers; and (2) UV irradiation of the skin may disrupt immune responses in the skin and result in both local and systemic suppression. It has been hypothesized that UVR exposure may compromise the ability of the host to respond either locally or systemically to infectious agents.

Health Implications of Air Toxics

The body burden of toxics arises from food, soil/dust, drinking water, indoor air and occupational situations. A total of 31 of the 160 compounds detected in Toronto's air are known or suspected carcinogens.

At low concentrations, symptoms of carbon monoxide exposure include fatigue, headaches and dizziness, but higher concentrations can lead to impaired vision, disturbed coordination, nausea and death. High occupational exposures to exhaust increase the risk of some cancers. However, evidence of an increased cancer risk to the population at large is lacking.

Volatile organic compounds (VOCs) can cause irritation to the respiratory tract (increased rhinitis to asthma) as well as headaches and other non-specific complaints. At high concentrations, VOCs have markedly toxic effects, which include neurological effects.

Polychlorinated biphenyls (PCBs) enter the environment and persist for decades. PCBs accumulate in fatty tissues over a period of time, a process known as bioaccumulation. PCBs have imposed restraint on traditional native diet. Government contamination limits may be too broad to protect the health of indigenous populations, such as traditional Inuit who eat fish oil, caribou fat and bone marrow, and maktuq from the narwhal.

Health Impacts of Acid Precipitation on Air Quality

Nitrogen dioxide and sulphur dioxide have acute negative impacts on the respiratory system. Sulphur dioxide concentrations of up to 8 ppm cause respiratory changes in humans. The main effect of sulphur dioxide is bronchoconstriction. Individuals with asthma are particularly susceptible. Asthmatics who exercise typically experience symptoms at 0.5 ppm. Healthy exercising adults have shown significant reductions in lung function after exposure to 1ppm. Nitrogen oxides impair defences in the respiratory tract, increasing the incidence and severity of virulent bacterial infections, and markedly reduce the capacity of the lung to clear particles and bacteria. Finally, the oxides of nitrogen provoke bronchoconstriction and asthma.

Hospital admissions for respiratory illnesses are increased during contemporary air pollution episodes when levels of ozone, acid aerosols or particulates are elevated. Acidic contaminants can affect human health directly when inhaled, and indirectly when they fall on surface water, land and plants.

Concentrations of NO_2 in Canadian cities are generally well below the levels at which adverse effects on human health are known to occur, but by reducing NOx, we can significantly slow ozone formation. Children in more polluted cities suffer more colds and upper respiratory tract infections than children in cities where the air is cleaner.

The assumption of air pollution with actual mortality is strongest for fine particulates and is relatively weak for acid-forming pollutants.

Levels of many Toronto air pollutants are sufficiently high on a periodic basis to raise concerns for public health. Persons with respiratory illness and healthy individuals exercising vigorously outdoors appear to be at greatest risk. People with asthma, emphysema and chronic bronchitis are estimated to comprise about 7.5% of the Canadian population or a projected 165,000 of Metropolitan Toronto's 2.2 million residents.

NO oxidizes to NO_2 which contributes to the formation of ozone. Transport of ozone from the United States and locally generated ozone raise ozone levels in residential neighbourhoods remote from traffic.

Health Effects of Acid Precipitation on Water Quality

Mercury, biotransformed into methyl mercury, readily enters the food chain, is biomagnified and distributed throughout the body.Sulphuric acid lowers pH, and causes toxic metals to dissolve and leach into the aquatic environment and kill fish. Toxic metals can bioaccumulate in fish tissues and in drinking water supplies. Some country foods of many northern aboriginal communities have become heavily contaminated by environmental pollutants. For example, large hydro-electric developments in James Bay have exposed northern Cree Amerindians to potentially dangerous levels of methyl mercury. But the blood mercury levels of the Greenlandic Inuit have declined due to a progressive decrease in the consumption of traditional Inuit food.

Health Effects of Smog

Tropospheric ozone is the major component of smog. High ozone concentrations can cause immediate short-term changes in lung function and increase respiratory symptoms. Healthy exercising individuals experience a decrease in lung function and an increase in respiratory symptoms during prolonged periods of exposure to ozone at concentrations as low as 0.12 ppm. Ozone produces eye, nose and throat irritation at levels as low as 0.01 ppm. Long-term effects of ozone include damage to the tissue lining the airways of the lung. Individuals with asthma experience reduced airflow and worsening of asthma. When air pollution is present, pregnant women or those with chronic diseases (e.g., emphysema) are at higher risk.

Ozone is the second-greatest cause of lung disease. Approximately 5%, and up to 15% in those under two years of age, of Ontario hospital admissions for respiratory disease may be attributable to elevated concentrations of ground-level ozone. Tens of thousands of deaths have resulted from acute pollution episodes (e.g., the smog in large cities in North America and Europe in the 1950's and 1960's).

Health Implications of Particulate Matter

The major health effects associated with exposure to suspended particulates are effects on pulmonary function, aggravation of existing pulmonary and cardiovascular disease, effects on mucociliary clearance and other host defense mechanisms, morphological alteration, and mortality. High mortality rates following exposure to high atmospheric levels of particulates coupled with exposure to sulphur oxides have been observed following pollution episodes in London, England, and New York in the 1950's and early 1960's. Groups that are at high risk during particulate pollution episodes include the young (school and preschool children), the elderly, those with chronic obstructive cardiovascular disease (heart patients and those with arteriorsclerosis), asthmatics, those with influenza or bronchitis, smokers, and those who are oronasal or mouth breathers.

Adaptation Approaches and Options

(1) Climate Change (Global Warming)

Thermal Extremes

Anticipatory responses should be considered to combat the problem of heat-related mortality. One potential response to thermal extremes associated with climate change is the development of a weather/health watch-warning system. Another potential policy for attacking the problem would be acclimatization assistance.

Continued research is necessary on particular aspects of the problem of climate change and human mortality. For example, the potential interactions between pollution and weather as they impact heat-related mortality are largely unknown.

Indirect Health Impacts

There is an urgent need to embrace broad transdisciplinary approaches to study the indirect health impacts of climate change, and to create a research institute which can address fundamental transdisciplinary policy-relevant issues.

(2) Stratospheric Ozone Depletion (and Increased Ultraviolet Radiation)

Sun protection should be practised by all individuals in both summer and winter, and in particular during vacation in lower latitudes, with stronger UV rays, since intermittent sun exposure has been found to be a risk factor for melanoma and non-melanoma skin cancer. The following strategies to reduce ultraviolet radiation exposure are recommended: (1) minimize sun exposure; (2) seek shade; (3) cover exposed skin; and (4) use sunscreen of SPF of #15 or higher.

(3) Air Toxics

Emission reduction measures will reduce air toxic levels. Other solutions include standards enforcement activities, monitoring, tracking studies and pollution prevention.

*(*4) Acid Precipitation

A control plan is already in place in Eastern Canada. Research in residual acidification may result in a further reduction in the critical loads to protect sensitive ecosystems. Other solutions include meeting targets, ecosystem studies, monitoring precipitation, renegotiating provincial reduction agreements, tracking, determining the effectiveness of control programs and studies regarding the effectiveness of the target loads.

(5) Smog

The reduction of ground-level ozone involves automobile inspection, education, ozone monitoring, "smog advisory", monitoring regional initiatives, pollution prevention activities and research.

(6) Particulate Matter

Economic and social development which led to the use of cleaner energy sources is leading to better air quality in urban areas.

Gaps and Needs

The "research climate" does not now favour innovative research strategies such as transdisciplinary approaches in Canada.

It is necessary to collect basic information relevant to health impacts of climate change. We have few, or no, reliable data on secular or geographic trends in the distribution and abundance of insect vectors of disease in Canada, nor data on the pathogens that they carry.

It is necessary to undertake surveillance and monitoring of the distribution and abundance of anopheline mosquitoes that carry malaria, and the migration of deer mice that carry the virus of hantavirus pulmonary syndrome. Surveillance and monitoring of many other pathogens have an equally high priority.

Public health surveillance of air-conditioning systems (possibly harbouring Legionnaires' disease) is required.

Surveillance and targeted research into threats to health need transdisciplinary mobilization.

Changes in human behaviour must begin to take place, such as understanding and dealing with the problems of climate change, and changing from the use of non-renewable resources to sustainable development.

Research is needed to end micro organisms and mosquitoes becoming resistant to pesticides. Research is needed for unequivocal evidence to establish the sequence from the damage to ozone by chemicals to the subsequent effects on human health. It is essential to close all the gaps in our knowledge as increased surface level UVR may be among the most dangerous factors associated with global climate change. Research requires new coalitions among several kinds of biomedical scientists (e.g., clinicians, epidemiologists and microbiologists) and social and behavioural scientists.

Acid fogs and mists are a serious respiratory irritant--especially for people who already have some respiratory system damage. Transdisciplinary research is needed to study the relationships among acid deposition, soil chemistry, botany and agronomy, and human health outcomes.

A high priority is the consideration, from a Canadian context, of the future of work, health, sociodemographic and urbanization trends, food security, resource availability and use, technology, etc., both within Canada and in the world as a whole.

Conclusion

This report describes the widespread and harmful human health impacts of the six air issues, namely climate change (global warming), stratospheric ozone depletion (and increased ultraviolet radiation), air toxics, acid precipitation, smog and particulate matter. These health impacts constitute a considerable public health problem.

In light of the resulting health problems, the need for an expanded research effort, particularly transdisciplinary research, and for improved monitoring of health-risk indicators in relation to atmospheric stresses is obvious. The three research councils (SSHRC, NSERC, MRC) should, therefore, recognize the high priority of examining the air issues and their relation to health.

INTRODUCTION

Health

Health has many different meanings (May, 1961; Dubos, 1965; Audy, 1971; Task Force Report, 1976; Stokes *et al.*, 1982; Last, 1983; and Gurinder *et al.*, 1997). However, the most commonly quoted definition of health is that presented in the Constitution of the World Health Organization (1946): "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". Moreover, health is "a resource for everyday life" (WHO, 1986) that is required to "enable people to lead an economically and socially productive life" (WHO, 1977) (Hancock and Davies, 1997).

In Canada, billions of dollars are spent on health each year. For example, in 1994, real total health expenditures (in constant 1986 dollars) were $56.78 billion dollars, and real total health expenditures per capita were $1,941.29. Total health expenditures represented 9.7% of GDP (Canadian Institute for Health Information, written communication, 1997).

The Determinants of Health

The determinants of health are numerous and wide-ranging. For example, determinants include: sufficient supplies of water; adequate and nutritious stocks of food; satisfactory housing on safe sites; acceptable services for waste disposal (WHO, 1992a); genetic make-up of individuals; support of social environments; sense of personal adequacy; and sufficient health care services (Evans *et al.*, 1994).

Strategies to influence population health status must address the broad range of health determinants in a comprehensive and interrelated way. The report on *"Strategies for Population Health: Investing in the Health of Canadians"* proposed grouping the many and various determinants of health into five categories:

(1) Social and Economic Environment. Income, employment, social status, social support networks, education, and social factors in the workplace.

(2) Physical Environment. Physical factors in the workplace, as well as other aspects of the natural and human-built environment.

(3) Personal Health Practices. Behaviours that enhance or create risks to health.

(4) Individual Capacity and Coping Skills. Psychological characteristics of the person such as personal competence, coping skills, and sense of control and mastery; as well as genetic and biological characteristics.

(5) Health Services. Services to promote, maintain and restore health.

The five categories of determinants make up a framework that could be adopted by the federal, provincial and territorial governments as the basis for strategies to improve population health.

The Environment and Health

Human health is intimately linked to the environment (Last, 1987; WHO, 1990a and b; WHO, 1992a and b; World Bank, 1992; Chivian *et al.*, 1993; McMichael, 1993; WHO, 1994a; and WHO, 1996). For a first example, climatic variables such as temperature, precipitation and humidity play a major role in controlling human comfort and disease vectors (WMO, 1987; and Meade *et al.*, 1988). Second, climatic hazards such as hurricanes, tornadoes, floods, storm surges and lightning cause injury, illness and death. Third, sustained exposure to ultraviolet radiation may damage skin, eyes and immune systems of humans (IARC, 1992; Armstrong, 1994; UNEP, 1994; WHO, 1994b; and McMichael *et al.*, 1996a and b).

"The sustained health of human populations requires the continued integrity of the Earth's natural systems" (IPCC, 1996). "Human health ultimately depends on society's capacity to manage the interaction between human activities and the physical and biological environment in ways that safeguard and promote health but do not threaten the integrity of the natural systems upon which the physical and biological environment depends. This includes maintaining a stable climate" (WHO, 1992a).

Atmospheric Issues

Human activities are altering the Earth's climate and changing the chemistry of the Earth's atmosphere (IPCC, 1996). As a result, six air issues are receiving much attention in Canada. These issues include: on a global scale, (1) climate change (global warming) and (2) stratospheric ozone depletion (and increased ultraviolet radiation). On a regional scale, these issues include: (1) air toxics, (2) acid precipitation, (3) smog and (4) particulate matter).

A brief discussion of global air issues and regional air issues follows. Global air issues are first defined and second discussed within global and Canadian contexts. (The discussion regarding climate change is limited in order to avoid duplication, as climate change is the subject of the Canada Country Study). But regional air issues are defined and then discussed within only Canadian contexts.

Global Issues

(1) Climate Change (Global Warming)

Climate change refers to the warming which is predicted to result from increasing greenhouse gases (GHG) in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (1996) predicts, based on a doubling of atmospheric CO_2 ($2xCO_2$) concentration, that the mean surface temperature of the Earth will increase by 1.0-3.5°C over the coming century; this represents "an unprecedented, rapid rate of change for the world's human population". This predicted increase in temperature is expected to cause changes in climatic variables (e.g., temperature and precipitation) and climate-related parameters (e.g., sea level).

The Canadian Climate Centre General Circulation Model (CCCGCM) predicts, based on a $2xCO_2$ concentration, a warming of 4-8°C in the south of Canada, "with little season-to-season change". In the north of Canada, the model predicts a warming of 8-12°C in winter and a warming of 0-6°C in summer. Winter precipitation is expected to increase across Canada. However, precipitation during the growing season is expected to increase in the north of Canada and decrease, or remain relatively unchanged, in the south of Canada. Sea level rise is expected to cause large-scale flooding of: (1) important coastal wetlands such as the Hudson Bay Lowlands and the MacKenzie Delta; and (2) populated centres such as Vancouver and St. John, New Brunswick (Hengeveld, 1995).

2) Stratospheric Ozone Depletion (and Increased Ultraviolet Radiation)

Stratospheric ozone depletion refers to decreases in the protective ozone (O_3) layer, 15 to 35 km above the surface of the Earth. The depletion is largely due to anthropogenic chlorine and bromine compounds (IPCC, 1996). Decreases in stratospheric ozone have occurred since the 1970's (WMO, 1992). The most obvious example of stratospheric ozone depletion is the Antarctic “ozone hole”. The October average total ozone values over Antarctica are 50-70% lower than those observed in the 1960's (IPCC, 1996). Statistically significant losses of total ozone have also occurred in the mid latitudes of the northern and southern hemispheres (WMO/UNEP, 1995; and IPCC, 1996). Little or no downward trend in ozone values has been observed in the tropics. If the Montreal Protocol (1987) and its Amendments are complied with fully, the greatest stratospheric ozone losses will occur near the end of this century. Maximum ozone losses, compared to the ozone levels of the late 1960's, may be 12-13% greater at northern mid latitudes in winter and spring, and 6-7% greater at northern mid latitudes in summer and autumn (WMO/UNEP, 1995; and McMichael *et al.*, 1996b). These losses in stratospheric ozone are predicted to persist for several decades due to the long residency of industrial contaminants in the stratosphere. Stratospheric ozone is predicted to return to 1990 levels by the middle of the next century (UNEP, 1994).

Stratospheric ozone depletion has resulted, in recent years, in increased ground-level ultraviolet radiation (UVR), particularly at mid to high latitudes (Kerr and McElroy, 1993; WMO/UNEP, 1995; Madronich *et al.*, 1995; and McMichael *et al.*, 1996b). It has been estimated, providing other factors remain constant, that maximum ozone losses would be accompanied by a 15% increase in ground-level UVR in the northern mid latitudes during the winter and spring, and an 8% increase in ground-level UVR in the northern mid latitudes during summer (WMO/UNEP, 1995).

Ozone has been measured in the Canadian Arctic since 1960. The averages of pre-1980 ozone levels are considered to be normal values. Between 1980 and 1992, ozone values declined 5 to 10% over the Arctic for the January to April period. Ozone values over the High Arctic during March 1997 were as much as 45% below normal, and as much as 7% below the average in the mid latitudes over Canada. The total loss of ozone in the Arctic in 1997 is comparable to the loss experienced in recent years in the Antarctic. The effect of the Arctic loss of ozone on mid latitude UVR "will not be large" because: (1) most of the UVR occurs during the summer months of May, June, July and August; and (2) the area of ozone loss, relative to the total area of the mid latitudes in Canada, is small (Fergusson, written communication, 1997).

Regional Issues

(1) Air Toxics

Air toxics can be gases, particulates or aerosols (fine solid particles and liquid droplets combined), which may have immediate or long-term adverse effects on human health and the environment. Some health effects include cancer, birth defects, nervous system problems and death due to massive accidental releases, such as that which occurred at the pesticide plant in Bhopal, India. They may also have environmental effects, including contamination of water, soil, or food.

These pollutants include a wide variety of chemicals, such as polychlorinated biphenyls (PCBs), unburned hydrocarbons, such as polycyclic aromatic hydrocarbons (PAHs), benzene, dioxins, furans, formaldehyde, trichloroethylene, and trace metals, such as lead, arsenic and mercury. Air toxics are released by sources such as chemical plants, dry cleaners, printing plants, and motor vehicles.

Volatile organic compounds (VOCs) are organic chemicals that contain the element carbon (C) and that exist predominantly in gaseous form in the atmosphere. Organic chemicals are the basic chemicals found in living things and in products derived from living things, such as coal, petroleum and refined petroleum products. Many of the organic chemicals we use commonly do not occur in nature, but were synthesized by chemists in laboratories. Volatile chemicals produce vapors readily; at room temperature and normal atmospheric pressure, vapors escape easily from volatile liquid chemicals. Volatile organic chemicals include gasoline, industrial chemicals such as benzene, solvents such as toluene and xylene, and tetrachloroethylene (perchloroethylene, the principal dry-cleaning solvent). Many volatile organic chemicals are also hazardous air pollutants; for example, benzene causes cancer (Air Quality Glossary- EPA, internet).

Volatile organic compounds (VOCs) are substances that may originate in plant matter or from human activity and that evaporate readily at ordinary pressures and temperatures. By far the greatest source of VOCs in British Columbia is vegetation, but the greatest source from human activity is from transportation. Hydrocarbons, which form part of this group of chemicals, are solely made up of carbon and hydrogen and are a prime component of such fuels as methane, propane, natural gas, gasoline and kerosene.

VOCs contribute to the formation of ground-level ozone, with the deleterious effects noted above. A number of VOCs are also toxic and are described under Hazardous Air Pollutants.

Combustion of coal and other solid fuels can produce smoke (containing polycyclic aromatic hydrocarbons - PAH) and other agents, such as those also produced by:

- Combustion of liquid petroleum products, which can generate carbon monoxide, oxides of nitrogen and other agents. Industry and incineration can generate a wide range of products of combustion such as oxides of sulphur and nitrogen, polycyclic aromatic hydrocarbons, dioxins etc..

- Combustion of fuel can also generate hazardous substances in other ways, besides by chemical oxidation, such as by liberating benzene (from the "cracking" of petrol) or lead (from leaded petrol).

The Canadian Environmental Protection Act has a priority list of 44 substances that are potentially toxic and need further assessment.

(2) Acid Precipitation

Acid precipitation refers to precipitation acidified by atmospheric pollutants, such as sulphur dioxide (SO_2) and nitrogen oxides (NOx), emitted from smelters and fossil-fuel power stations. These pollutants are converted chemically to sulphuric and nitric acid in the atmosphere. The contaminants may travel long distances before being washed out of the atmosphere. Diluted forms of these acids fall to the Earth as rain, hail, drizzle, freezing rain or snow (Environment Canada, 1996a).

Sulfur dioxide, a gaseous pollutant, is mainly generated from coal- and oil-burning power plants, ore smelters, industrial boilers, and oil and gas processing. Some industrial processes, such as the production of pulp in some plants, also produce sulfur dioxide. From 1974 to 1992, the mean annual sulphur dioxide concentration in Canada decreased by 61% (Environment Canada, 1995a). Sulfur dioxide and sulphates are the principal components of acid precipitation. These gases are easily transported great distances away from their source, and may cause acidification of water and soils if local conditions are insufficient to neutralize the acid.

Nitrogen oxides are produced by combustion in vehicles. However, nitrogen dioxide is a secondary pollutant created by the oxidation of nitrogen oxide under conditions of sunlight, or it may be formed directly by higher temperature combustion in power plants, or formed indoors from gas stoves (Nadakavukaren, 1995). Levels of exposure to nitrogen dioxide, as stipulated by WHO guidelines, are 0.21 ppm for one hour or 0.08 ppm for 24 hours exposure (WHO, 1987). Public awareness and legislation have contributed to a 38% decrease in the average annual nitrogen dioxide levels across Canada between 1977 and 1992 (Environment Canada, 1995a). There is a concern that these gains may eventually be offset by greater vehicular traffic.

In 1992, EEO provided the following information regarding acid rain in Canada. First, more than 80% of Canadians live in areas with "high acid rain-related pollution levels". Second, a total of 300,000 lakes are vulnerable to acid precipitation; 150,000 lakes are being damaged by acid rain and 14,000 lakes are acidified. Third, 84 % of the most productive agricultural lands in eastern Canada annually "receive more than the acceptable levels of acid deposition". Fourth, about 55 % of eastern Canada's forests are in areas where rainfall is acidic. Last, extensive damage to materials, historic buildings and monuments has been widely documented throughout eastern Canada. The preceding five statements clearly show that acid rain is a pervasive national problem in Canada.

In 1994, SO_2 emissions in Canada were down 50% from 1980 levels to approximately 2.5 million tonnes. Sulphur dioxide emissions have decreased by approximately 12% since 1980 in the United States - the country responsible for more than half of the acid deposition in Canada. The United States has an Acid Rain Program which calls for a 40% reduction in SO_2 emissions by the year 2010. These reductions are not expected to protect some of the more sensitive ecosystems (APAC, 1997a).

(3) Smog

The term "smog" originally referred to heavy layers of smoke and fog over London. Today smog refers to air pollution caused primarily by industry and motor vehicles. In North America the

term “smog” has been used to describe a characteristic form of air pollution that generally occurs from late spring to early fall (Stieb *et al.*, 1995). It is also known as photochemical air pollution because its essential chemical reaction is driven by light.
Photochemical smog is produced through complex photochemical reactions when two pollutants, hydrocarbons and nitrogen oxides, react in the presence of strong sunlight, high temperatures (above 18°C), and stable air masses. Sunlight is needed to initiate ozone formation, and high temperatures increase the rates of the chemical reactions that form ozone. Therefore, photochemical smog levels peak during the summer. Photochemical smog is characterized by high concentrations of tropospheric ozone (ground-level ozone) and peroxyacetyl nitrate (PAN).
The concentration of tropospheric ozone is often used as an indicator of the overall severity of smog (Bunce, 1994). Fluctuations in an area's ozone level can be attributed partially to variations in regional weather conditions.

The physical charateristics of photochemical smog include a murky yellow-brown haze, which reduces visibility, and the presence of substances which both irritate the respiratory tract and cause eye-watering. The yellowish colour is due to a form of nitrogen dioxide, while the irritant substances include ozone, nitrogen dioxide, aliphatic aldehydes, and organic nitrates (Bunce, 1994).

Tropospheric ozone is one of the major components of photochemical smog. It is produced indirectly by burning coal, gasoline and other fuels, and chemicals found in products including solvents, paints, and hairspray; it is highly reactive with many other gases in the atmosphere, as well as living and non-living materials. Ozone is a secondary pollutant, catalyzed from oxygen by other air pollutants under sufficient conditions of temperature and light.

Sources of hydrocarbons include forest fires, decomposition of organic matter, organic solvent evaporation, industrial processes, and engine exhausts. Sources of nitrogen oxides include internal combustion engines, and furnaces fueled by coal, oil or natural gas. Ozone precursors are emitted from millions of mobile and stationary sources ranging from motor vehicles, aircraft, boats, and forest fires, to power plants, dry cleaners, and gas stations.

Drift of the urban plume can affect neighbouring rural areas (Bunce, 1994). Transnational drift of air pollution occurs across the Canada-U.S. border, and especially across the southern Ontario border.

Although air quality in Canada has generally improved over the past 15 years, smog episodes still occur. These episodes are primarily a summer phenomenon and consist principally of elevated concentrations of ground-level ozone (Stieb *et al.*, 1995).

More than half of all Canadians live in areas in which ground-level ozone may reach unacceptable levels during the summer months (Olivotto, Written communication, 1997). Table 11.1 shows the number of days per year with ozone levels in excess of the one-hour air quality objective of 82 parts per billion (average of the three highest years 1983-1990).

The three regions of Canada that are most prone to smog problems are: (1) the Windsor-Quebec City Corridor; (2) the Lower Fraser Valley; and (3) the Southern Atlantic Region (Environment Canada, 1995a). Maximum ozone concentrations in these areas occur almost exclusively between May and September, and often exceed the one-hour average maximum acceptable level of 82 parts per billion (ppb) (Olivotto, written communication, 1997).

Table 11.1. Number of days per year with ozone levels in excess of the one-hour air quality objective of 82 ppb (average of the three highest years 1983-1990)

Location	Number of days
Victoria, British Columbia	0.0
Vancouver, British Columbia	10.7
Edmonton, Alberta	1.3
Calgary, Alberta	2.3
Regina, Saskatchewan	0.7
Winnipeg, Manitoba	2.3
Sault Ste. Marie, Ontario	3.0
Windsor, Ontario	30.0
Sarnia, Ontario	24.7
London, Ontario	20.7
Hamilton, Ontario	17.0
Toronto, Ontario	24.0
Oshawa, Ontario	22.3
Cornwall, Ontario	10.3
Ottawa, Ontario	7.3
Montreal, Quebec	14.7
Quebec, Quebec	5.7
Halifax, Nova Scotia	0.7
Kejimkujik, Nova Scotia	4.3
Saint John, New Brunswick	5.0

Source: Environment Canada, 1995a

The Windsor-Quebec City Corridor experiences higher-than-acceptable levels of ground-level ozone more often, and for longer periods of time, than any other area of the country (CCME, 1996). Stations representing "a spatial extent of several hundred kilometres" have simultaneously recorded ozone concentrations above 82 ppb for several consecutive hours, and up to 8 consecutive days. Peak one-hour concentrations during typical pollution episodes in the Windsor-Quebec City Corridor often reach 150 ppb; maximum recorded values have reached 200 ppb. Windsor experiences more smog than any other Canadian city. Windsor exceeds ozone air quality standards 30 days per year on average. In the Lower Fraser Valley, ozone concentrations are typically in the 90-110 ppb range during pollution episodes. In the Southern Atlantic Region, peak hourly ozone concentrations are in the 90-150 ppb range (Olivotto, written communication, 1997).

In response to the annual exceedences of the 82 ppb Canadian ozone objective, the Canadian Council of the Ministers of the Environment (1990) developed a management plan for ground-level ozone. The plan is designed to meet the 82 ppb objective throughout the country by the year 2005 (APAC, written communication, 1997b).

(4) Particulate Matter

Particulate matter is a term used to describe material that can be filtered from the air. It is not a clearly defined chemical or physical entity, and in many instances, the terms particulate matter, suspended particulate, total suspended particulate (TSP), and airborne particles are used interchangeably in the air pollution field.

Particulate matter includes particles such as dust, soot, ash, fibre, pollen and other tiny fragments of solid materials that are released and dispersed into the atmosphere by natural sources and human activities. In general, these particulates are produced by human activities, including the burning of diesel fuels by trucks and buses, incineration of garbage, mixing and application of fertilizers and pesticides, road construction, thermal-power generation plants and waste incinerators, industrial processes such as steelmaking, mining operations, agricultural burning, and operation of fireplaces and woodstoves. There are also some natural sources such as wind-blown dust, pollen and ash from forest fires (Environment Canada, 1995a).

Particulate matter is broken down into various size ranges. Fine particulates include the particle sizes PM 2.5 and PM10. PM 2.5 refers to particulates at or below a diameter of 2.5, whereas PM10 refers to particles that are 10 or less in diameter. Fine particulates are particles so small that they remain suspended in the air.

Particulates in the fraction PM 2.5 contain proportionately larger amounts of water and acid-forming chemicals such as sulfate and nitrate, as well as trace metals. These smaller particulates, also callled ultrafines, penetrate easily into buildings and are relatively evenly dispersed throughout urban regions. Unlike other air pollutants that have varying concentrations within an area, PM 2.5 tends to be relatively uniformly distributed. In the Lower Fraser Valley, diesel and gasoline vehicles are the major sources of PM 2.5. PM10 includes coarser particles that seem less significant in causing human health effects. Particulates of natural origin, such as pollen, tend to be coarse, with the exception of dust from fires and of volcanic origin (Environmental Protection, Province of British Columbia, Ministry of Environment, Lands and Parks, 1995).

Environment Canada has collected inhalable particles (< 10 in diameter) in 15 Canadian cities since May 1984. The coarser particles are mostly of natural origin (minerals from Earth's crust, sea salt, and plant material), whereas the fine particles consist of lead, sulfates, nitrates, carbon, and a variety of organic compounds, mainly resulting from human-made pollution. At eastern Canadian sites, fine particulate matter accounted for more than 60% of the inhalable particles; at sites in the Praire provinces, the fine fraction was usually less than 40% of the inhalable particles (Environment Canada, 1990).

The annual average level of airborne particles at all National Air Pollution Service (NAPS) monitoring sites in Canada, decreased by 46% between 1974 and 1986. This significant improvement in urban air quality relative to particulate emissions reductions reflects the fact that most major industrial sources of particulate matter are located outside urban areas. The average levels at more than 90% of the sites were well within the desirable range of air quality in 1986 (Environment Canada, 1990).

However, short-term exposure to high levels of particulate matter continues to be a problem. For example, the maximum acceptable level objective for a 24-hour exposure period was exceeded at least 10% of the time at some NAPS sites in Sydney, Rouyn, Windsor, Edmonton, Hamilton, and Calgary. As well, the 24-hour maximum tolerable level ambient air quality objective was exceeded once in 1986 at NAPS monitoring sites in each location of Edmonton, Calgary, and Yellowknife. High short-term particulate levels can be attributed in part to natural windblown dust, as well as to construction, industrial activity and the increasing number of motor vehicles on city streets (Environment Canada, 1990).

Aim

In light of the current awareness of (1) the intimate relationship between the environment and human health, and (2) the six Canadian air issues, namely climate change, stratospheric ozone depletion, air toxics, acid precipitation, smog and particulate matter, it seems useful to review the scientific literature regarding the possible impacts of these air issues on the health of Canadians. Specifically, this report aims to: (1) review the Canadian human health impacts of the six air issues; (2) put forth adaptation approaches and options; and (3) identify knowledge gaps and research needs.

It is important to note that the six air issues are inter-related. As a result, the air issues may interact to cause negative/positive effects on the atmosphere, the ecology of the Earth and the human population. Unfortunately, the six air issues have been assessed largely as individual issues. Moreover, the health impacts of each of the six air issues have been largely examined in relation to only one air issue--a notable exception is the health impacts of weather and air pollution.

HEALTH IMPACTS OF CLIMATE CHANGE (GLOBAL WARMING)

Global climate change would disturb the Earth's physical systems (e.g., weather patterns) and ecosystems (e.g., disease-vector habitats); the disturbances would, in turn, pose direct and indirect risks to human health. Direct risks involve climatic factors which impinge directly on human biology. Indirect risks do not entail direct causal connections between climatic factors and human biology (McMichael *et al.*, 1996a and b).

It is important to note that relatively little research has yet been undertaken that enables quantitative description of the probable Canadian health impacts; a notable exception is the work of Kalkstein which is later described. Scientific papers have speculated, therefore, on the most likely health outcomes of climate change (Guidotti, 1996). But major Canadian contributions include the work of the following: Last, 1989; Environmental Health Directorate, 1991; Canadian Public Health Association, 1992; Last, 1993a and b; Guidotti, 1994; Canadian Global Change Program, 1995; Environment Canada *et al.*, 1995b; Guidotti, 1996; and Hancock and Davies, 1997.

Potential Direct Health Impacts of Climate Change (Global Warming)

Health Impacts of Thermal Extremes

In a warmer world, heat waves are expected to become more frequent and severe, and cold waves less frequent, in Canada (Etkin, 1996). For example, in Saskatoon, the number of July days whose temperature exceeds 31°C could increase, under $2xCO_2$ conditions, from the current average of 3 days per year to 8 days per year. The number of January days with temperature below -35°C could decrease from the current average of 3 days per year to 1 day every 4 years (Hengeveld, 1995).

It has been suggested that an increased frequency and severity of heat waves may lead to an increase in illness and death, particularly among the young, the elderly, the frail and the ill, especially in large urban areas (CDC, 1989; Grant, 1991; Canadian Public Health Association, 1992; Kalkstein, 1993; Kalkstein and Smoyer, 1993a and b; Canadian Global Change Program, 1995; Environment Canada *et al.*, 1995b; Kalkstein, 1995; Guidotti, 1996; Kalkstein *et al.*, 1996; McMichael *et al.*, 1996a and b; Phelps, 1996; Tavares, 1996; and Hancock and Davies, 1997). Heat waves affect existing medical problems and affect all causes of death, not just those related to problems of the respiratory or cardiovascular systems (Canadian Global Change Program, 1995). Table 11.2 shows the number of deaths from excessive heat in Canada for the years 1965-1992. Finally, heat waves have been linked with outbreaks of violent and other antisocial behaviour (Canadian Global Change Program, 1995).

The heat-related deaths in the United States of 1700 people in 1980, 556 people in 1983 and 454 people in 1988 (CDC, 1995) may serve, although extreme examples, as possible indicators of what might occur if climate change scenarios are correct. More recent examples include the heat-related deaths of 118 persons in Philadelphia in 1993 (CDC, 1993; and CDC, 1994), 91 persons in Milwaukee in 1995, and 726 persons in Chicago in 1995 (Phelps, 1996).

Acclimatization of populations may, however, reduce the predicted heat-related morbidity and mortality in the future. Kalkstein *et al.*, (1993b) found that "both Montreal and Toronto might acclimatize somewhat to global warming conditions. Ottawa showed no signs of potential acclimatization." It is important to note that acclimatization to increasing temperatures occurs gradually, particularly among the elderly, and may be slower than the rate of ambient temperature change. Higher ambient temperatures are associated with higher body core temperatures. Higher body core temperatures in humans have been linked to elevated perinatal deaths, pre-term births, and an increased incidence of renal calculi (Canadian Global Change Program, 1995).

Table 11.2. Number of Canadian deaths due to excessive heat and excessive cold for the years 1965-1992

Year	Number of deaths due to excessive heat	Number of deaths due to excessive cold
1965	5	87
1966	15	98
1967	5	73
1968	10	91
1969	2	91
1970	5	110
1971	3	158
1972	3	118
1973	5	124
1974	-	126
1975	24	104
1976	1	106
1977	14	113
1978	5	106
1979	11	112
1980	3	120
1981	4	84
1982	-	132
1983	6	107
1984	3	116
1985	7	121
1986	10	93
1987	9	74
1988	19	75
1989	4	98
1990	5	86
1991	2	83
1992	3	69
Totals	183	2875

* It is not specified whether the number of deaths from excessive heat and excessive cold are due to weather conditions or other causes for the years 1975-1978.

Two empirical studies regarding climate change and heat-related morbidity and mortality for Canada are important to note. First, Tavares (1996) examined the relationship between weather and heat-related morbidity for Toronto for the years 1979-1989. A significant relationship was found between weather and all morbidity for people less than 65 years of age, with approximately 14% of the variability being explained by weather. Second, Kalkstein and Smoyer (1993a) undertook a comprehensive study which examined the potential impacts of climate change on human heat-related mortality for ten cities in Canada. Kalkstein and Sheridan provide the following discussion of the work.

The Impact of Climate and Climate Change on Heat-Related Mortality in Canada

Introduction

This discussion describes both the present and potential impact of global warming on human heat-related mortality for 10 cities in Canada. Four general circulation model (GCM) scenarios for the year 2050 are utilized, including the Canadian GCM. Results indicate that if the temperatures warm as expected under a doubling of atmospheric carbon dioxide ($2xCO_2$) several large Canadian cities which experience intrusions of hot, humid air masses during the summer season could be impacted very negatively.

Methodology

Statistics Canada has made available detailed mortality data for the following ten cities and their metropolitan areas for the years 1958 to 1988: Calgary, Edmonton, Halifax, Montreal, Ottawa, Quebec, St. John, Toronto, Vancouver, and Winnipeg. These cities were selected as they have a large enough population to record a sizable number of deaths each day, and they are representative of a variety of climates. Mortality data were subclassified according to age (less than 1 year, greater than 65 years, all ages) and cause of death (a weather-related group, including all respiratory causes, influenza, stroke/cerebrovascular, injury and heat stroke/heat stress, and all causes). There is conflicting evidence in the literature about the validity of factoring weather-related causes of death. As deaths from a surprisingly large number of causes appear to escalate with more extreme weather (Applegate et al., 1981; and Jones et al., 1982), weather-related and all-cause deaths were evaluated separately in this study.

A brief overview of the methods of data analysis is presented here. For greater detail, the reader may consult Kalkstein and Smoyer (1993a). Two procedures were utilized to ascertain the historical weather/mortality relationships which must be determined before employing climate scenarios:

(1) Threshold temperatures. A threshold temperature for a given city represents the daily maximum temperature above which mortality significantly increases (Kalkstein and Davis, 1989). It is measured statistically by evaluating the dissimilarity of mortality rates above and below a given temperature; the temperature with the maximum dissimilarity represents the threshold. Once the threshold has been established, a regression procedure is used to determine which additional weather elements (Table 11.3) are most highly correlated with mortality for days beyond the threshold temperature (Draper and Smith, 1981). The algorithms developed through these regression analyses are then determined to be worthwhile predictors of mortality by using tests suggested by Box and Wetz (1973).

(2) "Air mass" identification. This procedure depends upon the identification of offensive meteorological situations, or specific "air masses", which appear to be associated with particularly high mortality totals (Kalkstein, 1991a). The procedure assumes that the

combined impact of several elements is greater than the sum of the individual impacts of each variable (element as with the threshold temperature approach).

Table 11.3. Weather variables used in the mortality study

Maximum temperature (MaxT)
Minimum temperature (MinT)
Maximum dew point (MaxDPT)
Minimum dew point (Min DPT)
2 PM LST Cloud Cover (CC 1400)*
2 PM LST Wind Speed (Wsp 1400)*
Time of Season (Time)
Day in sequences (Day)
LST = Local Standard Time *Values represent cloud cover and wind speed measured at 1400 hrs (2PM LST)

An automated air mass-based index known as the temporal synoptic index (TSI) (Kalkstein *et al.*, 1987) was developed for each city to place each day into a particular category. The procedure groups days which are considered to be meteorologically homogeneous (Kalkstein, 1991a), by examining each day in terms of seven meteorological elements (air temperature, dew point temperature, visibility, total cloud cover, sea-level air pressure, wind speed, and wind direction) taken four times.

The mean daily mortality for each synoptic category was then determined to ascertain whether any particular categories were distinctively high. Potential lag times of one, two, and three days were also accounted for. As with the threshold temperature method, regression analysis was performed on all days within an “offensive” category utilizing the variables listed in Table 11.3.

With historical relationships established, the next step is an estimation of changes in mortality which might occur with climatic warming. This study uses a variety of general circulation model (GCM) scenarios as well as arbitrary scenarios to develop these estimates (Table 11.4). The number of days above the threshold and within offensive synoptic categories is established using the scenarios, and the algorithms developed through the historical analysis may then be utilized to estimate mortality.

Table 11.4. Climate change scenarios used in this study

General Circulation Models
Geophysical Fluid Dynamics Laboratory: GFDL Q-flux R15 model (Wetherald and Manabe, in press)
United Kingdom British Meteorological Office: UKMO model (Wilson and Mitchell, 1987)
Canadian Climate Centre: Canadian Climate Centre second generation model (McFarlane *et al.*,

in press)
NASA Goddard Institute for Space Studies: GISS model (Hansen *et al.*, 1988)

When measuring the impact of warming on future mortality, the question of acclimatization must be considered. That is, will people within each locale respond to weather as they do today, or will their reactions be similar to those of people who presently live in hotter climates and are acclimatized to heat? To account for such acclimatization, differences in mortality for each city during heat waves in cool and hot summers were examined. If people in a given city were to acclimatize, they would respond to heat in a more extreme fashion during cooler summers, when heat waves are infrequent, rather than during hotter summers, when heat waves are a more common occurrence (Kalkstein, 1991b; Rotton, 1983). Recent research in the medical community on the role of heat shock proteins, which synthesize in the body as a response to environmental stresses such as temperature change, implies that acclimatization may occur quite rapidly (Born *et al.*, 1990).

If mortality per hot day in a certain city is significantly and inversely related to the number of days above the threshold temperature over a series of summers, it is assumed that the population of this city could acclimatize to warmer conditions expected under $2xCO_2$ conditions. For these cities, estimates of acclimatized mortality under the various scenarios are developed and calculated by utilizing the slope of the regression line to estimate diminished mortality during the hotter summers as expressed by the scenarios. These acclimatization estimates account for only physiological and short term behavioral adjustments, not infrastructure changes. However, these may exemplify the most realistic estimates, as cultural or social adjustments, such as housing amenable to frequent heat, may lag far behind the physiological adjustments of the human body (Kalkstein, 1991b).

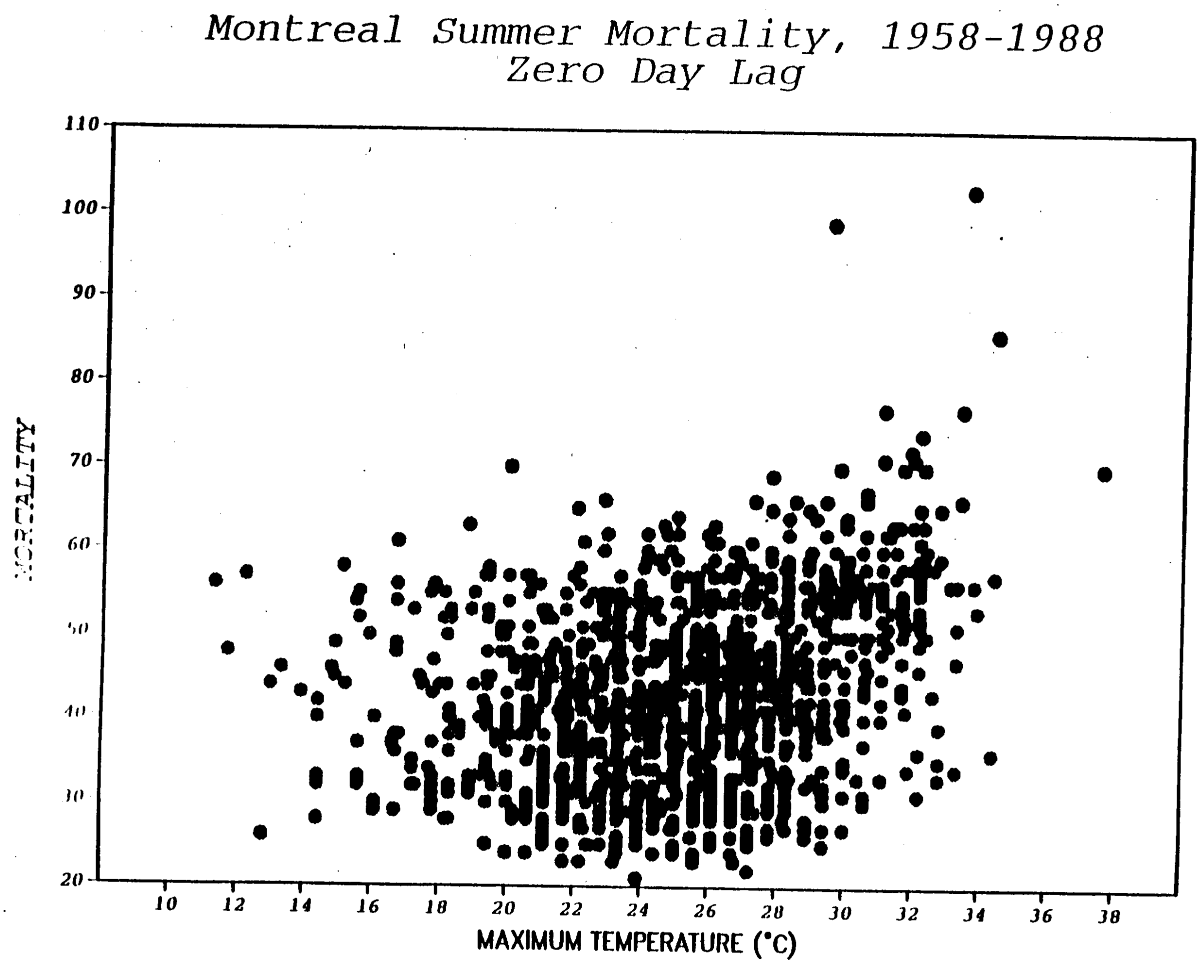
There are several shortcomings to the methods outlined above. First, the impact of air pollution, which may be closely related to weather (Schwartz *et al.*, 1988), is ignored. Second, while the global circulation models (GCMs) represent today's best estimates of future possible climate scenarios, they possess inherent limitations, and outputs from different GCMs often yield differing results for the same locale (Kalkstein, 1991b). Last, the acclimatization procedure is based on limited knowledge of human and societal responses to changing climate. There is no available research to determine acclimatization rates over periods of several decades, which represent the time period of a long-term, human-induced global warming.

Results

Historical Relationships

There appears to be a significant relationship between summer weather and mortality in several of the largest Canadian cities, particularly those with a warm and humid summer climate. Using the threshold temperature procedure, of the ten cities evaluated, only Toronto and Montreal demonstrated a significant relationship between maximum temperature and mortality (Figure 11.1). Threshold temperatures for Montreal and Toronto were 29°C and 33°C, respectively.

Figure 11.1. Maximum temperature vs. mortality for Montreal



The lack of a significant maximum temperature/mortality relationship at the other Canadian cities is likely due to several factors. For the cities of Vancouver, St. John's, and Halifax, heat waves of the intensity found in Toronto or Montreal almost never occur. The lack of significance of results from Winnipeg, Calgary, and Edmonton, which suffer from periodic heat waves, is likely a function of the dryness of hot air masses over the Great Plains which results in less stressful conditions than the more humid air masses which intrude further east. Results in adjacent U.S. cities (such as Minneapolis), which have a similar climate, demonstrate a similarly weak heat/mortality relationship. Also, the lack of a relationship in Ottawa and Quebec, combined with the relatively low threshold temperatures in Montreal and Toronto, compared to U.S. cities, suggests that the metropolitan regions of southeastern Canada are at the northern limits of an area having a significant heat/mortality relationship.

An evaluation of potential variables which could affect mortality above the threshold temperature in Montreal and Toronto shows that the populations of both cities react similarly if the weather is stressfully hot (Tables 11.5 and 11.6). In both cities, weather explains a sizable proportion of the variance in mortality at temperatures above the threshold. In Toronto, weather alone accounts for over 30% of the variance ($R^2 > .30$) in mortality when the maximum temperature exceeds 33°C. The foregoing represents a level of significance rivalling many of the most weather-sensitive U.S. cities. For both Toronto and Montreal, a long string of stressful days produces an adverse physiological response (positive coefficient of *Day* variable). Also, heat waves early in the season are more damaging than those late in the season (negative coefficient of *Time* variable), implying intra-seasonal acclimatization (Kalkstein, 1988). For both cities, the models are significant at the 99% level, and the coefficient of determination is sufficiently high to pass the Box and Wetz test, indicating that the algorithm developed from the analysis may be used for predictive purposes.

Table 11.5. Regression analysis for days above threshold for Montreal
(0 day lag threshold temperature = 29°C)

Total mortality						
Step	Variable	Coefficient	Partial R2 (%)	Model R2 (%)	F	Prob >F
	Intercept	11.5015			0.89	0.3456
1	Day	1.4972	8.81	8.81	18.17	0.0001
2	Time	-0.1315	4.86	13.67	33.35	0.0001
3	MinDPT	0.7529	5.83	19.50	19.28	0.0001
4	MaxT	0.9358	1.05	20.55	4.99	0.0260
Elderly mortality						
	Intercept	23.6256			105.99	0.0001
1	Day	1.6175	9.01	9.01	37.81	0.0001
2	Time	-0.1146	4.44	13.45	19.57	0.0001
3	MinDPT	0.6449	3.77	17.22	17.33	0.0001
4	Wsp1400	-0.1124	0.96	18.19	4.47	0.0352

Table 11.6. Regression analysis for days above threshold for Toronto
(0 day lag threshold temperature = 33°C)

Total mortality						
Step	Variable	Coefficient	Partial R2 (%)	Model R2 (%)	F	Prob >F
	Intercept	28.0129			16.62	0.0001
1	Day	4.0598	18.10	18.10	11.65	0.0011
2	MinT	1.0680	6.64	24.74	7.40	0.0083
3	CC1400	-0.7068	4.81	29.55	4.18	0.0449
4	Time	-0.0581	1.12	30.67	1.08	0.3028
Elderly mortality						
	Intercept	-50.0612			2.67	0.1072
1	Day	2.7389	16.55	16.55	13.89	0.0004
2	MaxT	2.1165	4.21	20.76	3.67	0.0597
3	MinDPT	0.6824	4.81	25.57	4.40	0.0397
4	Time	-0.0842	3.31	28.88	3.11	0.0822

The synoptic evaluation method uncovered an offensive air mass for Ottawa, as well as for Montreal and Toronto (Table 11.7). The stressful air mass possessed similar characteristics for all three cities. The cities were very warm, had high dew point temperatures, had moderate to strong southwesterly winds, and had a warm-core high pressure center to the south. The foregoing explains the lack of an offensive air mass at the three drier Great Plains cities, where such an airmass rarely occurs.

It is important to note that not every day with an offensive air mass coincides with high mortality. Although the mean daily mortality for the offensive air mass is 15% higher in Montreal and 20% higher for Toronto, standard deviations for the offensive air masses are also distinctively higher. This indicates that although most of the highest mortality days are associated with the offensive air masses, numerous days with these air masses possess much lower mortality totals--sometimes below the means of the other air mass types.

Both threshold and synoptic analyses were also performed on the available subsets of mortality data, from which the following conclusions can be made:

Table 11.7. Characteristics of offensive air masses: Montreal, Ottawa and Toronto

	Variable	**Mean value**		
		Montreal	Ottawa	Toronto
Midnight	Temperature (°C)	22.1	22.9	20.8
	Dewpoint (°C)	18.2	19.3	17.0
	Pressure (mb)	1008.9	1013.2	1018.2
	Windspeed and direction	Strong, SW	Strong, SW	Weak, WSW
	Cloud cover (tenths)	6	5	2
6 AM	Temperature (°C)	21.1	21.5	19.5
	Dewpoint (°C)	18.1	19.3	16.7
	Pressure (mb)	1008.9	1013.0	1018.6
	Windspeed and direction	Strong, SW	Strong, SW	Weak. WSW
	Cloud cover (tenths)	7	6	3
Noon	Temperature (°C)	26.2	29.8	30.1
	Dewpoint (°C)	18.9	20.6	18.6
	Pressure (mb)	1008.5	1011.9	1018.0
	Windspeed and direction	Very strong, SW	Strong, WSW	Strong, SW
	Cloud cover (tenths)	6	6	4
6 PM	Temperature (°C)	24.9	28.4	29.2
	Dewpoint (°C)	17.1	20.1	18.5
	Pressure (mb)	1008.1	1010.1	1016.0
	Windspeed and direction	Strong, WSW	Strong, WSW	Strong, SW
	Cloud cover (tenths)	6	6	4

(1) The elderly are not disproportionately affected by heat in Canada. This result is significantly different from that of most U.S. cities. The difference is possibly indicative of better health insurance and high-quality nursing homes for the elderly in Canada.

(2) No significant relationship was uncovered in any of the ten cities between infant (less than 1 year) mortality and the weather.

(3) When weather-related causes of death for the summer season were examined, weather/mortality relationships did not improve in any of the Canadian cities. Thus, it appears that a large variety of causes of death, even those not traditionally related to heat, increase when the weather is oppressively hot.

Present-Day Heat-Related Mortality Estimates

Estimates of present-day heat related mortality were developed for the threshold (Toronto and Montreal) and synoptic (Toronto, Montreal, Ottawa) approaches, utilizing the algorithms developed from the regression methods described previously. Mortality was estimated, using the algorithms, for every day with an offensive air mass or with temperatures above the threshold in the 30-year sample. These mortality estimates were compared to the 30-year mean daily mortality for the month, and the difference between the estimate derived from the algorithm and the long-term mean daily mortality was considered to be the day's heat-related mortality.

Table 11.8. Estimates of total present-day mortality attributed to weather during the summer 1958-1988: Montreal and Toronto[a] (For days above threshold)

	Average season				**Highest season**				**Lowest season**			
City	**June**	**July**	**Aug.**	**Total**	**June**	**July**	**Aug.**	**Total**	**June**	**July**	**Aug.**	**Total**
Montreal total	0.57[b]	1.56	0.49	2.62	0.61	3.69	3.12	7.42	0.38	0.15	0	0.53
Montreal elderly[c]	3.76	7.81	2.32	13.89	4.05	22.28	17.65	43.99	0.58	0	2.03	2.60
Toronto total	0.08	0.46	0.19	0.73	0.96	3.57	1.96	6.45	0	0	0	0
Toronto elderly	0.84	4.63	1.68	7.15	10.52	39.55	15.99	66.05	0	0	0	0

a=Values derived from algorithms in Tables 3 and 4
b=Death rate per 100,000 population
c=Elderly is defined as 65 years and older

Table 11.9 Estimates of total present-day mortality attributed to weather during the summer 1958-1988: Montreal, Toronto and Ottawa(For offensive clusters – synoptic approach)

	Average season				**Highest season**				**Lowest season**			
City	**June**	**July**	**Aug.**	**Total**	**June**	**July**	**Aug.**	**Total**	**June**	**July**	**Aug.**	**Total**
Montreal total	0.27	1.25	0.49	2.02	0	5.55	1.56	7.11	0	0.23	0.04	0.27
Montreal elderly[b]	1.45	7.23	2.60	11.29	0	34.44	8.10	42.54	0	0.29	0	0.29
Toronto total	0.15	0.46	0.31	0.92	0.15	1.19	1.50	2.84	0	0	0	0
Toronto elderly	1.26	4.21	2.10	7.57	2.10	11.78	13.04	26.92	0	0	0	0
Ottawa total	0.16	0.64	0.32	1.12	0	4.48	1.60	6.08	0	0	0	0
Ottawa elderly	0	5.91	3.94	7.89	0	29.57	9.86	39.43	0	0	0	0

a=Death rate per 100,000 population
b=Elderly is defined as 65 years and older

The estimates indicate that under certain conditions a sizable increase in death rates can be attributed to heat stress during the summer (Tables 11.8 and 11.9). It is estimated, on using both the threshold and synoptic methods, that Montreal's death rate is increased by more than 2 deaths per 100,000 residents due to heat-related deaths during an average summer. The elderly death rate shows a much larger increase: from 11.3 (synoptic) to 13.9 (threshold) extra deaths per 100,000 elderly people (attributable to weather). This approximately 6 to 1 ratio of elderly versus total death-rate increase approximates the overall elderly/total mortality proportion. Therefore, although deaths of the elderly make up the bulk of heat-related deaths, the elderly are not disproportionately affected. During an average summer, Toronto's heat-related death rate is much lower than Montreal's--under 1 per 100,000, using both methods. The reason for the lower death rate is not directly apparent, although it should be noted that Montreal's regression equation was a better fit to the data than Toronto's. For Ottawa, only the synoptic method was used, and this method estimated 1.12 excess deaths per 100,000 people per year due to the weather. For all of these estimations, it should be noted that death rates in extreme years are three to five times the mean, comparable to mean rates in the U.S. cities of Chicago and Philadelphia.

The death rates permit an evaluation of the importance of heat-related mortality when compared to deaths from other causes. For example, the combined death rate from bronchitis, emphysema, and asthma for Canada is 8.8 per 100,000 population (U.S. Bureau of Census, 1991). This rate is not much greater than Montreal's total heat-related mortality rate during the hottest summer (7.42 per 100,000, using the threshold approach). It should also be noted that heat-related mortality is confined to summer months only, while the respiratory illnesses occur year-round. Other causes of death with rates similar to Montreal's heat-related mortality include chronic liver disease, such as cirrhosis (9.4 per 100,000), and malignancies of the stomach (9.0 per 100,000). Thus, heat-related death rates are comparable to causes of death which are moderately important in today's society.

Estimates of Heat-Related Mortality Using Global Warming Scenarios

There are strong indications that global warming could significantly increase heat-related mortality, even if the population acclimatizes (Tables 11.10 and 11.11). Assuming no acclimatization, UKMO and GFDL estimates of heat-related death rates, under typical 2xCO_2 summer conditions, exceed 40 per 100,000 population in Montreal. These values are over 15 times the present heat-related death rates, primarily because many more days would be above the threshold temperature or coincide with an offensive air mass type (Table 11.12). For example, during a typical summer, 13% of days in Montreal exceed the threshold temperature of 29°C. Using the Canadian GCM 2xCO_2 model, 13% increases to 55%. Offensive air mass categories increase similarly; the frequency of the offensive category in Toronto is 5% today and 23% using the Canadian GCM scenario.

Table 11.10. Estimates of future Canadian mortality in summer attributed to weather using the threshold approach[a]

		UKMO		GFDL		GISS		Canadian GCM	
City	Present mortality	No Acc.	Acc.	No Acc.	Acc.	No Acc.	Acc.	No Acc.	Acc.
Montreal total	2.62[b]	43.16	24.79	40.69	24.95	16.35	8.29	22.39	11.69
Montreal elderly[c]	13.89	260.17	166.69	254.67	171.61	96.65	56.14	126.18	77.85
Toronto total	0.73	33.65	0	16.92	0.23	9.63	0.12	13.77	0.19
Toronto elderly	7.15	387.45	0	193.10	4.27	110.22	3.79	177.53	5.47

a=Values derived from algorithms in Tables 3 and 4

b=Death rate per 100,000 population

c=Elderly is defined as 65 years and older

Table 11.11. Estimates of future Canadian mortality in summer attributed to weather using the synoptic approach

		UKMO		GFDL		GISS		Canadian GCM	
City	Present mortality	No Acc.	Acc.	No Acc.	Acc.	No Acc.	Acc.	No Acc.	Acc.
Montreal total	2.02[a]	42.25	13.08	36.28	13.80	10.80	6.08	13.16	8.10
Montreal elderly[b]	11.29	250.04	166.40	216.18	150.20	68.88	45.73	79.01	54.4
Toronto total	0.92	23.52	0	13.58	0.12	12.93	0.19	7.44	0.15
Toronto elderly	7.57	221.70	0	122.84	0.84	112.74	2.10	68.15	1.68
Ottawa total	1.12	56.35	N/A	51.70	N/A	23.85	N/A	19.53	N/A
Ottawa elderly	7.89	457.35	N/A	406.10	N/A	187.28	N/A	143.91	N/A

a=Death rate per 100,000 population

b=Elderly is defined as 65 years and older

Table 11.12. Comparison between the present and scenarios: percent of days above the threshold or within an offensive synoptic category

Percent of days above threshold temperature			
Model		Montreal (29°C)	Toronto (33°C)
Present		13.1	2.5
UKMO		71.4	47.9
GISS		43.1	20.9
GFDL		62.3	30.0
Canadian GCM		55.1	28.5
Total number of days in period = 2852			
Percent of days in offensive synoptic category			
Model	Montreal (#105)	Toronto (#103)	Ottawa (#101)
Present	10.7	4.7	2.8
UKMO	38.6	39.1	42.4
GISS	21.1	30.0	27.3
GFDL	33.4	28.9	36.6
Canadian GCM	28.1	23.3	26.9
Total number of days in period = 2852			

Assuming no acclimatization, death rates from heat-related causes will exceed rates from relatively common causes of death today, especially in Montreal. Under the UKMO threshold temperature scenario for instance, the death rate increases twentyfold, and the 43 per 100,000 rate is considerably higher than the present death rate from breast cancer (34.4 per 100,000), suicide (13.9 per 100,000) and even traffic accidents (15.6 per 100,000) (U.S. Bureau of Census, 1991; Table 13). The Toronto death rates are somewhat similar to Montreal's, and actually exceed those in Montreal under the GISS scenario. The Ottawa synoptic estimates also yield death rates that are very high under 2xCO_2 conditions.

Using the approach to estimate the impact of acclimatization, it was determined that populations in both Montreal and Toronto might acclimatize somewhat to global warming conditions. Ottawa showed no signs of potential acclimatization, and the non-acclimatized estimates are probably most accurate for the city. Assuming acclimatization, heat-related mortality rates for both Toronto and Montreal are considerably lower (than they would be for non-acclimatization), but are still notably higher than present-day rates. For example, for Montreal utilizing the synoptic approach for the Canadian GCM, acclimatized total heat-related mortality rates are about four times present levels (2.02 per 100,000 today versus 8.1 per 100,000 for the Canadian GCM). The latter death rate is similar to the present combined death rate from bronchitis, emphysema, and asthma (Table 11.13). Considerably higher numbers are generated using the GFDL and UKMO scenarios, assuming acclimatization.

Table 11.13. Canadian and U.S. death rates from selected causes[a]

Cause of death	Canada[b]	United States[b]
Ischemic heart disease	188.1	193.4
Cerebrovascular disease	54.8	54.6
Lung cancer	52.2	54.9
Stomach cancer	9.0	5.5
Breast cancer	34.4	31.6
Bronchitis, emphysema, asthma	8.8	8.7
Chronic liver disease, cirrhosis	9.4	11.8
Motor vehicle accidents	15.6	18.5
Suicide	13.9	12.5

a=Source: U.S. Bureau of the Census, 1991. Rates per 100,000 population
b=Canadian and American rates based on 1987 values

Summary

The objective of this discussion was to estimate the potential impact of global warming on human heat-related mortality for 10 cities in Canada. Results indicate that if the temperatures warm as expected under 2xCO_2 conditions, urbanized areas in southeastern Ontario and southern Quebec could be impacted very negatively. These areas generally experience occasional intrusions of hot, humid air masses during the summer season.

In terms of actual populations of the cities mentioned above, an “average” summer in 2050 could result in a range of 240 to 1140 additional heat-related deaths per year in Montreal, 230 to 1220 in Toronto, and 80 to 500 in Ottawa, assuming no acclimatization. It should also be noted that questions, regarding "mortality displacement" (that is, the excess deaths which occurred would have occurred anyway within a few weeks) have been raised. Research performed on U.S. cities shows that only about 20 to 40% of the deaths are “displaced” (Kalkstein, 1993); thus, a significant true increase in premature loss of life could occur in the future.

Health Impacts of Extreme Weather Events

In a warmer climate, convective storms (severe thunderstorms producing hail, lightning, tornadoes, heavy rains and strong winds) are predicted to become more frequent and severe; floods, too, are expected to become more frequent. Two recent Canadian convective storms and floods occurred in July 1996: (1) damaging hailstorms hit Calgary and Winnipeg (Etkin, 1996); and (2) severe floods devastated the Saguenay region of Quebec (Carpentier, 1996). Finally, droughts are predicted to become more frequent and possibly more prolonged (Etkin, 1996).

It has been suggested that increased frequency and severity of extreme events may increase: (1) deaths, injuries, infectious diseases and stress-related disorders (Alexander, 1993); and (2) other adverse health effects associated with social disruption, environmentally-forced migration and settlement in urban slums (McMichael *et al.*, 1996b). Table 11.14 shows the number of deaths from lightning, storms and floods for Canada for the years 1965-1992.

Table 11.14 Number of Canadian deaths due to (1) lightning and (2) storms and floods for the years 1965-1992

Year	Number of deaths due to lightning	Number of deaths due to storms and floods
1965	7	-
1966	8	-
1967	8	-
1968	8	-
1969	9	-
1970	14	-
1971	9	-
1972	2	-
1973	3	-
1974	4	-
1975	11	-
1976	13	-
1977	8	-
1978	6	-
1979	6	2
1980	8	2
1981	10	1
1982	1	-
1983	4	2
1984	6	2
1985	3	13
1986	5	4
1987	6	28
1988	2	3
1989	5	-
1990	2	-
1991	5	-
1992	4	1
Totals	177	58

A recent extreme precipitation event was partly responsible for a 1995 outbreak of toxoplasmosis in the Capital Regional District of British Columbia. “Unusual precipitation events” caused contaminated runoff. It was suspected that the feces of infected domestic, feral or wild cats entered the Humpback Resevoir or its feeder streams and resulted in oocyst contamination of the water supply (British Columbia Centre for Disease Control, written communication, 1995).

Potential Indirect Health Impacts of Climate Change (Global Warming)

Introduction

There are virtually no studies which directly address the actual or potential impact of climate change on infectious diseases, nutritional health, water quality and quantity, and public health infrastructure in Canada. One is therefore left with making inferences from studies carried out with other purposes in mind (i.e., indirect studies of indirect outcomes). This is clearly unsatisfactory and must be remedied if Canadian health authorities are to be prepared for the challenges facing them over the next century.

Infectious Diseases

The incidence of almost all--perhaps all--infectious diseases in Canada changes seasonally. To the extent that seasonal patterns reflect purely social phenomena (e.g., schooling patterns), they may be expected to vary independently of climate. Even this inference may be misleading, however, if the social phenomena themselves change with climatic changes. For instance, increases in some foodborne illnesses in the late summer months are sometimes attributed to increases in the use of outdoor barbecues and handling of raw meats by consumers at this time. If climate change were to extend the warmer season in Canada, it might also be expected to extend the season for barbecue use. This behavioural change would interact with changes in the bacterial load in meats (which would be expected to increase with increased ambient temperatures) in a positive fashion. Similar feedback positive loops might occur with vector-borne diseases related to outdoor recreational activities.

Some of the diseases that might be expected to respond to atmospheric warming are outlined below; this is a representative, rather than a comprehensive list.

Vector-borne Diseases

Encephalitides

Arboviral infections, in general, given that they are already closely associated with climate variables (Sellers, 1983), are likely to be strongly affected by global warming. Of the viral encephalitides, western equine encephalitis (WEE), eastern equine encephalitis (EEE) and the snowshoe hare virus (SHV) would most likely see their ranges expanded in Canada. All three have already been reported in Canada or adjacent states, albeit sporadically (McLean *et al.*, 1985; Artsob, 1986; Tourangeau *et al.*, 1986; Keane and Little, 1987; Heath *et al.*, 1989; and Carman *et al.*, 1995). The natural cycle of these viruses is believed to involve mosquitoes and birds. The mechanism whereby the virus over-winters has long been in some dispute (Sekla, 1976). A re-evaluation of 1972 EEE outbreaks in Quebec and Connecticut (Sellers, 1989) and the 1980-1983 WEE outbreaks in Manitoba, Minnesota and North Dakota (Sellers and Maarouf, 1988) has put forth convincing evidence that infected mosquitoes could have been carried north on wind currents to “seed” a series of outbreaks. Changes in wind currents coupled with changes in local micro-climates--both plausible outcomes of global warming--would no doubt change the epidemiological patterns of these diseases, whatever their original source.

Reeves *et al.*, (1994) in a detailed review of WEE and St. Louis encephalitis have concluded that, under conditions of global warming, “WEE virus could disappear from much of its current endemic area, and become a more common infection in the northern states and Canada.” WEE is “very dependent” on *Culex* mosquitoes, which have recently increased their distribution in Canada; *Culex* was previously found only in Manitoba and is now found as far west as British Columbia. One outbreak of WEE has already occurred in the Okanagan Valley. With climate change, more outbreaks could occur further west (Mathias, personal communication, 1996; Duncan, 1997).

Malaria

It has been suggested that malaria may extend northward into Canada with global warming (Environmental Health Directorate, 1991; Canadian Public Health Association, 1992; Environment Canada *et al.,* 1995b; Pearce, 1995; Duncan, 1996; and Hancock and Davies, 1997). Brief descriptions follow of three empirical studies, which examine the possible role of global warming on malaria in Canada. First, Martens *et al.*, (1995) estimated that an increase in global mean temperature of several degrees by the year 2100 would increase the vectorial capacity of mosquito populations 100-fold in temperate countries. It was noted, however, that in temperate countries, continued and increased application of control measures, such as disease surveillance and prompt treatment of cases, would probably counteract any increase in vectorial capacity. Second, Martin and Lefebrve (1995), using a mathematical model, also predicted that malaria transmission could spread to higher latitudes, including Canada. Third, Duncan (1996) showed that mean daily temperatures, associated with a doubling of carbon dioxide, may allow for the development of malaria in Toronto. Increased mean daily temperatures may allow for: (1) the development of both *Plasmodium vivax* and *Plasmodium falciparum* in the mosquito; and (2) the transmission of both vivax and falciparum malaria. It was not, however, suggested that climate alone would permit the spread of malaria with global warming. Climate is merely one factor, among many, which is relevant to the aetiology of malaria.

It is important to remember that malaria once prevailed throughout southern Canada (Bruce-Chwatt, 1988). Malaria became widespread at the end of the 18th century, when refugees from the southern states settled in large numbers as far north as "the Huron", in the aftermath of the American War of Independence. Malaria was further spread with the building of the Rideau Canal (1826-1832) (Carpenter, personal communication, 1995; and Ghushalak, personal communication, 1995). By the middle of the 19th century, malaria extended as far north as 50°N latitude. In 1873, the great malarious district of western Ontario was only a fraction of a large, endemic area, “extending between Ontario to the state of Michigan”. In Canada, the disease disappeared at the end of the 19th century (Bruce-Chwatt, 1988; Haworth, 1988; Duncan, 1996; Duncan, 1997).

Dengue and Yellow Fever

It has also been suggested that both dengue and yellow fever may extend northward into Canada with climate change (Hancock and Davies, 1997; and Artsob, personal communication, 1996). In recent decades, the incidence of dengue and its complications (dengue haemorrhagic fever and dengue shock syndrome), has increased, and the diseases have expanded northward in the Americas to Mexico and to higher altitudes (Herrera-Basto *et al.*, 1988).

Heartworm

Dirofilaria immitis is a mosquito-transmitted parasite of dogs. When it occasionally infects humans, it causes pulmonary infarcts (Mandell *et al.*, 1995). The rate of development of the parasite in the mosquito is linearly related to temperature; furthermore, reported cases of the disease in dogs have been tracked through active surveillance of veterinary clinics for 20 years (Slocombe and Macmillan, 1978; Slocombe, 1990; Slocombe and Villeneuve, 1993; and Anonymous, 1994). From these reports, it seems clear that the disease has moved into various areas in Canada from the south during the twenty-year period, and, once established, has become endemic.

Lyme Disease and Rocky Mountain Spotted Fever

Tick-borne diseases may also extend their geographic distribution with climate change. Grant (1991) suggested that Rocky Mountain Spotted Fever may increase in some localities in Canada with warming. Lyme disease has also been predicted to spread in Canada with increased temperature (Grant, 1991; Canadian Global Change Program, 1995; Environment Canada *et al.*, 1995b; Guidotti, 1996; Mathias, Personal communication, 1997; Duncan, 1997; and Hancock and Davies, 1997).

Since the late 1980's, sporadic cases of Lyme disease, a tick-borne bacterial disease, have been reported in people and other animals in Canada (Lycka, 1986; Bollegraaf, 1988; Barker *et al.*, 1989; Todd and Carter, 1989; Costero 1990; MacKenzie 1990; Sekla *et al.*, 1990; Galloway *et al.*, 1991; Barker *et al.*, 1992; Anand *et al.*, 1993; and Banerjee 1993). While possible tick vectors have been reported from various parts of Canada, self-reproducing populations of infected ticks are believed to occur only in Long Point, Ontario (Barker *et al.*, 1992). Nevertheless, migratory birds are known to bring larval ticks into Canada annually (Klich *et al.*, 1996), and, given an increasingly receptive climate under conditions of global warming, it seems only a matter of time before Lyme disease becomes endemic in various parts of Canada.

Pest Species

Hantavirus

Hantavirus pulmonary syndrome is only rarely reported in Canada (Stephen *et al.*, 1994; and Werker *et al.*, 1995). A total of sixteen cases of hantavirus pulmonary syndrome have been identified in Canada. These cases have come from British Columbia, Alberta and Saskatchewan.

Sin Nombre virus has been found in deer mice in the afore-mentioned provinces, the Yukon Territory, and Manitoba. *Monongahela* virus has been found in deer mice in Ontario, Quebec and New Brunswick (Artsob, Personal communication, 1997; and Duncan, 1997). Like plague (*Yersinia pestis*), which is also related to a rodent reservoir, and is very occasionally reported in Canada, hantavirus pulmonary syndrome could undergo changes in its occurrence, related to increased contacts between rodents and people. Given that the virus is present in rodents in Canada, and given that changes in climate and ecology are known to affect rodent behaviour (as well as human behaviour), changes in the incidence of hantavirus pulmonary syndrome will result with global warming.

Environmental and/or Water Contamination

Anthrax

Epidemics of disease associated with *Bacillus anthracis* have been documented in cattle, bison and other species in the area of Wood Buffalo National Park. Spores of *B. anthracis* are known to survive for decades, and perhaps centuries, and are re-activated by changes in the environment--particularly in the availability of organic nutrients and water. Any lengthening of the warm season and changes in rainfall associated with atmospheric warming would be likely to result in changes in the appearance and distribution of anthrax (Gainer and Saunders, 1989; Dragon and Rennie, 1995).

Waterborne parasites

Giardia have apparently already infested a number of Canadian and American watersheds, resulting in widespread human exposure (Schantz, 1991; Chow, 1993; and Moore *et al.*, 1993). *Cryptosporidium* is considered to be one of the most common enteric pathogens world-wide (Meinhardt *et al.*, 1996). With increases in ambient temperatures, a prolonged summer season, increased heavy rainfall and/or run-off events, and many watersheds with mixes of intensive agriculture and urbanization, recent large outbreaks in the United States (Goldstein *et al.*, 1996; MacKenzie *et al.*, 1994; and Osewe *et al.*, 1996) and the United Kingdom (Bridgeman *et al.*, 1995) may well be indicative of the future. Both *Giardia* and Cryptosporidia appear to survive current municipal treatment protocols; however, no effective water treatments have been proposed. Furthermore, the disease in people does not respond well to any treatments (Meinhardt *et al.*, 1996).

While contamination of urban drinking-water supplies with Cryptosporidia, and surface water with *Giardia*, has been widely reported in North America in recent years, toxoplasmosis has rarely been associated with water. Recently, the largest-ever reported outbreak of toxoplasmosis was traced to the municipal water supply of the Greater Victoria area (British Columbia Toxoplasmosis Team, 1995; den Hollander and Noteboom, 1996; Mullens, 1996). The event should be a warning bell. Once considered to be primarily a risk for pregnant women, toxoplasmosis has in recent years been recognized as a significant cause of death in immunocompromised people. There is already evidence that exposure to the causative parasite in Canada is widespread (Tizard *et al.*, 1977; and Tizard *et al.*, 1978). Given the increasing number of feral cats in Canada, and the persistence of sporulated oocysts in a variety of environments (Dubey and Beattie, 1988), areas in Canada which are hospitable to oocyst survival, as a result of global warming, are likely to expand. The expansion should be of grave concern.

Leptospirosis

Leptospirosis has been reported across Canada in several species of wildlife (Kingscote, 1986), horses (Kitson-Piggot and Prescott, 1987), dogs (Prescott *et al.*, 1991), cattle (Kingscote and Proulx, 1986; Kingscote and Wilson, 1986; Prescott *et al.*, 1987; Kingscote, 1988 ;and Prescott *et al.*, 1988), pigs (Baker *et al.*, 1989) and people (Rivest *et al.*, 1989;and Prescott *et al.*, 1992). With a longer warm season, the probability of surface water contamination by urine from infected animals increases (Acha and Szyfres, 1987).

Sea-food Toxins

Of diseases related to marine environments, cholera is no doubt the most important globally (Huq and Colwell, 1996). Nevertheless, sea-food toxins are increasingly becoming a concern and are no doubt more important in the Canadian context, especially given the recent increases in seafood consumption by Canadians (Statistics Canada, 1996a and 1996b). Ewen Todd of Health Canada has reviewed the emergence of these diseases in Canada (1993) and globally (1994). Several authors have postulated the kinds of environmental changes, including global warming, which are leading to the emergence of new seafood-related diseases and to the changing patterns of those already known (Tester 1994; Todd 1994; Epstein and Rapport, 1996).

Water Quality

Changes in water quality as the result of global warming are likely to be expressed in terms of infectious disease outcomes--particularly parasitic, but also bacterial diseases. While there is no exact relationship between bacterial counts and the health of swimmers, any increase in microbial survival in warm contaminated waters is unlikely to be beneficial (Seyfried *et al.*, 1985).

Water Quantity

Global warming scenarios suggest that the greatest impacts of sea level rise on Canadians will occur in the populated centres along the Atlantic and British Columbia coasts. Along the coasts, large city blocks and shorefront facilities lie close to sea level. Lower Vancouver and municipalities on the Fraser River Delta are already experiencing occasional flooding problems. “At Charlottetown, on the Atlantic coast, a 1-metre rise would flood the city's new harbourfront development at high tide, while major storm surges, which occur once about every 20 years, would be high enough to inundate large parts of the downtown residential and commercial districts.” In Saint John, New Brunswick, road and rail transportation routes, sewage disposal systems, and downtown buildings would be vulnerable to frequent flooding (Hengeveld, 1996). Possible impacts of sea level rise include: salt water intrusion from the ocean into ground water supplies; inundation of water systems from a rising water table, with possible contamination by chemicals and pathogenic organisms; and flooded treatment plants with concomitant contaminated receiving waters (Grant, 1991).

Global-warming scenarios also suggest that the water levels in the Great Lakes could fall by 0.5 to 1.0 metre or more, while the volume of water flowing out of the St. Lawrence River could be reduced up to 20%. Extremely low lake levels, such as those of 1963-1965, could occur 4 out of every 5 years. Such changes could cause a deterioration in water quality (Duncan, 1997).

Finally, it seems reasonable to assume that increases in the variation of precipitation, and changes in the timing of spring run-off events (which have been documented for west-central Canada; see Burn 1994), are likely to result in more forced evacuations from communities near rivers.

Foodborne Diseases (salmonellosis, campylobacteriosis, yersiniosis, various diseases caused by vero-toxin-producing *Escherichia coli)*

Socio-economic and ecological interactions have resulted in a global increase in reported foodborne illnesses; the complex interactions have been reviewed by Waltner-Toews (1996). One study in the United Kingdom has looked specifically at the effects of global warming, based on the reported foodborne illnesses and warming trends in the 1980's (Bentham and Langford, 1995). The investigators predicted increases in the incidence of foodborne illnesses in the United Kingdom greater than 10% by the year 2030. High ambient temperatures have their most significant impact at points in the United Kingdom food system before the food reaches the consumer. No similar studies have been done in Canada.

Nutritional Health

Longer summers and milder winters may be beneficial to Canadian crop growers (Wittwer, 1990), but such seasons will also influence the distribution of pests that grow on the Canadian crops (Jahn *et al.*, 1996). Greenhouse effects on wheat grain lipids (Williams *et al.*, 1994) will influence milling and baking qualities. Any effects on nutrition from the preceding effects on crops are likely to be mediated through changes in incomes for those involved in the relevant industries, rather than in any direct way.

Since Canadians, in response to concerns over personal health, are eating more and more imported fresh fruits, vegetables and fish (Statistics Canada, 1996a and b), any effects of global warming on Canadian nutrition are likely to be associated with the effects (of global warming) on the foods brought in from other countries (e.g., effects of unpredictable weather on citrus growers in the United States).

Food importations are likely to be associated with increases in outbreaks of some viral, parasitic and bacterial diseases: for example, imports leading to outbreaks of hepatitis A. This has less to do with climate than with the naive idea that food trade can remain distinct from enforced environmental, public health and labour regulations in the countries from which the foods are imported.

Respiratory Disorders

Global warming may affect the seasonality of certain respiratory disorders (Emberlin, 1994). Increased air temperature may exacerbate air pollution in both urban and rural areas, and thus exacerbate respiratory disorders (Shumway *et al.*, 1988; Schwartz and Dockery, 1992a and b; Dockery *et al.*, 1993; Katsouyanni *et al.*, 1993; Pope *et al.*, 1995; and Phelps, 1996).

In Canada, asthma and hay fever can be triggered by aero-allergens which cause high seasonal morbidity. With global warming, the severity of allergies may be intensified since heat and humidity contribute to breathing difficulties (Environment Canada, 1995b).

Two empirical studies are worth noting. First, "highly significant associations between respiratory-related hospital admissions and levels of SO_2, O_3 and temperature in July and August in southern Ontario" have been reported (Canadian Public Health Association, 1992).

Second, the frequency of days with temperatures greater than 30°C could increase, under a $2xCO_2$ climate, from the current average of 10 days per year, to almost 50 days yearly. This may lead to an increase in the number of days with smog episodes in Ontario; smog concentrations are highest on hot, sunny days when NO_x and VOCs react in sunlight. An increase in the number of smog days may, in turn, lead to a greater number of hospital admissions (Environment Canada, 1995b).

Migration

There are likely to be increased numbers of environmental refugees. Refugees may bring with them disease agents into an increasingly hospitable environment. Internal refugees may migrate because of flash floods, contaminated water supplies, and flooded low-lying coastal areas.

Public Health Infrastructure

Currently, the public health infrastructure is not organized to cope with the interconnections among fiscal, agricultural, transportation and energy policies, their effects on climate, and subsequent climatic effects on health.

HEALTH IMPACTS OF ULTRAVIOLET RADIATION

Introduction

Exposure to ultraviolet radiation from the sun is associated with a number of human health effects: some effects are well-established and some need to be further elucidated in terms of ultraviolet radiation (UVR), human behaviour and human susceptibility. The relationship of ultraviolet radiation to human health is important for at least three reasons: the universality of population exposure; the potential for prevention of health effects; and the thinning of stratospheric ozone and increased ultraviolet radiation.

UVR is divided into a spectrum of various wavelengths of electromagnetic radiation--UVA, B and C--each with a progressively longer wavelength. UVC is completely absorbed by the ozone layer, and although UVB is partially absorbed by ozone, some radiation of this wavelength reaches the Earth and is able to damage human cellular DNA. UVB is well known to be responsible for sunburn and has been implicated in many of the health effects due to UVR exposure. Although the UVA spectrum is less likely to cause erythema and sunburn, researchers are now directing more attention to the relationship between this wavelength and possible health effects.

When studying health effects associated with UVR, many investigators, in epidemiological and laboratory studies, have examined the relationship among patterns of behaviour, host factors and UVR exposure. The impact on health includes cancers of the skin, cataracts of the eye lens and effects on the immunologic system.

Skin Cancer

There are three types of skin cancer--melanoma, basal cell carcinoma (a non-melanoma skin cancer) and squamous cell carcinoma (a non-melanoma skin cancer).

Melanoma

The incidence of melanoma has increased significantly in recent decades (Elwood, 1992; Goldstein and Tucker, 1993; and Balzi *et al.*, 1997). Recent analyses of trends in the European community have found that mortality from melanoma has increased for both men and women, with statistically significant trends in all ages (Balzi *et al.*, 1997). Although melanoma overall is less common than non-melanotic skin cancers, it has a greater tendency to be invasive, and therefore a higher mortality rate. There have been numerous studies in which the association between ultraviolet radiation exposure and risk of melanoma are examined, and the relationship has been found to be a complex one.

Constitutional Factors/Skin Sensitivity

Holman *et al.,* (1986) conducted the West Australian Lions Melanoma Research Project, one of the initial population-based case-control studies, and examined the risk of melanoma with various consitutional traits. Persons with poor tanning ability and other pigmentary traits typical of a low level of protection against the sun were found to have a higher incidence of melanoma. This suggested a causal effect between sunlight and melanoma. In the Western Canada Melanoma case-control study, pigmentation, ethnic origin and skin reaction to sunlight were found to be strongly associated with the risk of developing melanoma (Gallagher *et al.*, 1986). When skin reaction to sunlight was controlled, sunburn history and history of suntanning were found to be of less importance as risk factors for melanoma occurrence. White *et al.*,'s (1994) case-control study supported earlier studies with the finding that the constitutional factor most strongly associated with risk of melanoma was sun sensitivity, measured as either reaction to chronic sun exposure or reaction to acute exposure.

Exposure in Early Adulthood

Osterlind *et al.*, (1988) carried out a population based case-control study in East Denmark called the Danish Case-Control Study of Cutaneous Malignant Melanoma. This study found a significantly increased risk of melanoma associated with a severe sunburn before the age of 15. Five or more blistering sunburns occurring between the ages of 15 and 20 years of age were associated with an increased risk of melanoma--independent of constitutional risk factors. Holly *et al.*, (1995) in a recent case-control study of women in the San Francisco Bay area also found that having severe sunburns before age 12 was strongly associated with melanoma. Having large numbers of sunburns during any time period from elementary school through age 30 years, or having sunburns during the 10 years prior to the diagnosis of melanoma, was associated with a doubling of risk. Weinstock *et al.*, (1989) also examined the relationship between the timing of severe exposure and melanoma incidence and found that blistering sunburns between the ages of 15 to 20 years of age were associated with increased risk of melanoma, even when a history of burns after age 30 was controlled (White *et al.*, 1994). White *et al.*, 's (1994) recent Washington case-control study revealed that, in tanners, a deep or moderate tan from chronic sun exposure appeared to be protective up until age 20. However, poor tanners were not protected. These authors concluded that the number of burns received in childhood may not be a risk factor itself but may be a marker of a lack of protection from the sun in childhood.

Occupational/Cumulative Exposure

Although a review in the mid-1980's by Austin and Reynolds (1986) studying occupational cumulative exposure and melanoma reported that many studies had found an association between the two, the Danish Case-Control Study of Cutaneous Malignant Melanoma reported that occupational exposure was associated with a decreased risk for melanoma (Osterlind *et al.*, 1988). Graham *et al.* (1985) revealed that persons with the greatest lifetime exposure to sun had a decreased risk of melanoma. These authors suggested that the lowered risk may be due to the fact that susceptible individuals purposely avoid sun exposure because of their reaction to sunlight (Austin and Reynolds, 1986). The accurate documentation of lifetime sun exposure in adults to determine the true relationship of cumulative exposure and melanoma is difficult due to problems with long-term recall.

Intermittent Exposure

D'arcy *et al.* (1986) were the first to suggest that melanoma was related to occasional bursts of recreational sun exposure during a susceptible period in early adult life. Green *et al.* (1986) analyzed risk factors in Queensland, Australia, and found that cumulative solar ultraviolet radiation exposure was associated with development of melanoma. However, this association existed with two patterns of exposure—with cumulative exposure and with repeated episodes of severe short-term exposure. Nelemans *et al.* (1993) found that indoor workers and sun-sensitive individuals who sunbathed, participated in water sports, and vacationed in sunny countries—all associated with intermittent exposure—had a higher risk of melanoma.

A tendency to burn rather than to tan, therefore, and intermittent exposure to bursts of sun during a susceptible time of life appear to be significant risk factors for melanoma. A history of sunburns may actually be a marker of the risk factor of sun sensitivity. Tanning may be protective for those without any sun sensitivity.

Non-Melanoma

Non-melanoma skin cancers, which include two types, basal cell carcinoma and squamous cell carcinoma, are the most commonly diagnosed of all cancers. The incidence of these types of cancer has been increasing in recent decades (Gallagher, 1992; Kricker *et al.*, 1994; Marks, 1996). Between 1973-1987, the incidence of non-melanoma skin cancers rose by 60% in the Province of British Columbia for each tumour type (Gallagher, 1992). Basal cell carcinoma is the most common of the two types, but squamous cell carcinoma has a greater tendency to be aggressive.

Non-melanoma skin cancers tend to occur most often on the areas frequently exposed to sunlight-the head, neck, arms and hands. In the last few decades, both squamous and basal cell carcinomas have increased on the head and neck sites (Gallagher, 1992). Other observational evidence linking these cancers to ultraviolet radiation has included the fact that countries close to the equator have a higher incidence of non-melanoma skin cancers (Kricker *et al.*, 1994). Individuals migrating to countries with a high incidence of melanoma have a lower incidence of these cancers than natives of the country, as long as they migrated after age 10 (Gallagher, 1992).

Recent studies have confirmed and questioned the relationship between cumulative sunlight and risk of non-melanoma skin cancer. The South Wales Non-Melanoma Skin Cancer and Solar Keratoses Study examined several factors associated with non-melanoma skin cancers and found that the risk factors in Australia were consistent with those studies in sunnier countries—cumulative sun exposure and constitutional factors were both independently associated with prevalent non-melanoma skin cancers (Harvey *et al.*, 1996). However, Gallagher *et al.*, (1995b), in a population-based case-control study in Alberta, also examined the relationship between the timing and character of sunlight exposure and the risk of squamous cell carcinoma while controlling for phenotypic and pigmentary factors. Once constitutional factors were controlled for in the analyses, there was no association between squamous cell carcinoma and cumulative lifetime exposure. There was, however, a strong trend of increasing squamous cell carcinoma risk with chronic occupational exposure to the sun in the 10 years prior to the diagnosis.

Intermittent exposure to sunlight, particularly in childhood, has also been found to play a role in the development of non-melanoma skin cancer, particularly basal cell carcinoma (Gallagher *et al.*, 1995a). It was found that skin colour, childhood freckling and a history of severe sunburn in childhood were associated with a higher risk of basal cell carcinoma occurrence. Although there was no association between mean annual cumulative summer sunlight exposure and basal cell carcinoma risk, there was an increased risk in persons with higher amounts of recreational sunlight exposure up until age 19. This relationship between intermittent sun exposure and basal cell carcinoma was most pronounced in sun-sensitive persons who tended to burn, rather than tan, in the sun.

Eye

A number of epidemiologic investigations have studied the question of whether the risk of cataract is increased with long-term chronic exposure to solar UVR (Brilliant *et al.*, 1983; Taylor *et al.*, 1988; and the Italian-American Cataract Study Group, 1991). An early study by Brilliant *et al.*, (1983) examined the relationship between cataract and sunlight hours of exposure in a large national probability sample in Nepal. They found a positive correlation between cataract prevalence and sunlight hours. Sites with an average of 12 hours of sunlight had almost 4 times as many cataract cases as compared to an area with only 7 hours of sunlight. An Italian case-control study of factors related to the risk of cataract also found an association between UVR and cataract, but not for all types of cataract. This study was a clinic-based case-control study in Parma, Italy. Persons with job locations, or with significant amounts of recreation, in sunlight had an increased risk of cortical and mixed cataracts, but not nuclear cataracts (Italian-American Cataract Study Group, 1991). Wearing a hat in the summertime was also associated with an increased risk of posterior subcapsular, cortical and mixed cataracts; the type of hat worn did not provide a sufficient protection from UVR, and the authors concluded that wearing a hat was actually a marker of exposure and not of protection.

A study by Taylor *et al.*, (1988) examined the relationship between occupational UVR exposure and cataract by studying 838 watermen who worked on Chesapeake Bay. The annular ocular exposure was calculated for each waterman from age 16 by combining a detailed occupational history with laboratory and field measurement of sun exposure. The study found that watermen with high cumulative levels of ultraviolet B exposure had the greatest risk of cortical cataract. A dose effect was also found for risk of melanoma.

Dolezal *et al.*,'s (1989) case-control study found no association between cumulative sunlight exposure and risk of cataract. However, persons with nuclear cataracts did report a more severe acute skin response on exposure to sunlight for the first time each summer when compared to age- and sex-matched controls. This suggested that susceptibility to the sun may influence the development of cataract. Dolezal *et al.*,'s (1989) analysis also found that average lifetime use of head coverings in summer, thereby shading the eyes, was associated with a lower risk of developing cataract.

Immune System

The skin is considered to be the front line defense in the body's immune system. Non-ionizing radiation in the ultraviolet radiation spectrum has been suspected to alter this function of the skin. The evidence for the effect of ultraviolet radiation on the immunologic system and subsequently on carcinogenesis, infectious disease and autoimmune reactions is still incomplete, but some preliminary results are available.

Immunosuppression and Carcinogenesis

Researchers have found that when UVR-induced skin cancers were transplanted into genetically similar mice, the tumours were rapidly destroyed (McKenzie and Sauder, 1994). However, if investigators irradiated the host animal prior to transplanting the tumour, it was possible for the tumour to grow in the animal. This response suggested that UVR irradiation is capable of suppressing the rejection response in the animal receiving transplanted skin cancer. This finding, combined with the fact that recipients undergoing immunosuppressive therapy are at much greater risk of skin cancer than the normal population, has led to the suggestion that the immune system is involved in the development of skin cancers (Bouwes Bavinck *et al.,* 1996). Bouwes Bavinck *et al.,* (1996) carried out a long-term retrospective follow-up study on 1098 renal transplant recipients in Queensland, Australia, in order to evaluate the risk of skin cancer. They found that the cumulative incidence of developing skin cancer increased progressively from 7% after 1 year of immunosuppression, to 45% after 11 years, and to 70% after 20 years of immunosuppression. These findings led to the conclusion that there was an increased risk of skin cancer while the transplant patients were being immunosuppressed.

Suppression of Contact Sensitization

UV radiation of the skin may disrupt immune responses in the skin and result in both local and systemic suppression (McKenzie *et al.,* 1994). One of the most extensively studied immune reactions in the skin is allergic contact sensitivity. Animal experiments have been performed with the use of allergens to provoke chemical sensitivity. When UV-irradiated animals were tested, they did not respond. This was considered to be due to the influence of the ultraviolet radiation on the most potent antigen-presenting cells on the skin--Langerhan cells. These cells activate T-lymphocytes, another cell involved in the immunolgic system.

Alcalay *et al.,* (1989) investigated the number and morphology of Langerhan cells in the epidermal component of sun-exposed squamous cell carcinomas of 10 patients and compared them to non-tumourous skin specimens from sun-exposed or non-sun-exposed sites. One skin cancer patient showed a normal number of, but profound change in the morphology of, these cells, and in 6 cancer patients there was a decrease in the number of Langerhan cells, in addition to a change in morphology. In none was the number of cells increased. The researchers concluded that a decreased number and altered morphology occur in some but not all squamous cell carcinomas of the skin. The number of Langerhan cells in sun-exposed versus non sun-exposed non-cancerous skin from the same individual was the same.

Infectious Disease and Autoimmune Disease

Due to the fact that radiation is thought to affect the immunological defense of the skin, and since the skin is the first barrier of the body to foreign agents, it has beeen hypothesized that UVR exposure may compromise the ability of the host to respond either locally or systemically to infectious agents. To date, there are no epidemiologic data to suggest this. Morison (1989) found reports of susceptibility to a variety of bacterial and fungal infections in mice following exposure to UV radiation.

In addition, it has long been considered that patients with certain autoimmune diseases such as SLE are photosensitive, and exposure to sunlight may induce or exacerbate cutaneous or systemic disease. The mechanism of this effect is not clear but has been assumed to be due to an interaction between radiation and the immune system. The laboratory evidence demonstrating the effect of UVR on suppression of normal immune response in experimental animals would seem to support this theory. More information is needed in these important areas.

HEALTH IMPLICATIONS OF AIR TOXICS

Of increasing concern are the health implications of exposure to trace toxic compounds in ambient air (“air toxics”) and their attendant contribution to the body burden of toxics from multiple exposure routes, including food, soil/dust, drinking water, indoor air and occupational situations (City of Toronto, Department of Public Health 1993).

Trace toxic compounds of concern in Toronto’s ambient air include benzene, chromium, nickel, 1,3-butadiene, 1,1,2,2-tetrachloroethane, 1,2-dichloroethane, dichloromethane, trichloroethene and 1,1,2-trichloroethane, formaldehyde, manganese and polycyclic aromatic hydrocarbons (PAHs). These carcinogens occurred at several sampling sites at levels for which lifetime exposure exceeded a one-in-a-million cancer risk level (Carey 1987; Chan *et al.*, 1991; and Campbell *et al.*, 1995). Other important sources of air toxics in Toronto include incinerators, electric utilities, local industries and commercial operations such as dry cleaners, printers and gas stations (City of Toronto, Department of Public Health, 1993).

A study done by Campbell *et al.*, (1995) found that, overall, 31 of the 160 compounds detected in Toronto’s air are known or suspected human carcinogens, based on designation by the International Agency for Research on Cancer and the U.S. Environmental Protection Agency. Four substances (benzene, nickel, strontium and chromium (Vl) are human carcinogens; and another 27 chemicals are suspected to be carcinogenic to humans because they have been shown to be carcinogenic to experimental animals (Campbell *et al.*, 1995).

Carbon Monoxide (CO)

At high concentrations, carbon monoxide can pose an acute health threat since the body can become starved for oxygen when the gas is inhaled and absorbed into the bloodstream. Concentrations of 0.1% can cause death, while lower doses, commonly found in city corridors during traffic congestion, may impair perception and reflexes. Carbon monoxide also indirectly adds to the greenhouse effect by interfering with the natural breakdown of methane, a greenhouse gas (Environmental Protection, Province of British Columbia, Ministry of Environment, Lands and Parks, 1995).

Although high occupational exposures to exhaust (especially from diesel combustion), and to benzene do increase the risk of some cancers, reliable direct evidence of an increased cancer risk to the population at large, from the lower levels to which the population is exposed, is lacking.

Informed by the groundbreaking work of the Internal Joint Commission, the scientific community is much more aware of other classes of airborne, regionally transported and globally dispersed contaminants--for example, the "persistent organic pollutants" (POPs) that include many pesticides, PCBs, dioxins, and other compounds. These POPs are of special concern to

Canadians because of their tendency to accumulate and concentrate in the North, as a consequence of the unique characteristics of life in the Arctic. Our understanding of this problem is just beginning (Guidotti, 1996).

The contribution to water pollution by synthetic chemical fallout is surprisingly large--the major portion of PCBs and other toxic chemicals in the Great Lakes, and a substantial amount of the hydrocarbons found in the oceans, entered these waters through airborne deposition (Nadakavukaren, 1995).

In recent years, fears regarding a progressive contamination of local foods with polychlorinated biphenyls (PCBs) have imposed growing restraints upon advocacy of a traditional native diet (Shephard and McMillan, 1996).

Carbon monoxide is produced primarily by the incomplete burning of fossil fuels--for example, by cars and other gasoline-powered engines, and by charcoal or oil heaters. It is odourless and colourless, and because it is slightly heavier than air, it tends to collect in confined spaces and affect people without warning. Basically, as carbon monoxide concentrations go up, oxygen concentrations in the blood go down; oxygen molecules are literally being replaced by carbon monoxide molecules, which have a stronger bond to haemoglobin than oxygen. Exposure to high concentrations of carbon monoxide for short periods of time has the same negative effect as exposure to low concentrations for long periods of time. Normal amounts of carbon monoxide in the blood are in the range of 1%. Smokers can have higher concentrations, and if one were to exercise at rush hour in heavy traffic, levels of 3-4% could be expected. People at increased risk include those with heart and lung problems. At low levels, symptoms of carbon monoxide exposure include fatigue, headaches and dizziness, but higher concentrations can lead to impaired vision, disturbed coordination, nausea and eventually death.

Volatile Organic Compounds (VOC)

Volatile organic compounds include benzene, chloroform, methanol, carbon tetrachloride, and fromaldehyde, among hundreds of other compounds. Gasoline is a mixture of many such compounds. In the past two decades some 261 VOCs have been detected in ambient air. While the majority of these chemicals occur in the environment at very low levels, some of these VOCs are highly reactive. Like nitrogen compounds, they cause indirect effects (such as helping to create ozone) as well as having direct human physiological effects. They may originate from household products, such as painting supplies, dry cleaning establishments, refineries, gasoline stations, and many other sources. They can cause irritation to the respiratory tract (from increased rhinitis, or runny nose, to asthma) as well as headaches and other non-specific complaints. At high concentrations they have markedly toxic effects, some of which vary by compound, but which include neurological effects in all cases. Direct toxicity from VOCs is primarily an indoor air pollution problem and an occupational hazard, as levels indoors and in the workplace can reach many times that of outdoor levels.

Polychlorinated biphenyls (PCBs)

Once PCBs enter the environment they persist there for decades, resisting breakdown. Contamination of living organisms with PCBs generally occurs via the food chain, the concentration of the chemical increasing as it moves from lower to higher trophic levels ("biomagnification"). PCBs accumulate in fatty tissues such as liver, kidneys, heart, lungs, brain, and in breast milk, and increase over a period of time--a process known as bioaccumulation (Nadakavukaren, 1995). Shephard and McMillan (1996) found substantial quantities of PCBs in the traditional food available to Baffin Island Inuit.

A benefit/risk analysis of the consumption of traditional native foods for the Sahtu Dene and Metis of Fort Good Hope in the Northwest Territories, including in their analysis the risks that had arisen from the contamination of water resources was done. Polychlorinated biphenyls are the major source of concern in this particular community. The Canadian government has set a maximum PCB residue limit of 2000 ng/g wet weight for fish, and 200 ng/g for meat. Baked caribou is the only Dene food source with an excessive PCB content based upon current standards. The study found that the great majority of Dene residents consumed less than 5% of the maximum accepted daily intake of PCBs, as calculated from the observed product residues and reported eating patterns. Published ceilings are based upon the assumption that people consume an average of only 20 g of fish and 48 g of meat per day. Given that Arctic populations such as traditional Inuit and Dene Amerindian have substantially larger intakes of fish and meat, contamination limits which are probably acceptable for "white" city-dwellers may be too broad to protect the health of indigenous populations. The risk of ingesting an excessive dose of PCBs may be even greater for coastal populations such as the Inuit, because PCBs undergo bioconcentration in such traditional food items as fish oil, caribou fat and bone marrow, and maktuq (raw skin) from the narwhal (unicorn whale) (Shephard and McMillan, 1996).

HEALTH IMPACTS OF ACID PRECIPITATION ON AIR QUALITY

Sulfate is a major component of acid precipitation and particulate matter. Sulphate can affect human health by intiating bronchoconstriction (closing of the airways causing increased resistance to breathing) in individuals with airways reactivity. There are other acidic components of air pollution, such as nitiric acid; however, little is known about such components and their effects on human health.

Acidic aerosols, such as sulphur dioxide, sulfates and nitrogen dioxide, have a colloidal affinity to fine particulates, which provide the vector needed to penetrate deeply into the distal lung and airspaces. In general, nitrogen dioxide and sulphur dioxide are found to have acute negative impacts on the respiratory system (Campbell *et al.*, 1995).

Direct Effects of Exposure to Acid-Forming Chemicals

In 1953, a study was conducted to determine the effects of sulphur dioxide on humans and found that, at least in acute exposures, concentrations of up to 8 ppm caused respiratory changes that were dose dependent. Later studies revealed that the main effect of sulphur dioxide is bronchoconstriction, which is dose dependent, rapid, and tends to peak at 10 minutes (Folinsbee, 1992). However, these exposure levels are much greater than concentrations normally found in air pollution.

Individuals with asthma are particularly susceptible and may experience more bronchial reactivity from the effects of sulphur dioxide than the general public. Those with asthma, who exercise, typically experience symptoms at 0.5 ppm (WHO, 1987). The effects of sulphate on initiating asthma episodes in children with existing airways reactivity has been documented in several studies, particularly in southern Ontario. However, this effect is highly confused with the effects of ozone, and it has been difficult to separate the two epidemiologically.

Despite decades of research, the full effects of NO_2 are not known. Some of the recognized human health effects are increased incidence and severity of respiratory infections; respiratory symptoms; reduced lung function; and worsening of the clinical status of persons with asthma, chronic obstructive pulmonary diseases or other chronic respiratory conditions.

The direct effects of nitrogen dioxide include increased infectious lower respiratory disease in children, and increased asthmatic problems. Extensive studies of the oxides of nitrogen have shown that they impair host defences in the respiratory tract, increasing the incidence and severity of virulent bacterial infections after exposure. They have a marked effect in reducing the capacity of the lung to clear particles and bacteria (WHO, 1987). NO_2 also provokes bronchoconstriction and asthma in much the same way as ozone, but it is less potent than ozone in triggering asthmatic attacks.

There have been a number of studies reporting the effects of acid precipitation on human health. The following provides a brief summary of some of these studies.

Hospital Admissions

A number of studies (Bates and Sizto, 1987; Bates and Sizto, 1989; Thurston *et al.*, 1990; Tseng *et al.*, 1992; Burnett *et al.*, 1994; Delfino *et al.*, 1994; and Schwartz, 1994) have demonstrated that hospital admissions for respiratory illnesses are increased during contemporary air pollution episodes when levels of ozone, acid aerosols or particulates are elevated (Campbell *et al.*, 1995). Other studies indicate that the air pollution may indeed be increasing the amount of illness in the population. Researchers have examined the relationship between air pollution, temperature, and the number of admissions to hospital for respiratory ailments. One investigation, conducted in southern Ontario during the summers of 1974 to 1984, found that greater numbers of people were hospitalized for respiratory problems on days when pollution levels, particularly sulphur dioxide levels, were elevated (Bates and Sizto, 1989).

Hospital Admissions and Asthma

Both nitrogen dioxide and sulphur dioxide can increase susceptibility to respiratory infection and airway constriction in asthma patients. Studies in Vancouver have shown that emergency hospital visits rise when sulphur dioxide levels increase. Emergency visits by the elderly are similarly related to increased nitrogen dioxide levels. Both gases may be altered in the atmosphere to become fine particulates in the form of sulphates and nitrates, or acid rain when combined with water. Acidic contaminants can affect human health directly when inhaled, and indirectly when they fall on surface water, land and plants. Soils in southwestern British Columbia have all received elevated levels of acidic particles and rain in recent years. There has been concern that pH-related mobilization of trace elements in soil may lead to bioaccumulation and the potentional for toxicity, but this has not been substantiated.

Lung Function

Two epidemiological studies were conducted by the Department of National Health and Welfare on the effects of transported acidic air pollutants. The studies compared the lung function of children living in relatively unpolluted regions of Manitoba and Saskatchewan with that of children living in southwestern Ontario, a region with fairly high levels of of acid air pollution. On average, the children in Ontario had a 2% lower lung function than the Prairie children. The children in Ontario also had higher frequencies of chest colds, inhalant allergies, stuffy noses, and coughs with phlegm (Environment Canada, 1990). Similar studies in the United States strongly support the finding that children in more polluted cities suffer more colds and upper respiratory infections than children in cities where the air is cleaner (Dockery *et al.*, 1989).

The effects of acid precipitation on human health and welfare are thought to be primarily ecological and indirect rather than toxicologically significant to humans directly (Franklin *et al.*, 1985; Benarde, 1987; and Spengler *et al.*, 1989). However, local effects of sulfate and nitrate are closely associated with particulate air pollution, and are implicated in increased asthma attacks and mortality. These exposures are not typically considered in the context of acid precipitation, and are much more intensive than long-distance transport of acid species. There is preliminary evidence in animal experiments to suggest lung injury at environmentally relevant concentrations of acidifying agents (Last, 1991). Although some adverse human health effects have been demonstrated (Acid rain and human health, 1985; Franklin *et al.*, 1985; Goyer *et al.*, 1985; Benarde, 1987; Spengler *et al.*, 1989; Goldstein and Reed, 1991; and Last, 1991), the associations are weak and inconsistent, except for the correlation among acid haze, particulate air pollution, and individuals with reactive airways (Bates and Sizto, 1987; Balmes *et al.*, 1989; Hackney *et al.*, 1989; Raizenne *et al.*, 1989; Speizer, 1989), and between acid haze and certain types of cancer--a rather implausible association (Gorham *et al.*, 1989). Work by Canadian, American, and Italian investigators suggests possible direct effects of industrial exposure to acidifying agents that may have counterparts in environmental exposures to acid precipitates (Soskolne *et al.*, 1989).

Environmental levels of sulphur dioxide can adversely affect human health. In epidemiological and laboratory-controlled human health studies, effects on lung and the induction of chronic lung disease have been recorded. Although no clear threshold has been identified, short-term exposures to sulphur dioxide at concentrations of up to 1 ppm have not induced severe or irreversible effects; however, significant reductions in lung function have been observed in healthy exercising adults after exposure to this level (Kirkpatrick *et al.*, 1982; and Stacy *et al.*, 1983).

Mild respiratory symptoms related to airway dysfunction and transient bronchoconstriction have also been observed in exercising asthmatic subjects (Witek and Schacter, 1985).

Health effects of concern are asthma, bronchitis and similar lung diseases, and there is evidence correlating an increased risk of symptoms of these diseases with increasing concentrations of sulphur dioxide, ozone and other pollutants. It is less clear whether air pollution involving these exposures could cause these disorders at levels of exposure characteristic of Canada. Most investigators believe that ambient air pollution at these levels is sufficient to damage the respiratory tract enough to cause asthma or bronchitis, but few doubt that these same levels are enough to trigger effects in a subject with existing lung disease.

Symptoms of irritation and effects on pulmonary function are known to occur at levels as low as 100 ppb, especially in asthmatics and bronchitics. Epidemiological studies show that children are especially susceptible to effects such as bronchitis and pulmonary function changes, induced by chronic exposure to nitrogen dioxide concentrations of about 100 ppb (Shy *et al.*, 1973).

NO_2 is a lung irritant and at very high concentrations can produce pulmonary edema (EPA, 1982; Kolomeychuk *et al.*, 1983). Increases in airway resistance attributable to NO_2 exposure have been documented extensively (EPA, 1982; Kolomeychuk *et al.*, 1983). It is reported that healthy humans show increases in air resistance after 1-15 minutes of exposure to NO_2 concentrations ranging from 1.6 to 2.5 ppm (Neiding Von G. *et al.*, 1989). Short- and long-term exposure to high concentrations of NO_2 can enhance susceptibility to respiratory infections (EPA, 1982; Kolomeychuk *et al.*, 1983). However, concentrations of NO_2 in Canadian cities are generally well below the levels at which adverse effects on human health are known to occur. Even so, reducing NOx is a high priority. The purpose of reducing NOx emissions below current levels relates directly to the role NOx plays in the formation of ozone (Yassi and Friesen, 1990). By reducing NOx, ozone formation can be significantly slowed because NOx plays a key role in rate-limiting chemical reactions.

Mortality

The assumption of air pollution with actual mortality is strongest for fine particulates and is relatively weak for acid-forming pollutants. In epidemiological studies, short-term exposures to sulphur dioxide that lasted a day or so have been correlated with deaths, although there was concomitant exposure to high particulate levels of up to 50 ppb of sulphur dioxide-induced respiratory symptoms and disease (coughs and bronchitis), especially in young children and smokers. This may mean that the sulfur dioxide had less effect until high fibre particulate levels provided a delivery mechanism to the lower respiratory tract, consistent with the known behaviour of SO_2 at higher levels.

Outdoor Exposure Studies

Of particular concern for human health are vehicle-related pollutant levels (of NO, NO_2 and CO) which usually peak during periods of the day when the public is most likely to be exposed, such as during transit to and from work or school and during other routine activities. As urban intensification continues and population densities increase, especially in the Toronto area, more persons may become exposed in high traffic areas. With increased interest in recreational walking, running and bicycling, the number of persons exposed and the degree of exposure to air pollutants could increase (Campbell *et al.*, 1995).

While individual exposure to air pollution varies, available data show that, for many pollutants detected in Toronto's outdoor air, existing levels are sufficiently high on a periodic basis to raise concerns for public health. Serial peak levels of ozone, nitrogen dioxide and particulates overlap with levels suggesting adverse effects on health. Persons with respiratory illnesses such as asthma, chronic bronchitis, and emphysema, and healthy individuals exercising vigorously outside, appear to be at greatest risk. People with asthma, emphysema and chronic bronchitis are estimated to comprise about 7.5% of the Canadian population (Ontario Lung Association, 1991) or a projected 165,000 of Metropolitan Toronto's approximately 2.2 million residents. Individuals with compromised respiratory function, who spend several hours outside each day in areas with high pollution levels, may well be subject to adverse health effects, including wheezing, coughing, chest pain, respiratory inflammation and reduction in lung function (Campbell *et al.*, 1995).

While levels of CO and NOx tend to peak for about two hours during morning and afternoon rush hour, ozone levels tend to remain elevated for 6 to 8 hours each day. Although vehicles do not directly emit ozone, they do emit NO. NO is readily oxidized to NO_2 in the presence of oxygen and sunlight and contributes to the formation of ozone. Ozone levels typically are lowest in high traffic areas because the NO emitted from vehicles scavenges O_3 and converts it to oxygen (Campbell *et al.*, 1995). While long-range transport of O_3 from the United States is a major contributor of ozone to Toronto, locally generated ozone precursors can contribute to elevated ozone levels in residential neighbourhoods remote from traffic (City of Toronto Department of Health, 1993).

THE HEALTH EFFECTS OF ACID PRECIPITATION ON WATER QUALITY

Mercury is a pollutant of particular concern because, once biotransformed into methyl mercury by organisms in marine or aquatic sediments, it readily enters the food chain and is biomagnified in predatory animals. Methyl mercury is readily absorbed by, and distributed throughout, the body, and it is found in the human brain at concentrations six-fold greater than in the blood. It readily crosses the placenta and appears to accumulate in the fetus. Women whose diets are high in fish may have high levels of mercury in their bodies.

A number of epidemiological studies have been conducted in populations exposed to mercury through food-contamination incidents or through consumption of fish or fish-eating animals. In a 1985 study of Cree Indians from communities in North Quebec with known high organic mercury exposure in the diet, over 200 children born in 1975-1976 were examined using both neurological and developmental tests. Only 6% of the children had exposure levels exceeding 20 ppm. Abnormality of the tendon reflexes was positively associated with methyl mercury exposure only in boys (Health Effects Review, 1996).

Acid rainfall is a component of air pollution causing water quality problems. In recent years, surveys of soil and water acidity in the Northern Hemisphere have shown increased acidification (or rather, reduced buffering capacity) and presumably irreversible changes in pH and in metal mobilization in soils (Berden et. al., 1987). The cause is increased production and airborne transport of acidifying emissions from industrial sources--principally, sulfates and nitrates (Larson, 1989; Lioy and Waldman, 1989). The result has been extensive changes in vegetation and small lake biota (Berden *et al.*, 1987; Scott, 1989; The State of Canada's Environment, 1991; Nadakavukaren, 1995; Proceedings from the Acidifying Emissions Symposium, 1996). In the last 5 years, the impact of acid deposition on sensitive ecosystems in eastern Canada has been greatly reduced--by as much as 30% and more (Proceedings from the Acidifying Emissions Symposium, 1996).

Acid precipitation has serious effects on delicate aquatic ecosystems, marine biota, and also on some terrestrial species of plants and trees (Scott, 1989). The effects of acidifying chemicals (that is, oxides of sulphur and nitrogen) are at least additive and effective control requires attention to all sources of emissions capable of distant transport (Albert, 1989). Sulfuric acid lowers the pH of the water, eliminating many aquatic species, such as invertebrates, fish, frogs, salamanders, and aquatic insects (Nadakavukaren, 1995). A lowered pH in rivers or lakes also causes tightly bound toxic metals (such as aluminum, manganese, lead, zinc, mercury, and cadmium) to dissolve out of bottom sediments or soils and leach into the aquatic environment. Such metals, especially aluminum, can kill fish by damaging their gills, thereby causing asphyxiation. Acid-induced release of aluminum has resulted in fish kills at water pH which would not have been lethal in the absence of the toxic metal (Nadakavukaren, 1995).

Indirectly, acid precipitation may adversely affect human health if essential food chains are disrupted, and the economic consequences are severe. Some authors have speculated that if metals are leached into groundwater at excessive concentrations (Acid rain and human health, 1985; and Goyer *et al.*, 1985), there may be toxicological implications (Goldstein *et al.*, 1991). Distant migration of acid precipitation has been well documented within Canada (Stolarsky *et al.*, 1991).

Toxic metals in the water also can bioaccumulate in fish tissues, making them dangerous for humans to eat. Mobilization of poisonous metals also presents a direct threat to human health in drinking water supplies and as food contamination (Nadakavukaren, 1995).

In recent years, some country foods of many northern aboriginal communities have become heavily contaminated by environmental pollutants. The buying of "market" foods and an inappropriate choice of purchases have contributed to a worsening of nutrition with acculturation. One study concluded from their survey of Hare Dene/Metis living in the subarctic Sahtu region of central Canada that country foods still made a substantial contribution to satisfying several daily dietary needs, including protein (whitefish, caribou and moose flesh), iron (caribou, rabbit, moose flesh, and moose blood) and zinc (moose, caribou and rabbit flesh and whitefish). However, a shift from country to "market" foods was increasing the total fat content of the diet, and in particular, the ratio of saturated to polyunsaturated fat. Many other studies of arctic and subarctic communities have demonstrated similar changes in nutritional patterns with acculturation (Shephard and McMillan, 1996).

Country food is an important part of the diet of aboriginal peoples and therefore makes a significant addition to effective household income. Country food is highly nutritious, and for many it is the preferred food. Imported food available in local stores tends to be limited in variety, poor in quality, and high in cost. Thus, what people actually buy is likely to be high in carbohydrates and fats, and low in protein, vitamins, and other essential nutrients. However, country food is not only nutritious, but also the basis of social activity and the maintenance of social bonds through its production and distribution. Reduced country food consumption in northern Native populations, coupled with decreasing physical activity, has been associated with obesity, dental caries, anemia, lowered resistance to infection, and diabetes.

Many aboriginal communities are trying to return to country foods, since for decades many of them have abandoned traditional foods for processed and packaged food. That food, however, is being blamed for health changes in native communities. Those changes, in turn, have led to calls for a return to the nutritional foods that sustained native peoples for thousands of years. However, many natives are beginning to realize that country foods, such as fish and wildlife, have also become a potential health risk because of pollution. This threat is not only from pollution left behind by the military or mining, but also from long-range water and air pollution collecting in the Arctic.

Mercury (an example)

Studies have shown a concern that the large hydro-electric developments in James Bay had exposed northern Cree Amerindians to increasing, and potentially dangerous, levels of methyl mercury over the past two decades. Small quantities of inorganic mercury, present in the local rock, dissolve into the lake water, and when plants, bacteria and the submerged debris associated with reservoir construction act upon this solution, it is converted to methyl mercury. The organic mercury enters the food chain and accumulates in the fish which have formed a major part of the Amerindian diet (Shephard and McMillan, 1996). Blood mercury levels are now much higher in those who have persisted with inland trapping than in those who have adopted other lifestyles. Levels also show seasonal variation, peaking in the autumn (Shephard and McMillan, 1996).

A study noted high mercury levels in pregnant Inuit women who were living in remote areas of Greenland where there had been no direct exposure to factories, cars or other immediate human sources of mercury. They attributed their finding to the high concentrations of methyl mercury found in marine mammals. As in the people of the James Bay region, the blood mercury levels of the Greenlandic Inuit have declined progressively over the period of observation, from 1984-1988, and again this has been attributed to a progressive decrease in the consumption, with acculturation, of traditional Inuit food. The authors commented that the young Greenlandic Inuit reported a preference for “western” food, and that only 23% of the energy needs of the population were obtained from traditional sources. High blood mercury levels have also been reported among the indigenous populations of Alaska (Shephard and McMillan, 1996).

HEALTH EFFECTS OF SMOG

Tropospheric ozone, the major component of smog, damages the leaves of plants and trees. Some plant species, such as tobacco, spinach, tomatoes and pinto beans, are especially sensitive. Annually, ozone causes millions of dollars in crop loss. It also causes premature leaf drop in trees and reduced growth rates.

Ozone is a highly reactive compound that irritates mucous membranes of the respiratory system, causing coughing, nausea, shortness of breath, pulmonary congestion, and impaired lung function. It has an unusual effect on breathing patterns as the result of changes in the reflex breathing mechanism. It also aggravates chronic respiratory diseases, such as asthma and bronchitis, and can cause serious health problems for people in weakened health (the elderly). Lungs are ozone's primary target. Studies on animals show that ozone damages cells in the lung's airways, causing inflammation and swelling. It also reduces the respiratory system's ability to fight infection and remove foreign particles.

High ozone concentrations can cause immediate short-term changes in lung function and increase respiratory symptoms (Kolomeychuk *et al.*, 1983). Studies report a large range of susceptibility to the effects of ozone. Healthy exercising individuals have been shown to experience decrease in lung function and increase in respiratory symptoms during prolonged periods of exposure to ozone at concentrations as low as 0.12 ppm. Children and adults have experienced temporary reduction of lung function after one to two hours of ozone in the range of 0.12-0.16 ppm. Pronounced symptoms such as cough and pain on deep breathing are observed in some adults exercising heavily under conditions of ozone of over 0.18 ppm. More recently it was found that ozone levels as low as 0.08 ppm resulted in increased levels of inflammatory cells in subjects exposed for 6 hours; ozone has also been reported to produce eye, nose and throat irritation at levels as low as 0.01 ppm. There is increasing concern about the long-term effects of ozone. Ozone is known to damage the tissue lining the airways of the lung and is suspected of playing a role in the long-term development of chronic lung disease. In 1983, Bates and Sizto reported a significant relationship between excess hospital respiratory admissions and ozone, SO_2 and temperature with lag time of 24-48 hours, during the summer months of 1974 and 1976-1978. Bates and Sizto (1989) recently examined hospital admissions for acute respiratory diseases during June 1983 compared to admissions during the previously-mentioned years. They concluded that “probably neither ozone nor SO_4 alone is reponsible for the observed association with acute respiratory admissions, but that some unmeasured species, of which H_2SO_4 is the strongest candidate, or some pattern of sequential or cumulative exposure, is responsible for the observed morbidity” (Yassi and Friesen, 1990).

Ozone triggers a reflex response in the lungs that alters breathing patterns. People without asthma cannot inhale as deeply following ozone exposure and show small changes in airflow. Kleinman *et al.*, (1989) demonstrated a dose-response curve indicating how pulmonary function tests vary with dose of ozone. Over a short period, the effects of ozone are cumulative. However, over several days, people become tolerant to ozone and have fewer symptoms. Their breathing becomes more normal although persons with asthma may still develop airflow obstruction.

Individuals with asthma are obviously more affected by ozone. Within a brief period, the inflammation produced by the irritant effect of ozone results in a reduction of airflow and a worsening of asthma. Ozone also appears to make persons whose asthma is triggered by allergies more susceptible to the allergen. This is evidence that ozone may modify the way that the lung handles allergens. Ozone may provoke asthmatic attacks in people who already have asthma, although it is unlikely that exposure to ozone at typical levels in Canada could cause the disease in the first place. The episodes tend to occur one or two days after the ozone concentration is at its highest.

When air pollution is present, special populations such as pregnant women or those with chronic diseases (e.g., emphysema) are at a higher risk, as they are with other environmental hazards. Despite the mechanism of adaptation to ozone (Folinsbee, 1992), ozone may cause persistent biochemical changes in the lung at high concentrations. The way in which ozone affects humans is complicated, and dependent on activity level and pollutant concentration among other factors. Ozone attacks the epithelial cells in the bronchial tree; the attack in turn may cause airway inflammation and hyperresponsiveness. However, the process has been hard to prove in the laboratory, in part, because existing animal models are not adequate.

Current evidence suggests that ozone is associated with an inflammatory response manifested by increased airway membrane permeability and bronchial hyperreactivity (Devlin *et al.*, 1991; Crapo *et al.*, 1992). Pulmonary-function measures in children attending summer camps in southern Ontario were reduced on average by 3.5% to 7% when one-hour average concentrations of ground-level ozone reached 140 ppb (Raizenne *et al.*, 1989); approximately 5% of Ontario hospital admissions for respiratory disease may be attributable to elevated concentrations of ground-level ozone (Bates and Sizto, 1987; Burnett *et al.*, 1994), and up to 15% in those under two years of age. In Los Angeles the combination of ground-level ozone, nitrogen dioxide and temperature accounted for 4% of the day-to-day variability in mortality (excluding accidents and suicides) (Kinney and Ozkaynak, 1991).

Ozone may pose a particular health threat to those who already suffer from respiratory problems such as asthma, emphysema and chronic bronchitis. About 10% of the Great Lakes Basin's approximately 14 million residents would fall into this health category. Ozone may also pose a health threat to the young, elderly and cardiovascular patients.

Two expert panels reviewing the evidence on health effects of air pollution for the Canadian Smog Advisory Program concluded that health effects of ground-level ozone at levels that may plausibly occur in Canada include pulmonary inflammation, pulmonary function decrements, airway hyperreactivity, respiratory symptoms, possible increased medication use and physician/emergency room visits among individuals with heart or lung disease, reduced exercise capacity, increased hospital admissions and possible increased mortality (Stieb *et al.*, 1995). Some of these effects must be attributable to fine particulates, which appear to show no threshold for health effects at low levels. However, many of these effects are undoubtedly due to ozone.

The panels conceptualized the potential health effects of air pollution as occurring in a logical “cascade” or “pyramid”, ranging from severe, uncommon events (e.g., death) to mild, common effects (e.g., eye, nose and throat irritation) and asymptomatic changes of unclear clinical significance (e.g., small pulmonary function decrements and pulmonary inflammation) (American Thoracic Society, 1985; and Bates, 1992). Thus, while according to this model, severe health effects preciptated by air pollution would be rare, there is a potentially large overall impact on health and well-being (Stieb *et al.*, 1995).

Undoubtedly, tens of thousands of deaths have resulted from acute pollution episodes (e.g., the smogs in large cities in the early 1950's). Presently, some people, including persons with asthma, can be adversely affected by excursions in levels of urban air pollution (notably ozone) in some major cities. It is still unclear whether urban airborne pollution in the majority of cities complying with current air quality guidelines contributes to ill health. It is not clear whether the air quality guidelines applied in Canada are still sufficient to protect all the population.

Components of smog can damage lungs of the young and the old. For those people with asthma, smog can worsen an attack. It can raise the risk of getting respiratory diseases, such as bronchitis, and raise the risk of developing certain types of cancer. Smog also damages crops, natural vegetation and even buildings.

Hospital admissions for acute respiratory diseases, including asthma, go up when the concentration of ozone rises above 80 ppb. Researchers believe ozone is the second-greatest cause of lung disease after fine particulates from smoking, second-hand smoke, vehicle exhaust and wood burning (Environmental Protection, Province of British Columbia, Ministry of Environment, Lands and Parks, 1995).

Recent studies (Bates and Sizto, 1987; Bates and Sizto, 1989; Thurston *et al.*, 1990; Tseng *et al.*, 1992; Burnett *et al.*, 1994; Delfino *et al.*, 1994; and Schwartz, 1994) have demonstrated that hospital admissions for respiratory illnesses are increased during contemporary air pollution episodes when levels of ozone, acid aerosols or particulates are elevated (Campbell *et al.*, 1995).

Subsequent studies using more sophisticated testing (e.g., Pulmonary function testing) have also found that healthy persons can demonstrate effects from ozone exposure. This is especially true when they have an increased respiratory rate--for example, when they are involved in outdoor physically strenuous activities. Symptoms associated with ozone exposure include upper respiratory symptoms (nasal discharge, throat irritation), lower respiratory symptoms (cough, wheeze, chest pain), and non-respiratory symptoms (headache, fatigue).

Peroxyacetyl nitrates (PAN) and other oxidants that accompany ozone are powerful eye irritants. Exposure for 6-7 hours or more reduces lung function significantly in healthy people during periods of even moderate exercise.

HEALTH IMPLICATIONS OF PARTICULATE MATTER

The association between air pollution and health is an extremely complex issue and is confounded by existing weather conditions. Changes in temperature tend to have a more obvious effect on mortality and morbidity than changes in air pollutant concentrations (Seaton, 1996). In recent years we have learned a great deal about the health effects of particulate matter. In particular, concern has been raised over the health effects of fine particulate matter. Current research indicates that fine particulate matter is the air pollutant with the greatest immediate health impacts (Environmental Protection, Province of British Columbia, Ministry of Environment, Lands and Parks, 1995).

Adverse health effects induced by exposure to inhaled particulate matter are dependent upon depth of penetration, deposition, and retention of the matter in the lung. Those particles deposited in the thoracic region of the lung have the greatest health effects. It is well established that only particles with a diameter of 10 or less enter the thoracic region, and therefore have the greatest effects (Environment Canada, 1990).

Fine particulates are associated with respiratory symptoms, airway hyperreactivity, impaired lung function, reduced exercise capacity, pulmonary inflammation, pulmonary function decrements, increased number of emergency room visits for asthma, increased hospitalizations, increased absence from school or work, and increased mortality from cardiopulmonary disease and lung cancer. Children, the elderly, smokers, asthmatics and others with respiratory disorders are especially vulnerable to this type of air pollution (Environmental Protection, Province of British Columbia, Ministry of Environment, Lands and Parks, 1995; Stieb *et al.*, 1995; Seaton, 1996; and Choudhury *et al.*, 1997).

It is now generally acepted that exposure to fine particulates is associated with an increased mortality in urban areas, particularly among populations such as asthmatics and the elderly. These particulates are released from fireplaces, wood and coal stoves, tobacco smoke, diesel and automotive exhaust, and other sources of combustion. Why fine particulates are associated with such dramatic human health effects remains to be explained although toxicological studies confirm that this particulate fraction is much more toxic than its size mass would suggest.

A number of studies support the above health consequences. Several authors have reported particle effects on hospital admissions for respiratory diseases, either in the summer (Bates and Sizto, 1987; Thurston *et al.*, 1992; and Burnett *et al.*, 1994) or for the entire year (Pope, 1991). Particulate matter has also been associated with increased respiratory-related visits to emergency departments in Vancouver (Bates *et al.*, 1990) and Seattle (Schwartz *et al.*, 1993). Particle effects on cardiorespiratory mortality have been well documented (Schwartz, 1994).

Schwartz and Morris (1995) examined the association between cardiac hospital admissions for the elderly (> 65 years of age) in Detroit, Michigan, and particulate matter < 10 m in diameter (PM10) over the period 1986-1989. Relative risks for coronary artery disease, heart failure, and cardiac dysrhythmias were observed for a 32 g/m increase in PM10. This change in PM10 corresponds to an approximate 13 g/m increase in sulfate levels in Ontario (Burnett *et al.*, 1995). When bacteria are injected into the lungs, particulate suspensions have been shown to increase bacterial infectivity, an effect that correlates with toxicity to alveolar macrophages in culture (Hatch *et al.*, 1985). An increase in respiratory hospital admissions, following episodes of ambient particulate pollution, is compatible with these experimental observations (Burnett *et al.*, 1995).

The major health effects that are associated with exposure to suspended particulates are effects on pulmonary function, aggravation of existing pulmonary and cardiovascular disease, effects on mucociliary clearance and other host defense mechanisms, morphological alteration, and mortality (Holland *et al.*, 1979). High mortality rates following exposure to high atmospheric levels of particulates coupled with exposure to sulphur oxides have been observed following pollution episodes in London, England, and New York in the 1950's and early 1960's. Groups that are high at risk during particulate pollution episodes include the young (school and preschool children), the elderly, those with chronic obstructive cardiovascular disease (heart patients and those with arteriosclerosis), asthmatics, those with influenza or bronchitis, smokers, and those who are oronasal or mouth breathers (Environment Canada, 1990).

PM 2.5, sulfate and ozone cannot be easily separated because they tend to occur together in urban air pollution. In the few studies in which their effects can be separated (as in the Utah Valley), PM 2.5 seems to have by far the strongest effect on mortality (Pope, 1991). Recent research suggests PM 2.5, and to a lesser degree, sulfate, and probably ozone as well, cause an increase in deaths in affected cities. The higher the air pollution levels for these specific contaminants, the more excess deaths that seem to occur on any given day, above the levels that would be expected for the weather and the time of year.

In a study by Burnett *et al.*, (1995), sulfate levels were found to be the highest in the southwestern region of Ontario and declined towards the north and east. A significant association between cardiorespiratory admissions to acute care hospitals in Ontario, Canada, and sulfate particulate matter was observed in this study. The associations showed clear evidence of a marked dose-response relationship (Burnett *et al.*, 1995).

The effect of sulfates on cardiac and respiratory admissions appeared to be pervasive in the population. Effects were observed in all six disease groups examined, in both males and females, and in all age groups considered. A positive association between ambient sulfate levels and admissions was also noted within the six-year study period. The effects of sulfates were associated with hospital admissions for a large and diverse poplutation consisting of people living in large cities, small communities, and rural areas spanning a geographic region 1000 km in breath (Burnett *et al.*, 1995).

Recent studies (Bates and Sizto, 1987; Bates and Sizto, 1989; Thurston *et al.*, 1990; Tseng *et al.*, 1992; Burnett *et al.*, 1994; Delfino *et al.*, 1994; and Schwartz, 1994) have demonstrated that hospital admissions for respiratory illnesses are increased during contemporary air pollution episodes when levels of ozone, acid aerosols or particulates are elevated (Campbell *et al.*, 1995).

ADAPTATION APPROACHES AND OPTIONS

Climate Change(Global Warming)

Thermal Extremes

Unlike some other health-related problems, the problem of the heat itself cannot be mitigated via specific prescriptions--except for a reduction in emissions of "greenhouse gases", which could slow any potential global warming. Therefore, anticipatory responses should be considered to combat the problem. One potential response is the development of a weather/health watch-warning system. People are often unaware that dangerous weather conditions exist which might contribute to heightened mortality rates. A watch-warning system is advised (much like the systems presently available to warn of tornadoes and severe snowstorms) to inform people when stressful weather conditions are imminent. A system has already been developed for Philadelphia (Kalkstein *et al.*, 1996), and in the summer of 1995 was credited with saving over 300 lives. Systems are presently being developed for other U.S. cities as well, including Phoenix, St. Louis, and Washington. Weather stress algorithms could be developed and tailored for population centres such as Toronto and Montreal.

Another potential policy for attacking the problem would be acclimatization assistance. For example, can dwellings be altered at low cost to lessen the heat load on living spaces? Should government incentives be provided to individuals so they may purchase air conditioners or fans? During extremely hot weather, will shelters be available to provide temporary quarters for people who do not have access to air conditioning? Some of these policy options are presently being explored by the U.S. Environmental Protection Agency and may be applicable to Canada, where the percentage of homes and businesses with air conditioning is much lower than in the United States.

The uncertainties which continue to surround the issue of climate change and human mortality underscore the need to continue research on particular aspects of the problem. For example, the potential interactions between pollution and weather as they impact heat-related mortality are largely unknown. It is possible that the synergistic action of high pollution levels and extreme heat might have an even more dramatic impact on mortality if the climate changes. At present there are conflicting results on the impact of pollution upon daily mortality totals. Our research for 10 U.S. cities has indicated that weather is much more important than pollutant levels (ozone, nitrous oxides, and suspended particulates) in affecting day-to-day mortality (Kalkstein, 1991a). When a synoptic climatological approach to develop summer air masses was used, it was determined that in seven of ten cities, an "offensive" air mass is associated with the highest mean mortality. In addition, a large proportion of the highest mortality days occurred when these air masses were present. It appeared that the offensive air masses did not contain relatively high concentrations of pollutants. However, Schwartz and Dockery (1992a and b) show evidence that pollution might be more important than weather. They also found strong correlations between particulate concentrations and daily mortality. The disagreement arising from these studies requires that further research be performed to determine if pollution can contribute to large day-to-day increases in mortality.

Indirect Health Impacts

Given that the organization and structure of the biosphere have evolved primarily through microbial action, and that, through horizontal trading of genetic material, microbes co-evolve much more quickly with the environment than people, it should be no surprise that the major effects, related to global environmental change, in human populations will be in the area of infectious diseases. What is perhaps surprising is that, despite some rhetoric, there has been no concerted effort to interpret emerging infectious diseases as indicators of ecosystemic change.

Because there is still a very strong vested interest in the research, government and professional communities in viewing health issues as being synonymous with disease-care issues, and in considering ecological, health, agricultural and nutritional problems as occurring in parallel, occasionally related, universes. Instead, there is an urgent need to embrace broader transdisciplinary approaches based on complex systems and inter-active (post-normal) science (Funtowicz and Ravetz, 1993). With the demise of the TriCouncil EcoResearch Program, and the disciplinary retrenchment at universities in the face of financial cutbacks, such research is increasingly difficult to undertake.

The problem is that detection and response take place on one scale (local) and interpretation requires a much larger scale (at least national). Currently, there is a tendency to respond to the fires (outbreaks, extreme events) and ignore the arsonist (global warming) or the school for arsonists (public policy on agriculture, transportation, etc). For instance, disease outbreaks are investigated in such a way that one can identify the local determinants (e.g., water contamination from a farm or sewer), but this author is not sure anyone is looking at the pattern of outbreaks to see what they tell us about overall system functions. For instance, the strawberry-related hepatitis outbreak in the U.S. was both predictable and preventable. We need to have strong local ability to detect and investigate events tied to strong central units capable of interpreting those events. At this point, both local and national capabilities in this regard are weak and under attack financially.

The three granting councils (SSHRC, NSERC, MRC), and the political departments which reflect the application of their work (in all areas including health, agriculture, environment, human resources, culture and economics) pool their resources to create a research institute or centre which can address fundamental transdisciplinary policy-relevant issues.

On the applied side, this institute would 1) draw on outbreak and disaster information from across the country to develop systemic lessons for national and regional policy and 2) train staff from municipal, provincial and national health, agriculture and environment offices to recognize disease and environmental signs of ecosystem distress.

On the research side, there would be calls for specific projects to address key areas to recognize which indicators are appropriate and what kinds of systemic lessons are reflected in patterns of outbreaks. Thus, one would ask, what are the lessons for agricultural, environmental, public health and economic policy of the pattern of bacterial and parasitic watershed contaminations across Canada? What are the implications for international trade policy of changing patterns of foodborne illnesses, and vice versa? What are the long-term public health impacts, mediated through global environmental changes, of economic and trade policies?

Stratospheric Ozone Depletion (and Increased Ultraviolet Radiation)

Sun protection should be practised by all individuals, including children, in order to reduce exposure to ultraviolet radiation and prevent adverse human health effects. Sun protection practices should be undertaken in both summer and winter, and in particular when on vacation in lower latitudes, with stronger UV rays, since intermittent sun exposure has been found to be a risk factor for melanoma and non-melanoma skin cancer.

In 1994, Health Canada held a workshop to develop recommendations for the public on behaviours to reduce ultraviolet radiation exposure (Mills and Jackson, 1995). The strategies recommended by this workshop included the following:

(1) Minimize sun exposure. Avoid exposure at times of day when sun rays are strongest by planning outdoor activities before 11:00 am and after 4:00 pm. If being outdoors during these peak times is unavoidable, practise sun protection (seek shade, cover up and use sunscreen).

(2) Seek shade. Trees, canopies and shelters can all provide shade.

(3) Cover the arms and legs and wear a hat with a wide brim to shade the face and neck. Wear sunglasses that absorb UVR.

(4) Use sunscreen. Sunscreen is important but should not be used in place of sun protection practices and is not intended to lengthen the time spent in the sun.Sunscreens should be used in conjunction with the use of shade, clothing, hats and sunglasses; sunscreen should be used to provide protection when people cannot avoid being in the sun. A sunscreen with an SPF of #15 or higher, that has both UVA and UVB protection, is recommended.

Air Toxics

There are only limited data available on air toxics. Emission reduction measures that target volatile organic compounds and particulate matter will undoubtedly reduce air toxic levels. Air toxics is an emerging issue in terms of our knowledge of the extent of the problem and possible control options or initiatives. However, it is a high priority for the Department, based on public expectations and concerns, possible international actions and the crosscutting nature of the issue i.e., NOx/VOC, acid rain. It is anticipated that the Priority Substances List (PSL) review will designate 25 CEPA toxics, with 15 having air as their major pathway (Environment Canada, 1996b).

Short-term Solutions:

(1) Maintain enforcement activities for CEPA emissions requirements for asbestos, lead and mercury.

(2) Maintain special air toxics monitoring in National Air Pollution Surveillance Network in Atlantic region for PM10, acid aerosols and VOCs.

(3) Maintain awareness and track the development of National Action Plan for Hazardous Air Pollutants (HAPs) via AIB, HQ and National Air Issues Coordinating Committee (NAICC).
(4) Support and participate in studies on long- and short-range mercury input levels via the air pathway in co-operation with the provinces (Environment Canada, 1996b).

Medium to Long-term Solutions:
(1) Track National Action Plan for HAPS initiatives, and ensure delivery in the various Regions.
(2) Promote pollution prevention in affected industries and ensure linkages are made to NOx/VOC initiatives, in co-operation with the provinces (Environment Canada, 1996b).

Acid Precipitation

A control plan is already in place in Eastern Canada; emissions forecasts indicate Canada will meet its international obligations. Research in residual acidification and ecosystem impacts, however, may result in a further reduction in the critical loads to protect sensitive ecosystems, which may require additional emissions reductions beyond the year 2000 (Environment Canada, 1996b).

Short-term Solutions
(1) Track and confirm that provinces are meeting their targets, via emissions inventories and provincial discussions.
(2) Support, on an ongoing basis, scientific ecosystem studies, and monitor precipitation and fog in various Canadian Regions.
(3) Conduct science studies, on an ongoing basis, with emphasis on studies in residual acidification and nitrification (Environment Canada, 1996b).

Medium-term Solutions:
(1) In 1997/1998, renegotiate with the four Atlantic provinces the acid rain reduction agreements to extend beyond the year 2000.
(2) Track provincial SO_2 emissions to determine if emission targets are being met.
(3) Monitor precipitation and undertake trend analysis to determine the effectiveness of control programs.
(4) Conduct ecosystem studies to confirm the effectiveness of target loads and effects of NO_3 deposition (Environment Canada, 1996b) .

Long-term Solutions:
(1) Track provincial emissions and established targets.
(2) Monitor precipitation, trend analysis and ecosystem studies to confirm the effectiveness of control programs and target loads, and effects of NO_3 deposition (Environment Canada, 1996b).

Smog

The reduction of ground-level ozone is a complex problem and requires co-operation among governments, businesses and individuals. Industrial and automotive emissions may be controlled by: conservation measures, such as utilizing public transportation, car-pooling, bicycling, walking, and conserving energy; the use of alternative fuels; and development of new technologies, such as the use of solar power to heat homes, power cars, or cook meals. Perhaps the most promising solution to ozone reduction lies in a combination of technological, social, and economic changes.

The 1990 Clean Air Act has set-up provisions to reduce and eliminate ozone-destroying chemicals' production and use. The WHO guidelines for ozone exposure are 0.076-0.1 ppm for one-hour exposure and 0.05-0.06 ppm for an eight-hour exposure (WHO, 1987).

In 1990, smog was recognized as a Canadian pollution issue in the federal “Green Plan”, and in 1993, Environment Canada introduced the Canadian Smog Advisory Program to address issues related to smog (Stieb *et al.*, 1995).

Short-term Solutions

(1) Conduct a follow-up implementation study for an automobile Inspection and Maintenance (I&M) program to reduce VOC and NOx emissions from vehicles.
(2) Promote public awareness, citizenship and pollution prevention by using educational media, such as vehicle-emissions clinics, and educational material, including pamphlets on the state of Canada’s ozone emissions and reductions.
(3) Review existing ground-level ozone monitoring and determine options for maintaining, reducing or expanding monitoring in co-operation with the provinces.

Medium to Long-term Solutions

(1) Investigate expansion of "smog advisory" system to include other pollutants, such as particulates.
(2) Monitor and report progress on regional initiatives under the NOx/VOC Management Plan.
(3) Promote pollution prevention activities under the national plan.
(4) Support research on air quality as a Canadian problem.

Particulate Matter

Over the long term, economic and social development--which has led to the use of cleaner energy sources (e.g., natural gas instead of coal and wood), modernization of older city centres, cleaner streets, more grass and asphalt cover, and the upgrading of industrial and commercial facilities, including installation of equipment to control pollution--appears to be leading to better air quality in urban areas with respect to particulate matter (Environment Canada, 1990).

GAPS AND NEEDS

Introduction

This discussion is on health-related research gaps and needs in Canada; some conclusions and recommendations may be applicable to other countries.

Research Policy and Funding

One consequence of the federal government's policy of encouraging pharmaceutical company support of biomedical research (as a trade-off for enhanced patent protection of proprietary drugs) is a possibly undue influence of pharmaceutical companies in setting research priorities. Support for randomized trials of drug treatments has increased, and there has been some reduction in support for basic and other types of applied research. The "research climate" does not favour innovative or unconventional research strategies such as transdisciplinary approaches.

Several expert groups have recommended transdisciplinary approaches to research problems, including the development and program support for research that breaks out of the reductionist, departmentalized mode that has characterized biomedical research for many decades. The Health Issues committee of the Canadian Global Change Program (1995), and members of expert panels (McMichael *et al.*, 1996c) of the Intergovernmental Panel on Climate Change (IPCC) have proposed new research coalitions among biomedical, behavioural and social scientists. Innovative research strategies are needed to study some of the problems mentioned below. However, there is little evidence that such research is occurring in Canada, and the research councils and other funding agencies do not appear to be encouraging the research to happen.

Surveillance and Monitoring of Health-related Phenomena

Basic information relevant to health impacts of climate change is urgently needed. It is essential to collect the missing information, although this is often not regarded as research, before formal research can even begin. We have few, or no, reliable data on secular and geographic trends in the distribution and abundance of insect vectors of disease in Canada, and on the pathogens that they can carry.

A very hardy culicene mosquito, *Aedes albopictus*, was introduced into the Southern United States in a shipment of used automobile tires in the early 1980's. This mosquito is a highly efficient vector for hemorrhagic dengue and for several types of viral encephalitis. *A. albopictus* occupied a vacant ecological niche, and has spread throughout the southern states, up the Atlantic seaboard and through the mid-west at least as far as the Canadian border. The mosquito's distribution and abundance, its breeding cycles and ability to withstand the cold, and the capability of viral pathogens to over-winter during periods of hibernation, require ongoing surveillance and monitoring in Canada.

Surveillance and monitoring the distribution and abundance of anophelene mosquitoes that carry malaria is an equally high priority. Malaria occurred in the Ottawa area when the Rideau Canal was being surveyed and built, and could be reintroduced at any time in these days of rapid air travel. Indigenous cases of malaria were recorded near Kennedy Airport, New York, in 1995; malaria parasites were likely introduced by air travellers and transmitted by domestic anophelene mosquitoes to residents in the Far Rockaway neighbourhood near the airport.

We also need to monitor the migration of deer mice. These mice carry the virus of hantavirus pulmonary syndrome.

Surveillance and monitoring of many other pathogens have an equally high priority. Over the past 10-20 years, antibiotic-resistant organisms have proliferated. The proliferation is a human-induced phenomenon, brought about by indiscriminate use for many years of broad-spectrum antibiotics both in medical practice and in animal husbandry; the proliferation of resistant organisms fits under the rubric of "global change" although its relationship to climate change may be tenuous.

One emergent infection related to climate change is Legionnaires disease, spread in moist air from poorly maintained air-conditioning systems that have become contaminated with the causative organism. Therefore, another form of surveillance and monitoring is required, viz. public health surveillance of air-conditioning systems, especially in public places such as hospitals.

A form of surveillance that merges with epidemiological research (case-control, cohort studies and randomized controlled trials) is required to establish the linkages among stratospheric ozone attenuation, surface-level ultraviolet radiation (UVR) flux, adverse effects on human health of increased exposure to UVR (including acute sunburn, skin cancer, cataract, immune system malfunction, etc.), and behavioural responses to increased solar radiation (such as sun avoidance, use of sunscreens, protective clothing, sunglasses, etc.).

These examples of surveillance and targeted research into threats to health almost all require mobilization of expertise of physicians, epidemiologists, microbiologists, entomologists, public health engineers, etc., and meteorologists, climatologists, atmospheric physicists, staff in cancer registries, etc.—in short, a transdisciplinary approach.

Transdisciplinary Approaches to Research

Human Behaviour and Climate Change

Climate change is primarily a human-induced phenomenon, and its mitigation requires human action--by all of us. Therefore, there must first be a change in our way of thinking and in our values, for only with this essential prerequisite will the essential changes in human behaviour begin to take place. In order to control any health problem, at least the following five elements all must be in place (Last, 1995):

(1) awareness that a problem exists;

(2) understanding of the causes of the problem;

(3) capability to control the cause(s);
(4) a values system that identifies the problem as important; and
(5) political will to deal with the problem.

Changing Values, Motivation and Behaviour

Among the challenges confronting us is our profligate use of non-renewable resources, notably fossil fuels. Canadians are the largest per capita consumers of fossil fuels in the world. A high priority is to develop ways to change our values and behaviour in the direction of sustainable development, away from profligacy. If we do not make the necessary changes, the consequences will manifestly include health impacts; and all of us are behaving in ways that contribute to harmful climate change.

Research on determinants of human behavioural patterns, including research on the connections among values, motivation and health-related behaviour, should be applied to those aspects of human behaviour that have actual or potential harmful impacts on sustainability.

The "Arms Race" Against Pathogens and Pests

Research is needed to find ways to end the "arms race" between humans and pathogenic micro organisms. The race is a war we can never win: pathogenic micro organisms have many orders of magnitude, more generations per unit time than we have, and therefore they very rapidly and efficiently produce dominant strains resistant to antibiotics. The same pattern applies to mosquitoes and other insect vectors that have been exposed for many insect generations to pesticides--the pests become resistant to the pesticides, and we must forever be developing new pesticides, many of which are toxic to other species, including humans. Faced with the challenge presented by these inexorable biological forces and the failure as yet to develop a malaria vaccine, malaria control programs are beginning to rely more than hitherto on "ecological" control methods and more determined efforts to separate mosquitoes from humans (e.g., by using mosquito netting) (Litsios, 1996). Or we may say that malaria control programs are beginning to rely on methods that acknowledge the capability of humans and the pests and pathogens that afflict us to live in harmony with one another.

Similar approaches may be the best research strategy for the deteriorating situation with antibiotic-resistant infectious pathogens. Strategy will require new coalitions among several kinds of biomedical scientists (including clinicians, immunologists, epidemiologists, microbiologists, and specialists in animal husbandry), social and behavioural scientists, and economists; all groups must collaborate with, for example, pharmaceutical companies that have a vested interest in maintaining the status quo with respect to antibiotic use. This is a high priority because the consequences of proliferating antibiotic-resistant pathogens are becoming progressively more serious. There is a connection to climate change because many pathogenic micro organisms are more dangerous in warm climates. As noted above, the *Legionella* responsible for Legionnaire's disease is a greater risk in hot climates because air-conditioning, which is the main method of transmission, is needed and used more.

Health Effects of Increased Exposure to UVR

In addition to surveillance, monitoring, and epidemiological studies already described, more fundamental research questions about effects of UVR require study--much of it transdisciplinary in character (McKenzie *et al.*, 1994). We do not have unequivocal evidence to establish beyond doubt the sequence from ozone-damaging chemicals to stratospheric ozone attenuation, to increased surface-level UVR, to immediate short-term, medium term and long-term effects on biological systems and human health; our existing beliefs about the sequence are based on a combination of inference and extrapolation. As increased surface level UVR may be among the most dangerous factors associated with global climate change, it is essential to close all the gaps in our knowledge. Filling the gaps will require a combined operation involving scientists in many fields, ranging from atmospheric and theoretical physics to molecular biology. The precise nature of biological changes in human skin and other body tissues, and the pathogenesis of skin cancer, cataract and disruption of immune responses remain at least partly speculative. Therefore, more research by dermatologists and immunologists, among others, working in collaboration with scientists in the atmospheric environment service, would help to clarify some of the remaining uncertainties.

Health Impacts of Acid Deposition

Carbon, nitrogen and sulfur emissions from industrial processes and especially automobile exhausts combine with water vapour, rain, fog, mist, and snow to load the atmosphere with carbonic, nitric and sulfuric acid. The harmful effects of acid rain and fog on fresh-water ecosystems and on certain varieties of vegetation have been well known for many years. The evidence that acid deposition has adverse effects on human health is more elusive. Although on both intuitive and empirical grounds, there may be enough suggestive evidence to justify action against acid deposition, the economic consequences for industry and automobile transport have been deterrents to action in many parts of the world, including Canada. Thus, we do nothing about the fact that acid fogs and mists, along with other common forms of urban and peri-urban air pollution, are a serious respiratory irritant--especially for people who already have some respiratory system damage. A well-known example was the excess deaths attributable to the London smog of 1952--several thousand excess deaths in a few weeks, mostly among people who already had chronic respiratory disease. In Canada, Bates and Sizto (1987) have demonstrated the same sequence. But for action to be taken, more evidence is needed. It has been suggested that acid deposition can leach certain chemicals out of the soil, which enter run-off water and subsurface aquifers, and may, perhaps, accumulate in food and drinking water. Both lead and aluminum have been mentioned in this context, and although it is unlikely that toxic levels of lead can occur, or that aluminum mobilized in this way is a factor in the etiology of Alzheimer's disease, the evidence available to date does not rule out the possibility of such accumulation and resultant harm to health. Therefore, another transdisciplinary research priority is careful study of the relationships among acid deposition, soil chemistry, botany and agronomy, and human health outcomes.

"Futures" Studies

A high priority is the consideration, from a Canadian context, of the future of work, health, sociodemographic and urbanization trends, food security, resource availability and use, technology, etc., both within Canada and in the world as a whole. This consideration is an example of transdisciplinary research that can be conducted in several ways: for example, by mathematical models; by using scenarios based on realistic assumptions and extrapolation; and by "visioning," (the consideration of probable, possible, desirable and undesirable futures) (Health Futures Research, 1994). Each of the foregoing approaches must be accompanied by long-range planning aimed at maximizing the likelihood that a desirable future will eventuate.

Summary

The above are merely examples of research gaps and needs, and not an exhaustive list. Readers can doubtless add many examples of research gaps and needs. To cope adequately with the many challenges to health attributable to climate change, we need more research, and innovative research policies, strategies and tactics.

CONCLUSION

This report describes the widespread and harmful human health impacts of the six air issues, namely climate change (global warming), stratospheric ozone depletion (and increased ultraviolet radiation), air toxics, acid precipitation, smog and particulate matter. These health impacts constitute a considerable public health problem.

In light of the resulting health problems, the need for an expanded research effort, particularly transdisciplinary research, and for improved monitoring of health-risk indicators in relation to atmospheric stresses is obvious. The three research councils (SSHRC, NSERC, MRC) should, therefore, recognize the high priority of examining the air issues and their relation to health.

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CHAPTER TWELVE

IMPACTS OF CLIMATE CHANGE ON RECREATION AND TOURISM

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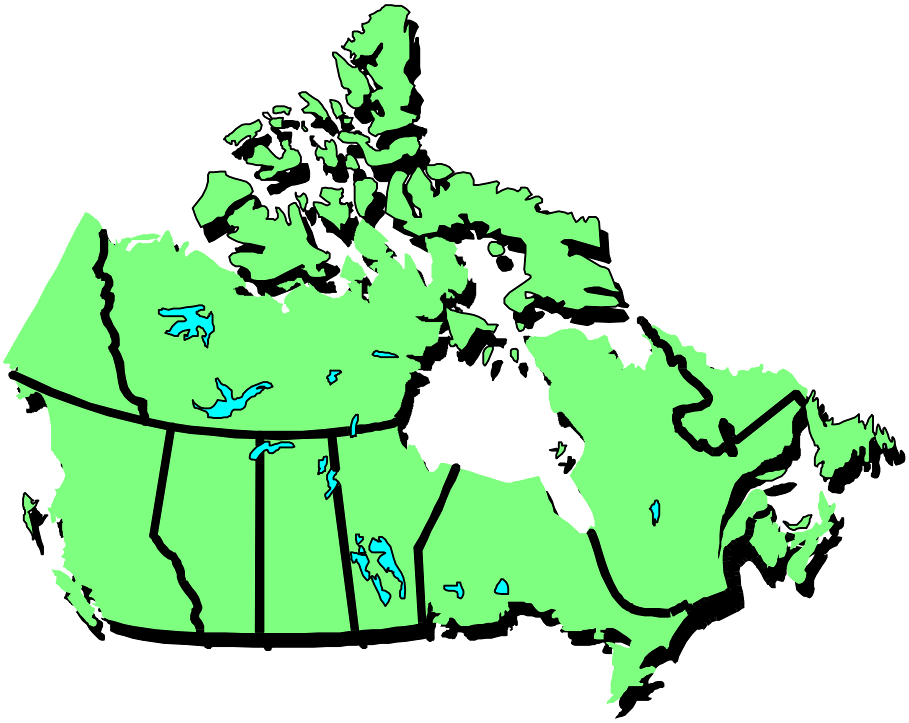

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INTRODUCTION

The purpose of this chapter is to examine possible implications of climate change for tourism and recreation in Canada. Studies of leisure, recreation and tourism are plagued by imprecise terminology (Wall, 1989a). In spite of the existence of a considerable body of literature devoted to explaining the differences in the meanings of these concepts, common acceptable definitions have yet to be derived. For philosophical purposes, the distinctions may be important but, in practice, recreationists, including tourists, often end up in the same locations doing similar things. Thus, no rigorous attempt will be made in this document to separate tourists from recreationists of other types and the terms will be used interchangeably.

It will be suggested that changes in global climate may have far-reaching consequences for tourism and recreation, for many current tourist destinations and for places contemplating involvement in tourism. Global climate change may place constraints upon and provide new opportunities for the tourism industry, and may encourage the search for alternative types of tourism and recreation which are compatible with the new climatic regimes.

Tourism and recreation involve a wide variety of activities which depend upon or are strongly influenced by climate, weather and their variability. Both the availability of recreational opportunities and the quality of associated experiences can be influenced by the presence or absence of specific conditions associated with weather and climate, such as the availability of snow, or air or water temperatures.

The climatic and weather parameters which influence tourism, both singularly and in combination, vary from activity to activity. Also some activities are much more sensitive to meteorological conditions than others. The diversity of activities is such that variations in a wide variety of climatic parameters, or parameters depending on climate such as water quantity and quality, are likely to have repercussions for tourism and recreation e.g. wind for sailing, snow for skiing, cloud cover and ozone concentrations for sunbathing, water temperatures for bathing and water depth for boating. Also it may be very important, for example, to know whether precipitation falls as rain, snow, sleet, freezing rain or ice pellets. Although there is some information on the minimum climatic conditions necessary for particular activities to take place (Crowe *et al.*, 1978) and suggestions have been made concerning the responses of participants in different activities to changes in the weather (Paul, 1972), more work in these areas is needed.

In addition to the relatively direct impacts of climate upon tourism and recreation, climate also impinges upon them in less direct fashions. Access to tourist destinations and recreation areas is influenced by the efficiency of transportation systems which are also impacted by weather and climate. For example, an abundance of snow may make the skiing conditions very good but the journey to the slopes impossible. Conversely, recent observations in Alberta indicated that, although snowfall was reduced, many skiers were attracted to the hills by the mild, sunny weather.

On a longer time scale, climatic change will influence the distribution of the resources on which tourism and recreation depends, such as the distribution of fish and wildlife which may be the quarry of both consumptive (e.g., hunting) and non-consumptive (e.g., photography) forms of recreation as well for the ecology of areas which attract tourism and recreation uses (e.g., national parks). For example, Brotton and Wall (1997) have shown that the availability of caribou to sport hunters in the Mackenzie Basin may be reduced in the future. Staple and Wall (1996) have suggested that while, perhaps surprisingly, white-water rafting may prove to be resilient in Nahanni National Park Reserve, it will probably take place in a modified environmental setting.

Fluctuations in climate at meso and macro scales have implications for water levels and discharge, and influence amenity and property values. Much tourism takes place on or near the shoreline and the presence of water enhances many forms of tourism even if water contact is not required. Hare (1985) has pointed out that, at the low-water point of the mid-sixties in the Great Lakes, the water retreated hundreds of meters from some of the beaches and shores of Lake Huron. Furthermore, the volume of water has implications for water quality and, in some locations, such as parts of the Great Lakes where beaches are closed periodically because of pollution, this is already marginal for body-contact recreations.

Thus relationships between climate and weather, and tourism and recreation are extremely complex.

THE SIGNIFICANCE OF TOURISM AND RECREATION

Before returning to the topic of climate and weather it is appropriate to make some brief comments on the significance of tourism internationally and to Canada

At a global level, international tourism has been growing steadily and, according to some estimates, is exceeded only by oil in the magnitude of its contribution to world trade (Pearce, 1981). Furthermore, it has been predicted that tourism will become the largest industry in the world by the twenty-first century (Leisure Industry Digest, 1985; Papson, 1979). Already it is the largest economic sector in many countries in both the developed and developing world. Thus, while associated with pleasure, tourism is certainly not a frivolous activity. The World Tourism Organization reports that there were 592 million international tourist arrivals in 1996 and that these tourists expended $US 423 billion in destination countries (World Tourism Organization, 1997). Canada was ranked tenth in number of international arrivals (17,345,000) with 2.93% of world market share and twelfth in international tourism receipts (US $8,727 million) or 2.06% of world market share.

In 1995, according to the Canadian Tourism Commission, total tourist spending in Canada was $41.8 billion, which was an increase of $2.8 billion or 7.1% from 1994. The direct effect of this spending on GDP was $17 billion which was an increase of 7.0% at a time when overall GDP rose by 3.9%. Total direct and indirect effects totaled $27.6 billion, which was an increase of 7.1% over 1994. Government revenues from the direct tourism expenditures totaled $13.2 billion in 1996 or 31 cents of every tourism dollar spent in Canada.

In 1995, tourism employment in Canada was 488,500 person-years, which was up by 8,100 from 1994 i.e. tourism employment increased by 2 % compared with a static situation for the business sector overall. Tourism employment was projected to increase by between 120,000 and 130,000 person-years by 2005.

The above statistics indicate that tourism is one of the largest employers in Canada, ranking fifth after retail trade, wholesale trade, business services and agricultural industries. It is also the fifth largest revenue generator: tourism receipts exceed the gross outputs of such industries as motor vehicles, primary metals, paper and chemicals, as well as major resource sector industries such as crude petroleum and natural gas, mining, logging and forestry.

Such statistics confirm the importance of tourism to the Canadian economy. However, tourism is not evenly distributed across Canada and its effects are often highly localized. If population distribution is taken into consideration, while in absolute terms tourism and recreation are concentrated in areas with large populations, it is often the less-populated areas, which are often areas most in need of economic diversification, which have a high dependence on tourism and recreation (Wall, 1991).

Tourism may be even more important in its positive contribution made to the quality of life. Although the commodities produced from Canadian renewable resources are still much in demand, the demand for their recreational and environmental outputs appears to have increased even more rapidly. Jackson (1986) cites several studies that indicate a decline in values associated with materialism and an increase in concern for quality of life and preservation of the environment. This shift from a consumer to a conserver society may strengthen if the environment deteriorates. Associated with this is a shift from consumptive recreational activities to appreciative activities. For example, according to Harrington (1991), the demand for wildlife-related services, especially recreation, will continue to increase, at least in the near term, and the fastest-growing part of wildlife-related recreation will probably continue to be to be non-consumptive uses such as birdwatching and nature study. A shift to pro-environmental attitudes would increase the demand for natural areas in which to recreate and increase tourism in those areas that can provide pristine environments. Public support for the protection of natural areas may also increase. Thus, resources once viewed as obstacles to economic progress until they were tamed or replaced are now recognized as essential to the diversity and quality of the environment and our recreational opportunities (Frederick and Sedjo, 1991).

A concise overview of the evolution of the supply of and demand for outdoor recreation opportunities can be found in Clawson and Harrington (1991).

DATA AVAILABILITY

Tourism and recreation are areas which are data rich but information poor. There is a wealth of studies of tourism and recreation but most are site-specific and few have addressed relationships with weather and climate. The output of the General Circulation Models (GCMs) is not suited to site or even regional studies and usually does not include variables in a form which are pertinent to recreation. Climate varies over short distances, and with height and aspect in mountainous regions, and at a scale which is important for recreation but beyond the resolution of existing models. In consequence, it is difficult to combine the available recreation and climatic modelling information.

The wealth of existing data on current weather and climate is generally not well-used by tourism and recreation operators at present. For example, the lengths and variability of seasons suitable for undertaking specific activities in particular locations can be calculated under existing conditions with considerable implications for the economic viability of recreational businesses, but such investigations are not often undertaken, particularly by small operators who manage a large proportion of recreation businesses. In fact, there is an as yet unrealized potential for practical work using existing weather and climate information which could aid the decision making of tourism and recreation enterprises.

ASSESSING THE IMPACTS OF CLIMATE CHANGE FOR TOURISM AND RECREATION

The magnitude of the implications of climate change for tourism and recreation will depend upon both the distribution and importance of tourism and recreation phenomena and the characteristics of climate change. Other things being equal, locations whose economies are highly dependent on tourism appear to be at the greatest risk. Writing in an international context, Wall (1992a, 1993) has suggested that domestic travel patterns are likely to be more stable than international travel because the former often take place in relatively short periods of free time, and time limitations place constraints on the destination choices of travelers (Lundgren, 1989). Similarly, long-haul destinations are more at risk than those depending largely on a local market. However, even destinations which have an international reputation (such as Niagara Falls) rely heavily upon the regional market for a large proportion of their visitors and it appears that remote locations, distant from large urban markets are likely to be most at risk.

Furthermore, destinations which rely primarily upon their natural resource base to attract visitors, such as mountains and coasts, are likely to be more at risk than those which depend upon cultural or historical attractions.

There are at least four perspectives from which the relationships between climate and recreation can be viewed (Riebsame, 1985). The first perspective is climate as setting. From this perspective, climate constitutes part of the environmental context in which tourism takes place. There are numerous documents which briefly describe the climatic characteristics of destination areas before discussing the activities which take place in them. However, in the majority of these studies, climatic variables do not constitute an element in subsequent analyses and such studies are of limited use in leading to an understanding of the implications of climate change.

A second perspective views changes in atmospheric processes as generators of change in participation in tourism and recreation. Studies of this type include some of the more thorough studies of atmospheric processes in relation to tourism and recreation, and their findings have been reviewed elsewhere (Wall, 1985). However, most such studies stress relationships between weather and recreation rather than implications of longer-term climate change.

A third perspective sees climate as hazard (Murphy and Bayley, 1989). Hazard implies loss or harm in the context of chance, risk or accident. The actual climatic phenomena thus termed can range in scale, character and effect from slight, common variations to rare, isolated effects; from global occurrences to local incidents. Resultant situations can vary from relatively minor inconvenience to unmitigated disaster. Although there is a large literature on hazards, there is little specifically on tourism, particularly in Canada, although it is evident that much of the property destroyed by coastal storms or avalanches previously had recreation functions. As an aside, it is interesting to note that impacted sites may become tourist attractions as visitors come to gaze on the misfortune of others or stop at the site of a major disaster.

Lynch *et al.* (1981) have combined the hazard approach with the second approach described above and view climate as both a resource and a resistance. Since human activity imposes limits on the favourable and unfavourable valuation of meteorological conditions, and human beings determine the socio-economic activity for a specific time and place, they, in effect, define the hazardousness and utility of the phenomena which interact with their activities. That is, if the conditions vary beyond acceptable limits, the weather becomes a liability rather than a resource. This liability is a function of human vulnerability or, in other words, the sensitivity of the activities and environments which are exposed to the elements.

Lynch *et al.* (1982) suggest that three important implications arise from these statements. First, the range of interactions resulting from the limitless variation in weather and social systems indicates an exceedingly complex system to examine and generalize. Second, an understanding of extreme events may be as, if not more important, than average conditions. Third, the observation that human beings are the resource and resistance determinants suggests that they have some control in reducing the sensitivity of human activities to weather and climate.

In order to make rational, objective, decisions concerning responses to the vagaries of climate, it is essential that the decision maker (in this case the tourist or the proprietor of a tourist enterprise) has an explicit understanding of weather-activity relationships. The identification and measurement of the economic impact of weather variation is a key exercise in the establishment of this interaction. The economic assessment of weather hazards, or "weather costing", is not only possible and practical, but it enables comparisons to be made between sites and greater efficiencies to be achieved (Taylor, 1970). However, "weather costing" has yet to achieve its full potential among tourism and recreation entrepreneurs.

Masterton (1982) has suggested that changes in the weather give rise to both physiological and psychological responses which influence levels of comfort and these, in turn, can be modified by the addition or subtraction of clothing. She proposes that climatic classifications can be devised based on comfort leading to studies of tourist destinations, on either a regional or local scale, and of individual recreational activities. While such studies are unlikely to be mutually exclusive, they both constitute potential directions for future research. Mieczkowski (1985) has employed the notion of comfort in his assessment and mapping of the tourism climates of the world.

The influence of weather conditions on tourism varies from region to region and activity to activity. Rain occurring in a region with a climate of 20 rain days annually will likely have a greater influence upon human behaviour than rain of the same intensity and duration occurring in a climate of 100 rain days annually (Crapo, 1970). Similarly, weather variables become more influential in affecting activities as the amount of atmospheric contact increases. However, weather influences both indoor and outdoor activities (Myers and Wall, 1989, Schlegel, 1994). Unsuitable weather for outdoor activities will drive people indoors and covered stadia are built to protect participants in outdoor activities from the vagaries of the weather.

SEASONALITY

One of the major attributes of most tourist destinations is seasonality. Not only is there a regular round of activities associated with the seasons, there is also variation in the volume of activity in areas lacking a marked seasonal climate. This is because seasonality in areas of demand results in seasonal variations in visitation to areas of supply. Thus, for example, the desire for many Canadians to escape the Canadian winter to warmer climates creates a seasonal peak in visits to temperate and tropical areas which do not have the same degree of annual variation in temperature as Canada. Smith (1990) has pointed out that in a warmer world, many winter vacations currently taken in Florida or Mexico by residents of the colder parts of the United States and Canada may become less compelling under the relatively large increment of winter warming projected for these latitudes.

The length of the operating season is of crucial importance, particularly for private sector operators of tourist facilities. In Canada, many tourist activities are seasonal and use is further concentrated on weekends and a limited number of holidays. Capital is invested all year round but, for many activities and destinations, the operating period is limited and profits must be made in a short period of time. Tourist businesses, whether focusing upon summer or winter activities, must gain their incomes in restricted time periods and a few inclement weekends may tip the balance between profit and loss. It follows that anything which influences the length and reliability of operating seasons, be they climatic factors or otherwise (such as the length and timing of school holidays) is likely to have an impact upon the viability of tourist businesses. Any changes in season length would have considerable implications for both the short-term and long-term viability of tourism and recreation enterprises and an enhanced ability to predict these would be of great value.

EXTREME EVENTS

It is changes in the magnitude and frequency of extreme events through which the implications of climate change will most likely be imposed.

Much tourism and recreation is concentrated in high energy environments such as mountains and coasts and it is these areas which appear to be particularly vulnerable to climate change through modifications in the hydrological cycle, particularly changes in water levels, streamflow and the magnitude and timing of snowfall. Changes in avalanche and flood frequency, major storms, and derivatives of weather and climate, such as fire frequency, could have considerable implications for both tourists and tourism plants. Declining water levels in the Great Lakes may have negative implications for marinas and recreational boating. At the same time, the threats associated with rising sea levels may be exacerbated by changing tastes precipitated by increased recognition of the health effects of diminishing ozone concentrations. Thus, while rising sea levels associated with the greenhouse effect may erode beaches and affect the infrastructure of marine coastal resorts, the tastes of their clientele may also change reflecting health concerns associated with ozone depletion. Tourism enterprises currently are not generally well-prepared for extreme events so that it can be assumed that few steps have been taken to plan for the possibility of climate change.

The above discussion has indicated the far-reaching consequences of weather and climate for tourism. However, there has been only limited recognition globally of the possible consequences of climate change for tourism and recreation (Wall and Badke, 1994) and most studies to date have been based upon short-term fluctuations in weather and climate; little has been written in the context of tourism on the implications of long-term climatic change. Several overview documents have been prepared previously on the possible consequences of climate change for tourism and recreation (Wall, 1994, 1995, 1996). However, the limited number of Canadian investigations of the implications of climate change for tourism and recreation have invariably been case studies which are restricted in area and in the activities investigated. It is not possible to cumulate the results of such studies to arrive at an overall quantitative assessment of the likely implications for Canada. Rather, the results of a variety of studies will be presented which together provide an overview of some of the likely consequences of climate change for various activities in diverse parts of the country.

IMPACTS

It is difficult to think of almost any area of land or water which, with or without human modification or management, does not have potential to provide some recreation opportunities. At the same time, the range of recreations is extremely large and they have varied environmental requirements. This makes it extremely difficult to generalize concerning the possible implications of climate change for recreation.

To these specific problems may be added a number of other issues common to all environmental impact assessments (Wall and Wright, 1977):

a. the difficulty of establishing a base level against which to measure change;
b. the difficulty of disentangling the changes attributable to human actions from those associated with natural processes;
c. spatial and temporal discontinuities between cause and effect;
d. the complexity of interactions which complicate the identification of second and third order effects.

Thus, it is necessary to impose some order on the assessment of impacts by grouping them in some way. In this paper, impacts will be examined under the following headings: water-based recreation, natural areas, winter recreations and summer recreations. Examples will be provided which illustrate possible implications of climate change under each of these headings.

Water-based Recreation

Almost all forms of recreation are enhanced by the presence of water. Some, such as bathing and fishing, cannot be undertaken in the absence of water of appropriate quantity and quality. Other activities, such as hiking and camping often are attracted to shorelines and may be enhanced by the presence of water even if no direct contact with water is involved. It follows that anything which impinges upon the quantity or quality of water is likely to affect outdoor recreation. Furthermore, if water is in short supply, recreation will come increasingly into competition with other uses of this scarce resource.

Coasts

One likely consequence of global climate change is sea-level rise. This may have considerable consequences for the provision of recreational opportunities on maritime coasts.

Coastal resorts

The economy of many coastal communities is dominated by the exploitation of sea, sun and sand for recreation. Anything which threatens these resources or the associated infrastructure is likely to be ominous for the economies of coastal resorts. Rising sea levels threaten beaches which are unable to extend inland because of the existence of built structures and expensive beach protection and restitution measures may be required for communities whose economic welfare depends on the availability of sand. Sanitation systems and freshwater supplies may be threatened by rising water levels and salination of coastal estuaries, and potable freshwater supplies may be reduced when seawater infiltrates subterranean water tables. Should the frequency of storms increase then there may be additional threats to coastal infrastructure from storm and flood damages. Perhaps fortunately, these may be less prominent concerns in Canada that for some of the milder regions of the United States.

The threats associated with rising sea levels may be exacerbated by changing tastes precipitated by increased recognition of the health effects of diminishing ozone concentrations. Tourism and recreation activities and places are prone to both tradition and fashion: some endure largely unchanged over long periods of time whereas others come and go very quickly. Sunbathing has only been a popular activity since the 1920s and, prior to that time, prevailing aesthetic tastes in western societies preferred a pale complexion to a tan. One wonders if positive attitudes towards sunbathing will be maintained in the face of climate change and increased exposure to UV radiation associated with ozone depletion. Last (1993) has suggested that research is needed on attitudes towards sunbathing and the use of protective measures.

Weather advisory messages warning about safe exposure levels have been used routinely on Australian radio and television for some years, and were introduced in Canada in 1992, but such advisories are not part of routine weather reports in the United States. Sunscreen ointments and creams require rigorous evaluation. Although there are reports of the protective effect of sunscreen against sunburn, their effectiveness in preventing skin cancer and malignant melanoma remains unclear. Should health education be employed to persuade people to relinquish the notion that a suntan is desirable? If so, research is needed to identify and evaluate ways to do this. What are the implications of such attitude changes to coastal communities whose economies are based upon the sale of sea, sun and sand?

Thus, while rising sea levels associated with the “greenhouse effect” may erode beaches and affect the infrastructure of marine coastal resorts, the tastes of their clientele may also change reflecting health concerns associated with ozone depletion.

Marine Wetlands

Marine wetlands are one recreational setting which has received some attention in the context of global climate change, particularly from the perspective of rising sea levels (Titus, 1988). Wall (1997) has recently reviewed the situation from a tourism and recreation perspective.

Marine wetlands are environments which have been declining in area as a result of subsidence and the encroachment of other land uses. According to Titus (1988), there are three major ways by which sea level rise can disrupt wetlands: inundation, erosion, and saltwater intrusion. In some cases, wetlands will be converted to bodies of open water; in other cases, the type of vegetation will change but a particular area will still be wetland. However, if sea level rises sufficiently slowly, the ability of wetlands to grow upwards - by trapping sediment or building upon the peat the sediment creates - can prevent sea level rise from disrupting the wetlands. The factors principally responsible for determining accretion rates are sediment loads, current velocity, and flooding frequency and duration. Tidal range, tidal regularity and substrate type also influence marsh boundaries and therefore help to determine adjustments to rising sea levels (Armenato *et al.*, 1988).

Along undeveloped coasts, rising sea levels will drown the seaward wetlands but will allow new wetlands to be created inland as formerly dry land is flooded. However, the impact of sea level rise on coastal wetlands will depend largely on whether developed areas inland of the marsh are protected from rising sea levels by levees and bulkheads. Along developed coasts, there may not be land available for wetland creation.

Inland Locations

Interior Wetlands

In contrast to maritime coasts where water levels are expected to rise, regardless of possible changes in precipitation which are at present poorly understood, increased temperatures may increase evapotranspiration and thereby reduce the water in inland lakes and streams and increase the competition for that water which exists. Thus, inland wetlands may be threatened more by too little water than too much, and a lowering of lake levels will have implications for the character and tourism potential of inland shoreline ecosystems (Martinello and Wall, 1993). Some of the greatest impacts of lake level changes will occur along the margins of the Great Lakes where wetlands constitute important waterfowl habitat and a source of recreation for many people.

The author examined the possible implications of climate change for Point Pelee National Park and Presqu'ile Provincial Park in on the Great Lakes shoreline in southern Ontario (Wall, 1988, Wall *et al.*, 1986a). Both parks contain large areas of marsh which are of considerable importance for wildlife and recreation. However they also constitute two different kinds of wetland systems with the potential to respond differently to changes in water levels. Point Pelee is a closed, protected marsh which is separated from the lake by natural barrier beaches. In contrast, the marsh of Presqu'ile is an open wetland system. In both cases the marshes are not influenced to any great degree by run-off from the mainland and water levels in Lake Ontario are a primary determinant of vegetational composition and functioning of the marshes.

In naturally confined marshes such as Point Pelee, lowered lake levels will cause the marsh to revert to marsh meadow and, eventually, to dry land. Because of the protective sand spits, the marsh will be prevented from moving lakewards and vegetation will shift from hydric to mesic conditions. Some plant species may change growth form to accommodate to drier conditions but vegetation will change dramatically as species intolerant of drying die and are replaced by species emerging from buried seeds. The trees which mark the landward edge of the marsh may advance due to a lowering of the flood line. Wetland species diversity will decline and the suitability of the marshes as a habitat for recreationally and commercially valued species, such as migrating waterfowl and muskrats, will be reduced. Sport fishing may also be affected by the reduced quality of shoreline marshes where fish feed and spawn. Other non-consumptive activities, such as canoeing and ice skating, will decline due to the lack of open water. The frequency of fires is likely to increase. In time, the marsh may lose its wetland character and, under extreme conditions, the waterfowl migration route may change resulting in the collapse of hunting and, more importantly, birdwatching.

In open shoreline marshes such as Presqu'ile, the effects of lowered lake levels are unlikely to be as severe. Instead of a draining of the marsh and a trend towards dry land, there will probably be a shift in the vegetation in a lakeward direction. The extent of this shift depends upon the magnitude of the lake level change, the slope of the bottom profile and the suitability of the substrate.

It is evident that the impacts of climatic change on shoreline ecosystems will vary considerably with the physiography of the littoral both because the configuration of the shoreline has implications for the ecological effects of changes in water level and because different recreation activities take place in different environments (Wall and Costanza, 1984). Presumably, should water levels in the Great Lakes fall, then, other things being equal and given sufficient time, a new equilibrium will develop which will include the establishment of new wetlands in locations where the physiography of the littoral is suitable. However, unfortunately, other things are unlikely to be equal. Many of the major wetlands are currently under protection in national, state or provincial parks or some other heritage designation. There is no guarantee that locations with wetland potential will be under public jurisdiction and existing landowners may discourage the development of new wetland areas adjacent to their property. The requirements of other users, such as navigation and hydroelectric power generation, which may encourage dredging and filling or stabilization of water levels, will also weigh against the formation of new wetlands. What are managers of existing wetlands to do if their holdings become less interesting ecologically and the original reasons for their designation as reserves evaporate?

While the potential loss of wetlands has become a major concern, contradictions and tradeoffs abound because wetlands are important sources of atmospheric methane, one of the more powerful greenhouse gases (Frederick and Sedjo, 1991).

Marinas and Recreational Boating

The Great Lakes have long been a Mecca for recreational boating and fishing, and their shores are the location of recreational facilities such as private cottages and public parks. The lakes are also used for water supply, navigation and power generation, and the lake levels fluctuate in response to climatic variations. Fluctuating water levels are required for the maintenance of ecological processes but some users, such as hydroelectric power generation and navigation, would prefer greater stability and relatively high levels, whereas others, such as cottagers, would prefer relatively stable lower levels. Marinas and recreational boating are harmed by extremes of both high and low water, particularly the latter which is the most likely situation under global climate change.

High water episodes were experienced in 1951-1952, 1973-1974, 1985-1986 with low water periods in 1934 and 1964. Thus, there is a long history in the Great Lakes of adjusting to climate variability in periods of both flood and drought (Great Lakes Commission, 1990, Scott, 1993, Parker *et al.,* 1993).

Surveys undertaken in 1992 of marina operators and recreational boaters on the Canadian side of the Great Lakes indicated that almost all had incurred costs at some time or other associated with fluctuating water levels (Bergmann-Baker *et al.,* 1992-1993, 1995). Since they had been operating their marinas (approximately one-third had been a marina operator for less than five years although most marinas were considerably older), in times of low water, 67% of respondents had experienced problems of access to docks or berths, 64% with inadequate channel depths, 62% had ramp access difficulties, 45% were forced to use fewer slips, 21% experienced short boating seasons and 13% had dry rot in wooden structures. In response to these problems, 55% had dredged, 45% had adjusted their docks, 44% restricted the sizes of boats, 44% had to relocate boats, 27% closed slips, 19% constructed floating docks, and 7% replaced rotted structures.

Unfortunately, it is not possible to put a precise dollar value on these adjustments but clearly it has been substantial. In addition, other adjustments were made in periods of high water. In fact, there are examples of marina operators experiencing low-water problems at times when they are still paying off loans acquired to build breakwaters to protect themselves from high water. Boaters also accrue a variety of costs but they are more mobile than marina operators and, thus, can adjust more easily. However, they may be affected in other ways. For example, global warming may increase fish productivity if water quality is not adversely affected but some significant species may decline and alien species may find it easier to colonize the lakes.

Similar findings have been reported for parts of Lake Huron by Stevens (1991) in his investigation of marina operations and by Duc (1997) in his study of recreational boating.

Although Alexander (1997) arrived at inconclusive results in her investigation of the possible consequences of climate change for outdoor recreation at Sauble Beach, it appears that the Great Lakes may provide a dramatic example of the implications of fluctuating water levels and, hence, climate variability, for recreational activities.

Natural Areas

Natural areas are important tourism and recreation resources whose attractions are based to a considerable extent on the species which they conserve and the ecological processes which they sustains. Biophysical factors play a role in the definition of natural areas, park selection, ongoing management, and interpretation. In addition, management tools such as zoning, the content of interpretive programmes and the determination of appropriate recreational activities are based upon the biophysical attributes of each area. Management of natural phenomena, such as flora and fauna, is directly associated with ecology and habitat and, therefore, climate. Should climate change occur the implications for natural areas are likely to be far-reaching (Peters and Darling, 1985).

Global warming may modify many ecosystems on which outdoor recreationists depend. For example, a study of Prince Albert National Park, Saskatchewan (Vetsch, 1986, Wall, 1989b), described future climatic conditions and corresponding vegetation changes and explored the array of potential implications of climate change for the study area and for the management of national parks. Vegetation was selected as the central variable of concern since it is the basis of habitat and a good indicator of environmental change. As is the case for much of the Great Plains and Prairies, climate scenarios suggest that Prince Albert National Park is likely to experience a warmer, drier climate in the future. Detailed examinations of theories of vegetation responses to environmental stimuli, climatic impacts upon vegetation, historical evidence of vegetation distributions, species' ecology, disturbance factors such as fire and grazing, and factors affecting species' distribution constitute the basis for speculating on the vegetation changes to be expected in Prince Albert National Park under the climate change scenarios. Based on these analyses, likely vegetation changes in Prince Albert National Park include an increase in the proportion of grassland in the park at the expense of boreal forest, and special resources within the park will be impacted by climate change with associated implications for park zoning, interpretive themes and recreation. Five such changes are outlined below:

i. The transition from Grasslands to Boreal Forest. The transition zone, or ecotone, between Boreal Forests and Grassland biomes is an important resource management and interpretive theme represented in the park. The edges of the biomes may be among the first areas to respond to an environmental change, with implications for the position and prominence of the transition zone. If climatic change is prolonged it is conceivable that the bulk of the transition zone may move north of the park. These vegetation changes may create the need to re-evaluate the unique and representative features of the park. In the immediate to short-term future, opportunities may exist to increase the emphasis placed on dynamic environmental processes in interpretation.

ii. Fescue Grasslands. The small areas of Fescue Grasslands are regarded as a special feature of the park because they are an outlier of the larger areas of Fescue Grasslands occurring approximately 60 km to the south, and because, for the past several decades, aspen has been encroaching onto the grasslands decreasing suitable habitat for elk and bison. Climatic change will promote the perpetuation of grassland communities in the park and could decrease the need for their special preservation as presently exists. However, continual alterations in the natural state of similar grasslands outside the park suggest that the Fescue Grassland communities contained within the park will still remain an anomaly for the region.

iii. American White Pelicans. The only protected breeding colony of American White Pelicans in Canada is situated on Heron Island in Lavalee Lake near the northwestern border of the park. Changes in climate, as depicted in GCM scenarios, may have deleterious effects by changing lake water levels, exposing nesting islands to the shore and allowing the invasion of predators. However, the 32 degrees F (0 degrees C) April isotherm approximates the southern boundary of American White Pelican range, as it reflects the availability of fish at the time of the birds' arrival in their nesting areas. Climatic change will extend the ice-free period, potentially opening up suitable habitat north of present park boundaries;

iv. Woodland Caribou. Woodland caribou in Prince Albert National Park are at the southern margin of their range and are concentrated in the northern portion of the park. They are considered a special feature of the park since they are generally found in more northern regions and because they are considered to be a rare species in Canada. The herd of approximately 38 animals migrates in and out of the park but does not move great distances. Preferred habitat is mature coniferous forest, such as black spruce muskeg, but this should decrease under warmer, drier climatic conditions. This might force caribou to find suitable habitat farther north, leaving no woodland caribou in the park;

v. Free Roaming Bison. The park supports a herd of free roaming bison whose primary habitat is the ecotone between grassland and forest. Encroachment on grassland by aspen and other woody growth has decreased bison habitat, causing them to move out of the park more frequently onto neighbouring agricultural lands. Bison in this situation are not protected and have caused some conflicts with landowners. A future warming trend should increase the area of bison habitat in the park, reduce their need to roam, and help to reduce land use conflicts.

Thus, under climate change scenario conditions, changes could occur in the resources currently deemed special or rare. For instance, the Fescue Grasslands may no longer require special management for preservation but portions of the Boreal Forest may increase in significance. The summer recreation season will elongate and the winter season shorten, possibly resulting in greater recreation pressures. Increased land use pressures brought on by more frequent drought (as depicted in the GCM scenarios) might result in a desire to convert currently marginal lands to agricultural uses. Such pressures may be manifest in increased conflicts between parks and uses of land for other purposes.

Climatic change also has implications for the amount of land devoted to parks and other natural areas, the size of each individual park, park selection and designation, and boundary delineation. The parks have a mandate to protect endangered species and act as ecological reserves. Prospects of climatic change and increased vulnerability of resources to such change, suggest a greater relevance of climatic criteria to the processes for designating parks and other reserves. For example, where possible, boundary designation should allow for the migration of species. The scenarios suggest a greater magnitude of climatic change in more northerly latitudes; hence, in such situations, greater emphasis should be given to placing parks in locations which are climatically optimal for the species being protected. There is a greater need for large parks with ecologically responsive boundaries.

In northern regions, the concept of ecological islands is not viable because of the extensive migratory paths of many animals. How does one successfully design ecologically optimal locations when the impending climatic change is wide-ranging and the animals that are being protected are highly mobile? It is clear that climatic change has far-reaching consequences for individual parks and for park systems which are beyond the scope of this report but which merit further investigation.

The points which have been made with respect to wetlands and Prince Albert National Park are applicable in a more general form to other ecosystems. A warming trend should lead to a poleward movement of biomes but individual species are unlikely to move at the same rate so that it is simplistic to view the process as one of intact ecosystems marching northwards (and upwards). Natural areas are often islands embedded in vast areas of modified landscapes, and in the absence of obvious routes for the spread of species or assemblages, it is unclear how the relocation of flora and fauna will occur. In fact, changes in the frequency of extreme events, such as fires or pest infestations, may be critical agents of change (Wall, 1992b).

What is natural in an era of pervasive, human-induced change? What is to be protected and why? Climate change thus poses fundamental questions concerning both the designation and management of natural areas and the natural resource base for tourism and recreation. These questions deserve much more attention than they have received to date.

Winter Recreations

The discussion of winter recreations will concentrate primarily on downhill skiing. However, cross-country skiing, snowmobiling (Hind, 1986), ice fishing (Wareing, 1994) and other activities dependent on snow or ice are likely to be impacted in a somewhat similar, negative fashion.

Lack of snow has immediate implications for skiing. Increased temperatures may reduce the proportion of precipitation which falls as snow. This may not be true in all cases for warmer air holds more water vapour than cooler air so there may be situations, as in extreme northern latitudes, where snowfall may actually increase. Also the climatology of mountain areas, where many ski hills are located is extremely complicated and not replicated in existing general circulation models. However, it is generally believed that the quantity and reliability (since snow may be followed by rain in marginal situations) of snowcover is likely to be diminished with an associated curtailment of the operating seasons of many ski areas. Many ski areas must recoup their investments in short operating seasons, particularly holidays and weekends, so that anything which reduces the reliability and length of operating seasons is likely to have negative economic consequences. It is important to acknowledge that in this, as in many other situations, it is not the average conditions which are important but the frequency of extreme events. Many ski areas can withstand a bad week, month or even a season and may expect this under current operating conditions. However, the juxtaposition of several poor seasons may be critical.

Of course, ski areas have and will continue to respond to the existence of adverse snow conditions by making snow. However, there are limits to the application of this technology which is very expensive, requires large quantities of water, and has its own climatic constraints. At best, snowmaking is a buffer rather than a solution to the vagaries of climate. Other possible adaptations include the extension of operations in mountainous areas to higher latitudes where snowfall may continue to be reliable, as has occurred in the European Alps, but this strategy has ecological consequences, particularly where operations are conducted above the tree-line.

A further adaptive strategy, which makes sense under current climatic conditions and will help to prepare for a modified climate, is diversification of activities to ensure that investments in property and infrastructure generate incomes for much of the year. Examples include the construction of water slides so that lifts can be operated in the summer, provision of golf courses, hiking trails and swimming pools, construction of condominiums to build a reliable year-round clientele, and the addition of conference facilities. Such strategies will reduce the seasonality of recreational enterprises and provide more reliable employment thereby strengthening surrounding communities and take advantage of possible increases in the length of summer (see Summer Recreations).

Downhill Skiing in Ontario

The sensitivity of recreation to climate variability was well-illustrated in Ontario, Canada, when a spell of unusually mild weather coincided with the 1979 Christmas holiday which is a critical period for the ski industry (Lynch *et al*. 1981; 1982). Newspapers reported "financial woes", "damaging effects" and "serious blows" to the Ontario ski resort operators, and effects rippled through the retail and service sectors, especially in resort areas. In the South Georgian Bay region, skier activity for the season was approximately 40% lower than expected, representing a loss of direct recreational expenditures alone in the order of $10 million. By the end of January, individual ski resorts had suffered losses ranging up to $2.5 million.

Some retailers had "written off winter" and two major sporting retail chains went into receivership. In January 1980, the Ontario Ski Resort Association appealed to the Provincial Government of Ontario for assistance to help meet fixed operating costs. Some individual operators also applied for and received direct aid or loan guarantees from the Ontario Development Corporation. Others cancelled or postponed planned improvements or expansions.

The vulnerability of ski resorts differs considerably depending on the type and amount of adjustment they have made in advance to offset or compensate for the effects of variable weather. A major adaptation is investment in snow-making equipment. This can improve marginal conditions and extend the season but it also has its own temperature limitations, is expensive, and requires access to large quantities of water. Other operators have pursued different adaptive strategies, notably enhancing flexibility by diversifying recreational facilities and income sources. For example, Blue Mountain Resorts has major investments in snow-making equipment, but also has developed year-round facilities. Although Blue Mountain suffered losses in the 1979-80 ski season, they were able to generate a profit (albeit reduced) for the whole year.

Great Lakes Skiing

Using the GCM climate change scenarios developed by Princeton University's Geophysical Fluid Dynamics Laboratory (GFDL) and the National Aeronautical and Space Administration's Goddard Institute of Space Studies (GISS) for doubled concentrations of greenhouse gases, an attempt was made to evaluate the resilience of downhill skiing in the Great Lakes area to climate change. Although the length of the ski runs is short and the vertical drop is small by many standards, and the resorts cater primarily to day and weekend skiers, such hills are the nurseries for the more challenging vacation ski resorts of North America and beyond. However, the author is unaware of investigations of the implications of climate change for such areas in North America. Therefore, what happens to ski areas in regions like the Great Lakes under global warming may become crucial for the ski industry as a whole.

Using six locations in the Great Lakes area in Canada and the United States, present-day ski season length was determined for each site using the methodology of Crowe *et al*. (1978). They determined that a day suitable for downhill skiing is one in which there is:

- a snow cover of at least 2 inches (5 cm);
- no measurable liquid precipitation (freezing rain, drizzle or rain);
- a maximum temperature less than 40 degrees F (4.5 degrees C).

They then determined the % age probability that a day in winter would meet these criteria. If the percentage probability of a day is:

- less than 50, the conditions are considered unreliable for skiing;
- 50 - 74, then conditions are marginally reliable for skiing;
- 75 or greater, then conditions are reliable or skiing.

Following the approach used in previous studies, (McBoyle *et al*., 1986, McBoyle and Wall, 1987, Wall, 1988; Lipski and McBoyle, 1991, McBoyle and Wall, 1992) the skiing season was taken to be the period when the snow cover is deemed to be marginally reliable or better. The present-day ski season length trisects the Great Lakes area:

- northern Ontario and Michigan have a season of 131 days extending from November 21 to March 31 while in southern Québec the season is 10 days shorter ending on March 20;

- central and southern Michigan have a ski season of 100 days starting later than the north on December 11 and ending on March 20 as does southern Quebec;
- southern Ontario has a season of approximately 70 days starting just before Christmas, December 21, and lasting until the end if February.

A similar pattern exists for the reliable ski season with a reduced length occurring as one moves south.

Under the two scenarios of climate change, the winter monthly precipitation is expected to increase by about 9% while the temperature is projected to rise on average by 6.2 degrees F (3.4 degrees C) under GFDL and 9.6 degrees F (5.3 degrees C) under GISS conditions. This will result in only the three most northerly sites, Thunder Bay, northern Michigan and southern Quebec, having monthly average temperature values below freezing under GFDL, while under GISS this condition will occur only at Thunder Bay and southern Québec. As a result, much of the precipitation will likely not fall as snow. In general, skiing conditions over much of the Great Lakes region will become marginal. For example, the ski season in Georgian Bay and southern Michigan, under GFDL, is curtailed to 41 days, none of which is deemed to be reliable. Under the more extreme GISS scenario, the ski season is eliminated in the southern part of the basin while in the north it is reduced to 59 to 80 days with only Thunder Bay having a reliable ski season of more than 10 days.

Are the above results extreme? What are the minimum temperature and precipitation changes required to produce situations similar to those suggested by the scenarios? Using Michigan as an example, if present-day Michigan temperatures are increased incrementally by 1 degree F (0.6 degree C) while maintaining present precipitation values, it would take only an increase of 4 degrees F (2.2 degrees C) to reduce the present-day reliable ski season to that projected under GFDL conditions. This is below what is forecast by the more conservative of the two scenarios. With a precipitation base of 110% of normal (close to the future winter average suggested by both scenarios), it requires an increase of 5 degrees F (2.8 degrees C) to reduce the present reliable ski season length to that postulated by GFDL. This again suggests that a temperature increase lower than the value projected by GFDL will create the ski season changes suggested above. However, a temperature rise of at least 9 degrees F (5 degrees C) is required before GISS conditions will occur. This sensitivity analysis suggests that the scenario results are not far-fetched.

Fortunately for the Thunder Bay area of northern Ontario, under GFDL conditions, the key ski business periods - the Christmas school break and the mid-February university and college breaks - will have reliable ski conditions. The major loss will be the elimination of skiing in March when only about 20% of skier visits occur. The value of the lost skier expenditure during March under GFDL conditions would amount to $2.675 million. In the southern area of Québec the situation is similar, resulting in a loss of $5.068 million.

The losses in the Georgian Bay region will be large. The Christmas break, which accounts for between 20 and 30% of the business, will be lost. Similarly, there will be a reduction of between 10 and 15% as a result of the elimination of skiing during the mid-February break. These losses could amount to between $4.877 and $7.316 million.

Lamothe and Périard Consultants (1988), using somewhat different techniques to those in the studies mentioned above, came to very similar conclusions for downhill skiing in the Laurentian of Québec. Ordower (1995), using a modification of the earlier methodology, also calculated reduced downhill ski seasons in southern Ontario as did Brotton and Wall (1993).

Because of the shorter season, ski operators will require more lifts, more snow-making equipment, improved grooming machinery and night lighting to generate the same revenue in a greatly reduced number of days. But all of these cost money. Such investments will be approached with caution because of the uncertainty concerning an economically viable future. For example, at an outlay of $4.12 per acre-hour of operating, the cost of snowmaking quickly comes prohibitive for all but the largest operators (Goeldner *et al*., 1990). Warm winter conditions may bring more risk of avalanches in mountainous areas which, in turn, may result in more frequent and costly closure of ski slopes and greater controls on activities like backpacking (Smith, 1990). On the positive side, there is the prospect of an extended summer season (see Summer Recreations). For this reason, many ski operations have diversified to become year-round resorts with golf courses, tennis courts, condominium villages, conference facilities and even operate their lifts to take holiday-makers to a waterslide or to nature walks that lead back to the lodge. In fact, some resorts have dropped the word "ski" from their name and have entered a four-season mode of operation. However, such expansion will likely be limited to only a few resorts adding further uncertainty to the smaller operations.

Summer Recreations

Climate change may raise the possibility of extended summer seasons (subject to water availability and institutional constraints) as is sown by Lamothe and Périard Consultants (1989) in their study of golf in Québec. This possibility is illustrated here by an investigation of camping in Ontario (Wall *et al*., 1986b). Camping is both an activity undertaken by tourists and a form of tourist accommodation, and it was selected as being a good indicator of summer activities.

Much as was done in the preceding section on skiing, present and future lengths of the camping season were calculated for eight provincial parks in Ontario. It was assumed that any elongated season would result in the same amount of activity in the additional weeks as is present at the margins of the current, normal season.

There are considerable regional differences in season length, with parks in the south experiencing a longer season climatically (although not necessarily administratively) than those farther north. However, a simple north-south pattern does not exist because of lake effects. In all cases, the reliable camping season is extended under both GISS and GFDL scenarios, sometimes by as much as 40 days. Marginally reliable seasons are displaced earlier in the spring and later in the fall. Information on numbers of campers, their lengths of stay and their expenditures were used to calculate the economic implications of the extended seasons. Should campers take advantage of the extended, potential, camping seasons there would be positive economic implications which vary in magnitude in different parts of the province. However, these economic benefits may occur at the expense of increased environmental deterioration as the parks host more visitors for longer periods of time.

It is important to acknowledge that impacts are not always negative, that change need not necessarily be bad, and that climate change may create opportunities as well as problems. The outlook is rosy for enterprises catering to the summer tourist provided that they are not likely to be adversely affected by declining water levels or the reduced availability of water.

LIMITATION AND ADAPTATION

Strategies to adopt in the face of global climate change are often considered under the headings of limitation and adaptation (Smit, 1993). Limitation refers to attempts to reduce the production of greenhouse gases and thereby to reduce the magnitude of speed of climate change. Adaptation accepts that climate change is likely to occur and attempts to identify steps which may be taken to restrict its adverse consequences and to take advantage of opportunities. Limitation and adaptation should not be regarded as alternative strategies for they are interrelated.

Limitation

With the major exception of energy consumed in transportation, tourism and recreation are not usually regarded as major contributors to the generation of greenhouse gases. Since people eat and sleep and most like to be comfortable whether they are home or away, the consumption of energy in transportation between origins and destinations is seen as the most important contribution of recreation to the rising concentrations of greenhouse gases. It is true that the temporary movement of people from temperate to tropical latitudes has local implications for energy and water consumption and waste disposal but on-site recreational activities are usually viewed as being minor net contributors to the global production of greenhouse gases.

While recreational trips are, by definition, discretionary activities for participants in outdoor recreation, they are certainly not discretionary for the businesses and communities which cater to tourists. It follows that policies designed to curb travel may have considerable implications for destination areas. In the 1970s, when gasoline was in short supply, the economies of such locations were adversely affected. However, it was found that many urbanites elected to save their gasoline for recreation, there being more alternatives for modifying the journey to work than the journey to play to dispersed locations which are poorly served by public transportation.

In summary, tourism and recreation are not viewed as major net generators of greenhouse gases, except perhaps in the travel phase, but policy initiatives taken to curb travel may have substantial implications for destination areas.

Adaptation

Both natural and human systems are adapted to an unknown extent to much of the variability in current climates. With respect to recreation for example, ski resorts make snow (although this, too, has climatic limitations) and marina operators on the Great Lakes have installed floating docks as an adjustment to fluctuating water levels.

Two main groups can be considered with respect to the potential to adapt to climate change. These are the participants themselves and the businesses which cater to them. Each will be considered in turn.

Participants

By definition, recreational participation is a result of choice and, although choices are not unconstrained, a great deal of flexibility is involved. A great deal of money is invested in recreational equipment. However, much of this equipment is mobile. Recreational participants have considerable choice concerning whether or not to participate, what activities to participate in, when to participate and where to participate. In fact, since the product of recreation is an experience, participants may be able to substitute activities and locations without a great deal of loss in the quality of their recreation. It is true that those wishing to observe particular species of plants and animals may find them less accessible or replaced by others, and fishermen may be required to change their quarry in particular locations, but in so far as there are still wild spaces and provision of recreational opportunities, most potential participants are likely to be able to satisfy their leisure needs. Thus, the ability of potential participants to adapt to climate change is substantial.

Businesses

The flexibility of participants may be a problem for those catering to recreational demands. Much recreational provision, be it a ski hill, a campground, a marina or a national park, is fixed in location with sunk capital that cannot readily be liquidated and re-invested. If the quality of the recreational resources and associated experiences is degraded or if the length of operating seasons is curtailed below economic viability, then there may be considerable economic dislocations for recreational businesses and the communities on which they depend. However, there are likely to be both winners and losers as participants exercise their choices in modified ways.

RESEARCH NEEDS

There is no question that greater spatial resolution, a greater variety of climate and climate-related variables, and a reduction in the uncertainty associated with climate scenarios generated from GCMs are required if improved estimations of the likely implications of climate change for tourism and recreation are to be made. However, the improvement of such information is insufficient, by itself, to further such understanding. In fact, complementary research strategies are required, such as investigation of the adaptation of participants and recreation businesses to existing and past climatic variability.

Since recreation involves, by definition, activities undertaken by choice, it is important to understand how alternative opportunities are evaluated by potential participants. Choices are not unconstrained and, if future choices are restricted by a modified climate, participants may be able to substitute one activity for another or one location for another. The assessment of the extent to which particular recreations and locations may be substitutes may thus be a fruitful area of research.

Assessment of the implications of climate change for natural area designation and management is an important research area which has yet to receive the attention which it deserves.

Other topics which are worthy of investigation include: assessment of the means by which recreational provision can be diversified to reduce vulnerability; evaluation of the role of extreme events in influencing recreational provision; and the influence of land use zoning, insurance and other social adjustments in influencing recreational provision in high-energy locations such as shorelines and mountains.

Climate is only one factor among many which influence tourism and recreation. There is a need to assess the relative importance of climate as compared to other variables for:

a. different recreations; and
b. different locations.

Much might be learned through the use of existing climate data to assess current lengths of operating seasons, their temporal and spatial variability, and the associated economic viability of recreation businesses. Such studies would have considerable practical applications. One outcome of such analyses might be the more widespread acceptance of the utility of including climate change as one factor among others in assessments of the viability of recreation investments.

However, even if climate change could be reliably forecast now, it is doubtful if the tourism and recreation industry has, at present, sufficient understanding of its sensitivity to atmospheric variability to plan rationally for future conditions.

SUMMARY AND CONCLUSIONS

This contribution has been concerned with the implications of atmospheric processes, particularly climate change, for recreation. The significance of tourism and the importance and complexity of weather and climate influences for tourism have been stressed. It has been shown that tourism and recreation make substantial contributions to national and regional economies but that these contributions are compromised, on occasion, by variability in present-day climate. However, present knowledge does not permit a full accounting of these substantial costs.

Although a literature has evolved which examines aspects of the links between climate and tourism, very little has been written concerning the implications of climate change for tourism and recreation. Correspondence with member nations of the World Tourism Organization and the World Meteorological Organization indicates that almost all acknowledge the importance of climate for tourism but virtually none have given serious thought to the implications of global climate change for tourism and recreation (Wall and Badke, 1994). This is a serious oversight at a time when humankind may be facing one of the most rapid, global climate changes in human history.

Climate variability and change have considerable implications for tourism and recreation and an increased ability to predict perturbations in weather and climate and their implications for natural and human systems at all scales is likely to be of benefit to both participants and to the businesses which cater to them. However, most studies to date have been based upon short-term fluctuations in weather and climate; little has been written in the context of tourism on the implications of long-term climatic change. Nevertheless, it is likely that future climates will influence the viability of alternative types of tourism, providing challenges and threats to some destination areas and enhanced opportunities for others.

Given the existing state of knowledge, it may be premature to make recommendations for policy but some pertinent observations can be made. Coastal areas appear to require careful attention given their susceptibility to changing water levels and their significance for recreation. Operators of ski areas in climatically marginal areas may need to upgrade their snow-making equipment and diversify their activities, strategies which could pay dividends even in the absence of climate change. Summer activities in middle and high latitudes may benefit from extended seasons provided that coastal processes are not disrupted and water is not in short supply.

Global climate change will present both problems and opportunities for destination areas. The climate changes which have been discussed are projected to occur within the lifetimes of many current investment projects and within the lifetimes of many of the Earth's present residents. Although the implications for tourism are likely to be profound, very few tourism researchers have begun to formulate relevant questions, let alone develop methodologies which will further understanding of the nature and magnitude of the challenges which lie ahead.

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