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December 3 to 6, 1996

R. W. Shaw (Editor)

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CLIMATE VARIABILITY AND CLIMATE CHANGE IN ATLANTIC CANADA

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by

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FOREWORD

Atlantic Canada's ecosystems, ranging across more than fifteen degrees of latitude, exist in a delicate balance under the influence of the air and the sea. Correspondingly, the socioeconomic conditions are extremely fragile in this part of Canada, and very dependent on the sustainability of our natural resources and environment. The continuing increase in greenhouse gas emissions is expected to result in a changing and/or more varied climate. Some experts maintain that this is already happening, and a greater frequency of weather extremes is now imposing additional stress on natural ecosystems. It is therefore critical that we identify the impacts of a changing climate, and take the steps necessary to adapt as best we can.

This symposium brought together scientists and other specialists from a variety of disciplines to discuss and synthesize the work that is, and has been done in the area of climate change impacts and adaptation in Atlantic Canada. This is a necessary first step to address knowledge gaps and establish new directions for an ***integrated*** research effort. These proceedings, including synthesis papers by lead authors identified for each discipline, will serve as a comprehensive document to be used as the major contribution to the Atlantic Canada input into Phase I of the Canada Country Study. Furthermore, this gathering has enabled us to develop partnerships to more easily identify a multidisciplinary and multi-sectoral (public, private, academia) group to coordinate and recommend research and monitoring related to climate change in Atlantic Canada leading to Phase II of the Canada Country Study. Finally, a high level of media coverage, as well as the evening public session helped improve public awareness and understanding of the impacts of climate change.

This symposium was organized by representatives from the federal Environment (EC), Fisheries and Oceans (DFO), and Natural Resources (Forestry(CFS)/Geological Survey(AGC)). The Program Committee was co-chaired by Jim Abraham (Atmospheric Environment Branch) and Tom Clair (Environment Conservation Branch) of EC; with membership including Ray St. Pierre, Peter Lewis, Gerry Teman and Geoff Wilson of EC, Ken Drinkwater from DFO, Dick Pickrill of AGC, and Roger Cox and Kevin Percy from CFS. Local arrangements were coordinated through the efforts of Sheila Klain, Libby Douglas, and Vikki Bewsher of EC.

The editor wishes to thank all those who provided input to the Proceedings, including the authors of the synthesis and other papers; Ms. Joanna Spencer Brown of the School for Resource and Environmental Studies at Dalhousie University who acted as a rapporteur at the Symposium; and Dr. Cindy Staicer of the Department of Biology, Dalhousie University, who acted as a rapporteur and who also drafted Chapters 2 and 10. The Proceedings would not have been possible without the hard work of all these people.

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EXECUTIVE SUMMARY

INTRODUCTION

The symposium *Climate Variability and Climate Change* was held in Halifax, Nova Scotia on 3-6 December 1996. Its purpose was to summarize the current state of knowledge in the Atlantic Region with respect to various aspects of climatic change. The results of the workshop will be used as a contribution to the Atlantic Regional input to the *Canada Country Study*, which is envisaged as being a two-phase study. Phase I of the Canada Country Study would start immediately and conclude in late autumn 1997. It would have as its objectives:

- Preparation of an integrated assessment of present knowledge concerning the impacts of climate variability and change on Canada and adaptive responses, and
- Identification of gaps in knowledge and the suggestion of priority areas where new knowledge is most urgently needed

Phase II would be the research phase which would address the gaps and priorities identified in Phase I. Planning of Phase II would begin in late 1997/98 with actual research being initiated in 1998/99 and continuing for approximately five years.

There were 181 participants registered at the symposium, drawn from the governmental, academic, industrial and private sectors with an interest in different aspects of climatic change: meteorology, oceanography, fisheries, geology, agriculture and forestry, among others.

The sessions were arranged according to various aspects of climate variability and change: climatology, oceanography, agriculture, extreme events, etc. The symposium ended with a panel discussion on gaps, priorities and next steps in climate research. There was also a concurrent poster session.

Some of the main points that were brought out in the Symposium now follow. These are drawn mainly from the synthesis papers; more details may be found in the main text of the Proceedings.

CLIMATOLOGY

The Atlantic provinces fall into two world climate zones: (1) The Moist Continental Zone (Nova Scotia, New Brunswick, Prince Edward Island) has a large annual temperature range, with warm summers, cold winters, and ample precipitation that peaks in the summer. (2) The Boreal Forest Zone (Newfoundland, Labrador) has greater annual temperature ranges, short cold summers, long cold winters, and low annual precipitation with a summer peak. No location fits these descriptions perfectly, however, and climate varies with latitude, proximity to coasts, ocean currents, sea ice, etc. (e.g. the most severe climate records are for St. John's, Newfoundland).

Temperature and precipitation provide an incomplete picture of this region's climate. Storms, wind, and fog may be more localized but nonetheless important features of the Maritime climate. Winds are typically higher in winter and at coastal sites, but the highest winds are those associated with storms. The high precipitation of this region is largely due to storms, including tropical storms. Most of the Atlantic region experiences 30-60 days of fog (150 days in some parts of Newfoundland).

Although there has been a worldwide warming trend of 0.3 to 0.6C, and a similar warming of 1.1C in Canada overall, the Atlantic Region has shown a warming trend from 1985 to the mid 1950s, followed by a cooling trend into the 1990s. During the period 1948-1995, Atlantic Canada has shown a marked cooling of 0.7C with seasonal trends as follows: winter (-2.2°C); spring (0.0°C); summer (+0.5°C); and autumn (-0.8°C). In the Maritime provinces during the period 1945-1993, There has been an increase in the mean daily minimum temperature of 0.3C, but a *decrease* in the daily maximum of 0.8C.

Atlantic Canada has had an increase in precipitation amount since 1948. Cloud cover in the Atlantic Region has appeared to increase by 1% since 1953, but this change is not statistically significant. There is also: a decreasing trend in the number of days per year with a maximum temperature above 25°C; 2) an increasing trend in the number of days per year with a minimum temperature below -15°C; 3) an increasing trend in the number of daily precipitation events above 20mm and; 4) a very slightly increasing trend in the number of daily snowfall events above 15cm.

FISHERIES AND PLANKTON

Fish stocks vary depending upon fishing practices and natural factors, including environmental change. It is difficult to resolve the relative importance of human and natural factors, but environmental factors such as temperature can have a pronounced effect upon growth of fish species, spawning and reproduction, distribution and migration, abundance and migration, and catchability and availability. The effects may be location- and species-dependent. One example of the effect of environmental factors on the fisheries given at the Symposium is that the incubation of Atlantic cod eggs on the Scotian Shelf vary from 8 to 42 days at 14C to 1C, respectively. Thus eggs in colder water are more vulnerable to predation due to longer exposure times and may, therefore, experience lower survival rates. Another example is that a wintertime index of the areal extent of sea surface temperatures (4C-8C) in the Labrador Sea conducive for salmon has been developed which shows a high positive correlation with the number of salmon returning to North America during the following spring and summer. This winter index is now used to predict prefishery abundance of salmon entering the rivers during the following late spring or summer.

Climate change can be expected to result in distributional shifts in species with the most obvious changes occurring near the northern or southern boundaries of their range. Migration patterns will shift causing changes in arrival times along the migration route. Growth rates are expected to vary with the amplitude and direction being species dependent. Recruitment success could be affected due to changes in time of spawning, fecundity rates, survival rate of larvae, and food availability. Another possibility associated with climate change is a change in stratification (due to differences in heating, freshwater, and vertical mixing rates) which may lead to changes in the ratio of pelagic to groundfish abundance. If stratification increased, more of the production is expected to be recycled within the upper layers of the oceans and less to reach the bottom. Under such a scenario higher pelagic production and lower groundfish production would be expected.

Qualitative predictions of the consequences of climate change on the fish resources of Atlantic Canada will require good regional atmospheric and oceanic models of the response of the ocean to climate change, improved knowledge of the life histories of those species for which predictions are required and further understanding of the role of environment, species interactions and fishing play in determining the variability of growth, reproduction, distribution and abundance of fish stocks. This multi-forcing and numerous past examples of "failed" environment-fish relationships indicate the difficulty fisheries scientists face in providing reliable predictions of the fish response to climate change.

COASTAL ZONE

The best estimate of global sea-level rise (SLR) by the Intergovernmental Panel on Climate Change is about +0.5 m by 2100. Associated changes in atmospheric circulation may also lead to changes in storm climatology, ocean wave climate, storm-surge probability, and other factors relevant to coastal stability. sea-level changes resulting from thermal expansion in the ocean will vary geographically, such that some regions may experience negative or negligible change, while others will be subjected to larger increases in mean sea level. Further complication is introduced by natural sources of variability in the climate system, such as El Niño and the Southern Oscillation, the North Atlantic Oscillation, secular variation in tropical and extratropical storm occurrence and ocean wave climate, arctic and sub-arctic sea-ice extent, and other factors. Demand for coastal property in Atlantic Canada is already on the rise, with upward pressure on prices, and similar trends along heavily developed coasts in the USA, southern Europe, and elsewhere have led to rapid growth in the value of structures within the coastal zone. Under these circumstances, the financial risk associated with a given physical hazard (e.g. coastal erosion or flooding) is greatly increased.

The reality of a human-induced greenhouse effect remains controversial. There is widespread evidence to suggest a recent increase in the rate of sea-level rise, part of which may be attributable to greenhouse warming. However, saltmarsh deposits and other coastal systems contain evidence for natural fluctuations in sea level at time scales of the order of 100 years, implying that accelerated SLR observed over the past century may be partly or wholly natural in origin.

There are two types of potential effects: 1) effects of accelerated sea-level rise; and 2) effects of variable storminess. These may be summarized as follows:

> Relative sea level is rising now along most parts of the coast in Atlantic Canada. Accelerated SLR over the past century may be a response to global climate change or it may represent medium-term (century-scale) natural variance in the rate of sea-level rise. There is evidence to suggest that global sea level is rising at a rate of 1 to 2 mm/year and a further increase of about 0.5 m is anticipated by the year 2100. This will be added to vertical crustal movement (subsidence at rates as high as 0.3 m/century) in many parts of Atlantic Canada. The result will be an enhanced flood risk in some areas and accelerated

coastal erosion in others. Sediment redistribution and coastal sedimentation will occur in some places.

Variations in storminess, including possible increases in storm frequency or intensity, can be expected to cause enhanced erosion in some places and may affect the risk of storm-surge flooding and dyke overtopping in the Bay of Fundy. Possible increases in open-water fetch and wave energy during the winter months, due to reduced extent and duration of winter sea ice, particularly in the Gulf of St. Lawrence and northeast Newfoundland, may also contribute to coastal erosion losses. The prediction of impacts is complicated both by our limited understanding of possible changes in storm climatology and by limitations in our ability to predict coastal response.

ECOSYSTEM SCIENCE AND WATER RESOURCES

Water resources

Persistent change or increased variability in climate will affect the present characteristics of the water resource. Precipitation and temperature are the principle driving forces behind the hydrological cycle and anticipated changes in climate are expected to significantly alter Canada's water resources. The amplification of the temperature trend signal through the hydrology cycle could be dramatic. The timing of the change could also be gradual or stepwise. Increased variation seen as seasonal time shifts or rapid swings in seasonal climate variables could change the normal characteristics of the water cycle, creating havoc for human or ecosystem users of the resource.

Habitat loss is a major concern especially in the Atlantic Region as there may be no alternatives for some species. Climate and hydrology play a major role in the health of freshwater ecosystems. The timing and magnitude of specific hydrologic events such as freeze-up/break-up, the severity of the spring freshet or the duration of the low flow period is vital to the life cycle of many species.

On the human side of the ecosystem, the accumulation of long term flow and climate data have been invaluable in aiding the safe and economical design of dams, bridges, water supplies and other infrastructure whose design and integrity are influenced by the extremes of the hydrologic cycle.

Preliminary analyses in Nova Scotia and on the Island of Newfoundland showed that the number of days with ice in rivers has increased since 1952. Preliminary comparisons of ice data with winter season temperatures showed that there was a cause and effect relationship between the temperature and ice, but for whatever reason it did not completely explain the trend.

During the last 25 years there appears to be a dramatic decrease in runoff in Nova Scotia streams especially during the winter. What appears to be a trend from 1970 toward lower winter runoff is also the same period of higher ice in rivers and a full cause effect relationship is being determined.

River Ice Jams

Ice jamming in Canadian rivers has a multitude of socio-economic impacts such as flooding, damage to private property and infrastructure, interference with navigation, and inhibition of hydropower generation. The average tangible cost of ice jamming to the Canadian economy is estimated at $60 million per year. A much greater amount is attributed to missed hydro-power generation opportunities due to inadequate understanding of river ice processes. Atlantic Canada is one of the most-seriously affected regions

Ice jams, and the surges that follow their release, have many detrimental impacts on aquatic life. Habitat loss due to bed and bank scour, fish mortality due to stranding on the floodplains, very high concentrations of fines, abrupt water quality changes, long range transport of pollutants, deposition of fine sediment and degradation of spawning habitat, are but a few examples. Ice jams also have positive ecological effects, such as the replenishment of floodplain habitat with nutrients and sediment for the sustenance of many aquatic, terrestrial and avian species, during the spring flood.

Considerable warming and changes in precipitation patterns are predicted by General Circulation Models under the well-known 2xCO_2 scenario. If these changes materialize, our understanding of river ice processes suggests that the ice regime may be modified in different ways over different parts of the country. In temperate regions such as southwestern Ontario, and parts of British Columbia and Atlantic Canada, the brief and capricious river ice cover may disappear completely, or become more intermittent. This should be good news on the socio-economic front, but could be disruptive to aquatic species that depend on the ice cover for winter survival.

Wetlands

Because they are defined by the location of seasonal and permanent water tables, wetlands are closely linked to climate. Balances between precipitation and temperature which control total water input and outputs are critical in determining the very existence of wetlands. Changes in the evapotranspiration balance leading to lower water tables may thus cause the disappearance of wetlands along with the ability of basins to absorb water and increase flood risks in certain areas.

Water levels and flows through wetlands also control their carbon content and fluxes. Aquatic dissolved organic carbon fluxes are closely linked to water flow through the basins. Furthermore, water levels control the level of methane and CO_2 emissions from wetlands. Shifts in water tables due to a changing climate will change the relative importance of the gases and their impact on the global atmospheric carbon cycle.

Migratory Birds

Boundaries of winter ranges of terrestrial birds will likely shift northwards with warmer winters; the northern boundaries of many species of songbird coincide with January isotherms reflecting daily energy requirements of about 2.5 times Basal Metabolic Rate.

Beyond general correlations between 'bad' (i.e. wet and cold) summer weather, and lower bird productivity, the influence of climate on breeding success has not been explored in Atlantic Canada. In many seabirds, both breeding distribution and the timing of breeding are related to sea-surface temperatures. Since these temperatures are likely to change as the climate warms, noticeable changes in distribution and breeding success of seabirds can be expected.

Among marine birds, changes in range will likely follow changes in the distribution of prey such as capelin, arctic cod, herring, sand-lance etc., which in turn will accompany changes in water-temperature and salinity. Compression of the boreal marine ecozone can be expected as the cold Labrador current becomes cooler from increased inflow of glacial melt as the Greenland ice-caps melts, at the same time that warm waters of the Gulf Stream move further north.

Rising sea level is likely to inundate coastal staging grounds which are essential for shorebirds and waterfowl migrating between arctic breeding grounds and southern winter quarters. The most obvious examples in this region are the saltwater marshes connecting New Brunswick and Nova Scotia, and the mud flats at the head of the Bay of Fundy.

The timing of many events in a bird's annual cycle, including migration, breeding and moult, is frequently triggered by changes in day length. This timing mechanism may prove maladaptive in a changing climate, when the linkage between day length and changing food supply, habitat availability, movement of air-masses, etc., becomes uncoupled as these climatic events change but daylength does not.

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, and summer storms can kill shorebirds on their breeding grounds and greatly reduce breeding success among bird groups as varied as songbirds and seabirds.

AGRICULTURE

The agricultural sector is particularly sensitive to climate change and variability because of its direct dependence on the weather and climate. Along with soils, climate, to a large extent, determines the types of crops that can be grown in the Atlantic region, where these are best produced, the yield and quality that is achievable with present-day technology and the types of management practices used.

The availability of heat units (CHU) has very significant impact on which crop species, varieties and/or hybrids producers choose to grow and on the productivity of their farms. For example, average CHU in the three Maritime provinces range from a high of about 2800 in the Annapolis valley to less than 1700 in northern New Brunswick. With present-day available hybrids, grain corn has good potential in areas with >2500 CHU, is marginal in 2300-2500 heat unit areas, and is generally not feasible in areas with <2300 CHU.

Growing degree-days above 5°C (GDD) vary from less than 1000 to over 1800 in parts of the Annapolis and lower Saint John River valleys. Differences in GDD particularly impact the potential on long season crops such as spring wheat, potatoes and forages.

Spatial variations in winter climates have significant impact on survival (and hence the suitability) of overwintering crops such as winter wheat, clover, alfalfa, strawberries, tree fruits and ornamental trees and shrubs. The susceptibility of winter injury to apples is rated from low in the Annapolis valley to high in many areas of New Brunswick

Significant climate-induced differences in soil moisture deficits and spring field workdays occur in the region. These differences impact farm management decisions such as machinery size, labour requirements, irrigation and drainage system design.

Temporal variability in climate exerts perhaps even greater impact on agriculture than the spatial differences that are encountered in the Atlantic region. Variations that likely have the greatest impact on agriculture include excess moisture, unusually late spring or early fall frosts, drought, unusually severe storms, unfavourable overwintering conditions and exceptionally cool growing season weather.

The Atlantic region has apparently not followed the national warming trend of about 1°C during the last 100 years. Trends indicate that there was slight gradual warming from around 1900 to the 1950's, cooling from the '50's to the 1970's and a levelling off in the '80's.). Overall, the temperature changes are relatively insignificant and likely have had little or no impact on agriculture compared to that of climatic variability.

Precipitation seems to have increased and become more variable over the past 100 years. This may have impacted agriculture through reduced drought stress but may have increased problems in coping with excess moisture. *While long term changes in precipitation are statistically significant, they are still relatively small in comparison to the yearly variability that growers must contend with.*

From the foregoing analyses, we can conclude that climate change over the past 100 years has had relatively little impact on agriculture compared to the variability, with the possible exception of precipitation which appears to have increased and become more variable. Changes over the longer term (centuries) likely have had significant impact, but these are beyond the planning time frame of agriculture.

Climatic changes that may occur in the future could have significant impact on agriculture in the Atlantic region. Rising CO_2 concentrations accompanied by a warming trend would be beneficial to agriculture, particularly if new crop varieties that are better adapted to any changed conditions are selected. Warming could be expected to improve the competitiveness of the agricultural industry by expansion of production in corn, soybeans, tree fruits and specialty crops. Change to wetter or drier conditions could have both positive and negative impacts. Increased moisture supply would reduce yield reductions due to drought, but likely result in increased disease pressure (particularly from foliar-type fungal diseases such as potato blight, which thrive in wet weather), increase the leaching of nutrients and chemicals to the ground water, reduce the number of days suitable for field work and result in greater soil erosion. A change to drier conditions would have the opposite effect. Milder winters could significantly impact the survival of many crops such as alfalfa, clover, winter wheat, strawberries, tree fruits and grapes, and improve the potential of these crops in many areas. However, negative effects on survival could be experienced in some areas where warming results in less reliable snow cover.

The agricultural industry should, in general, be able to adjust relatively well to any long term gradual changes in climate that may occur, taking advantage of any improvement in conditions while minimizing the negative impacts of less favourable climate. *Variability and extremes in climate that will occur will likely have greater impact and be more difficult for producers to cope with*[1]. In general, any progress that can be made in reduce the negative impacts of climatic extremes should help the industry to cope with any long term climate changes that may occur.

FORESTRY

Climatic factors may influence growth rates and carbon sinks: predicted temperature changes indicate warmer winters and springs but cooler summers for most of the Maritimes. This may increase growth rates of conifers if the length of growing season significantly increases due to the warmer springs. Warmer soils also means faster nutrient cycle and more nutrients. Certainly, earlier springs would have to be accompanied by an extension of frost free days here in Atlantic Canada, as late frosts or early extended thaws would be more damaging to the hardwood species with early phenology if refreezing occurred after dehardening of buds and roots.

Enhanced UV-B exposure due to the depletion of the statospheric ozone layer may also be a factor affecting tree growth. Although the majority of plant species that have been tested to date were agricultural plants, trees appear to run a higher risk of accumulating UV-B damage over their far longer lifetimes.

Changes in forest extent in the due to melting permafrost is not an issue in the Maritimes but changes in tree line at altitude may occur.

Gains in carbon storage due to higher productivity will be offset in some part by increased decomposition rates in the soils and peat. Transient losses in the mature forest due to disturbances may account for additional loss in carbon storage. Sink strength of the young forest could be negated by other stresses such as air pollution, especially tropospheric ozone, acid rain and acid fog.

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[1] Italics added by editor.

There is some expectation, for a move to a more temperate mixed forest, with some loss of boreal characteristics. In the short term, transient behaviour of our forests will depend on the adaptability of each species population in the current forest and the regional manifestation of climatic change.

The predicted changes in Fire Weather Index would vary from being reduced in the southeast boreal in southern Quebec, with only slight increases in the southern Maritimes, increasing slightly more over Cape Breton and east Newfoundland. The uncertainty in these predictions, however, are increased by other disturbances such as blowdown, insect outbreaks, and declines, which affect fuel quality and fire risk.

It is likely that the Balsam Woolly Adelgid would present a serious problem if the winter temperature of the boreal forest increased, because this insect seems to be controlled in its northward extension due to intolerance of dormant adelgids of temperatures <-34°C.

There is evidence that beech escaped beech bark disease (caused by the beech scale insect) at altitude and in the northern parts of their range, indicating that this insect too, may be limited by climate and thus, may pose a greater risk with warmer winters under climatic warming.

It has also been suggested that, in the northern limits of the spruce budworm, the ends of outbreaks may be associated with late spring frosts that destroy the early foliage. As climate warms, fewer late frosts may increase the length and severity of outbreaks in these northern areas.

Storm damage (blowdowns) may possibly increase in severity and frequency with global warming due to a more intense hydrological cycle. The effects of other forest disturbances serve to open the canopy and may exacerbate blowdown situations, as will the move towards more softwood plantations.

Warmer winters and less snow accumulation may lead to extensions of overwintering areas for deer which means more available food and decreased predation. These effects can, in turn, lead to higher population levels which can impact forest regeneration and lower species diversity.

EXTREME EVENTS

Two types of extreme events are major storms such as hurricanes, and associated phenomena such as storm surges and extreme waves. During most of the years 1970-87, the North Atlantic hurricane basin had experienced a relative lull in overall tropical cyclone activity. The below-normal activity was especially evident in drastically reduced numbers of hurricanes affecting the Caribbean Sea and Maritime Canadian regions and basin-wide numbers of major hurricanes (MHs), and almost a total absence of MH landfalls affecting the east coast of the U.S. After the experience of renewed "normal" activity in 1988 and 1989 (with five MH during those two years), it was suggested that the Atlantic basin was returning to a long-term period of higher activity such as what was experienced back in the decades of the 1950s and 1960s and some earlier periods. The heightened activity in 1988 and 1989 was followed, however, by a marked downturn in activity from 1991-94. As a result of the resumption of the below-normal activity, primarily attributed to wind anomalies driven by the highly anomalous, long-lasting warm sea-surface temperature (SST) event (El Niño) in the tropical Pacific, the notion that the Atlantic basin had entered a high-activity regime was pretty much discarded.

The warm event in the Pacific finally ended in early 1995 and was followed by one of the most active hurricane seasons in the Atlantic on record with almost every measure of activity over twice the long-term mean. Of particular note was that the season produced five MHs for the first time since 1964. The chief issue being addressed in the current study is whether or not the activity of the 1995 season was simply an anomalous "spike" or a harbinger of multi-decadal-scale climate shifts signaling the probability of greater activity over the next ~10-20 years.

There is evidence of certain multi-decadal scale changes in Atlantic SSTs with a shift towards warmer conditions in the Northern Hemisphere beginning around 1988. This shift was accompanied by a shift towards lower vertical shear in the main development region of the Atlantic hurricane basin (a band between ~10° and 20°N, stretching between the west coast of Africa and Central America), a condition more favorable for increased tropical cyclone activity, especially major hurricanes. If these changes are indeed taking place on decadal or multi-decadal scales rather than interannual scales, then the Atlantic basin may continue to see over the next decade or so, on the average, heightened activity on the order of what was seen in the 1950s and 60s rather than the suppressed activity of the 1970s and most of the 80s. What might be expected would be several years with very high activity, while most years would be close to average or slightly above average and only a few far below average. This would be dramatically different from the inactive decades when most years were below (often well below) average, some years were about average and very few years even just moderately above average. If the past holds the key to the future in this case, the overall increase would mean significant increases in the numbers of hurricanes affecting the Caribbean Sea and Maritime Canadian regions, basin-wide numbers of major hurricanes, and major hurricane landfalls affecting the east coast of the U.S.

The possible implications of these changes are staggering. The fact that major hurricanes have historically accounted for most of the damage and deaths due to tropical cyclones combined with the fact that there has been a dramatic population increase along hurricane-vulnerable coasts during the two inactive decades, add up to the potential for massive monetary loss, especially when major cities are impacted. In addition there is a potential for large loss of life in the case of an incomplete evacuation during a rapidly intensifying system.

There have been various studies investigating a possible impact, if any, on the number and strengths of Atlantic basin hurricanes *if* the earth experiences a long-term global warming. The results are inconclusive, with some studies documenting an increase while others suggest a decrease in associated activity. In addition, the historical multi-decadal scale variability in Atlantic hurricane activity is much greater than what could be "expected" at the present time from a small, gradual global temperature increase. It should be borne in mind that extrapolation, especially for decadal (and longer) time scales, certainly has a high level of uncertainty. One of the main difficulties in observing long-term fluctuations in tropical cyclone activity is that the reliable data extends back only about 50 years. Furthermore, increased activity during a particular year does not automatically mean increased storm-related damage. Even relatively inactive years can produce hurricane-spawned disasters. It is not how many systems develop in a particular year that determine the amount of damage, but how many systems actually impact land and where. Far more damage can been done by one major hurricane impacting a heavily populated area than by several major hurricanes hitting sparsely populated areas, or of course, not making landfall at all. It is still obvious, however, that active years have a greater overall *potential* for more regions to be impacted than inactive years.

CONCLUDING REMARKS

A very large amount of information on climate variability and climate change in the Atlantic Region was presented during the Symposium. These concluding remarks will concentrate on what directions work on climate change in the Atlantic Region should focus in the future.

It was obvious from the Symposium that virtually all aspects of life (including the economy) in the Atlantic Region are highly dependent on the climate which, even at present, is highly variable both in space and in time. Apart from any trends in the mean values of climatic variables, any possible increase in climatic variability due to an increase in atmospheric concentrations of greenhouse gases (including the frequency and severity of extreme events such as unseasonable frosts and thaws, hurricanes and storm surges) will have a profound effect upon the Region.

Research will in all likelihood result in improved estimates of the impact of climate caused by increasing concentrations of greenhouse gases, but reliable predictions of climatic change on a regional scale are still some time away. In addition, even if large reductions in the emissions of greenhouse gases were to take place now, there might still be changes in climatic means and variability because of the inertia of the ocean-earth-atmosphere system. Therefore, it would be prudent to assume that the management and use within the next several decades of natural and man-made resources such as forests, agriculture and coastal structures may have to be carried out in the face of climatic uncertainty.

In the closing panel discussion at the Symposium, the participants (including the audience) made it clear that they felt that, while the development of climate models with better regional resolution needed to proceed, the vulnerability of ecosystems to climate change should be a priority for the Canada Country Study. Of all the potential effects of climate change, we know least about how ecosystems may respond. This same view was expressed in 1995 at the symposium *Science and Policy Implications of Atmospheric Issues in Atlantic Canada* [2] in connection with climatic change. In answer to the question: "What aspects of climatic change are of greatest importance in the Atlantic Region?" the 1995 workshop replied:

> **Despite the uncertainty in the projections of climatic change in the Atlantic Region, it is important to have an estimate of the sensitivity of Atlantic Canada resources to climatic changes in either direction. Such resources include agriculture, forests, wildlife, the fishery, coastal infrastructure, transportation, tourism and the human population.**

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[2] R.W. Shaw (Ed.), 1996: *Science and Policy Implications of Atmospheric Issues in Atlantic Canada: Workshop Proceedings.* Environment Canada - Atlantic Region Occasional Report No. 6, 143 pp. Available from Environmental Conservation Branch, Environment Canada - Atlantic Region, P.O. Box 1590, Sackville, New Brunswick E0A 3C0, Canada.

To the question: " What activities are needed to achieve these results[3]?", the 1995 workshop replied:

> **Formation of an interdisciplinary and multisectoral (public, private, academia) group to develop a matrix of sensitivity of various components of the environment of the Atlantic Region to climatic change. One dimension of the matrix would be the aspect of the resource (using indicators such as freshwater availability or forest biodiversity); the other would be climatic variables such as temperature, precipitation, frequency of sea level rise or storm surges. This activity would make use of existing information, ecosystem studies and modelling results.**

The above conclusions of the 1995 symposium could apply just as well to the 1996 Symposium on Climate Variability and Climate Change, judging from the discussion at the closing panel discussion that was reported in Chapter 10 of these Proceedings. It is obvious that an assessment of regional sensitivity to climate change will be an interdisciplinary effort. Furthermore, the importance of data cannot be over-emphasized. While it is important to make the observing networks as efficient as possible, it is important to leave future generations a sufficient legacy of data. so as to not restrict their ability to address questions of importance to them. *We cannot look at a replay if we have not made the tape!* In 1997, we may not be able to perceive the ways in which the data will be used. There was a certain amount of dismay expressed at the Symposium at the closure of climate stations, and the cost-recovery policy being applied to information that was initially collected at taxpayers' expense. There is a danger of the privatization of data which could reduce accessibility.

Finally, it is important that the public be kept involved in climate work in the Atlantic Region through lectures and devices such as Environment Canada's Climate Exchange website on the Internet. It is through better communication with the public, including an appeal to the economic aspects of climate change (such as higher insurance premiums for extreme events), that incentives will be created to change people's behaviour and reduce the chance (albeit still incompletely known) of climatic trends and increases in climatic variability in a region which is already so sensitive to climate.

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[3] Editor's note: "results" meaning an estimate of the Atlantic region's sensitivity to climate change and variability.

1. CONTEXT AND PURPOSE OF THE SYMPOSIUM

The symposium *Climate Change and Climate Variability* was held in Halifax, Nova Scotia on 3-6 December 1996. Its purpose was to summarize the current state of knowledge in the Atlantic Region with respect to various aspects of climatic change. The results of the workshop will be used as a contribution to the Atlantic Regional input to the *Canada Country Study*. As stated in B. Maxwell's paper (Appendix C, Page 145), the *Canada Country Study* was envisaged as being a two-phase study. Phase I which would start immediately and conclude in late autumn 1997. It would have as its objectives:

- Preparation of an integrated assessment of present knowledge concerning the impacts of climate variability and change on Canada and adaptive responses, and
- Identification of gaps in knowledge and the suggestion of priority areas where new knowledge is most urgently needed

Phase II would be the research phase which would address the gaps and priorities identified in Phase I. Planning on it would begin in late 1997/98 with actual research being initiated in 1998/99 and continuing for approximately five years. (A more detailed description of the Canada Country Study will be given in Chapter 2, Overview, of these proceedings and in the paper by B. Maxwell in Appendix C.)

There were 181 participants registered at the symposium, drawn from the governmental, academic, industrial and private sectors with an interest in different aspects of climatic change: meteorology, oceanography, fisheries, geology, agriculture and forestry, among others. A list of registrants is give in Appendix B.

Appendix A shows the program for the symposium. After the initial overview session, the sessions were arranged according to various aspects of climate variability and change: climatology, oceanography, agriculture, etc. The symposium ended with a panel discussion on gaps, priorities and next steps in climate research. There was also a concurrent poster session.

This report is organized following the pattern of the symposium program. With the exception of Chapter 2 on the Overview session and Chapter 10 on the panel discussion, Chapters 3 to 9 are each broken into two parts dealing with each session: 1) a synthesis paper on the topic by a regional expert and 2) a summary of the other papers that were presented at the session, and the ensuing discussion. Many authors (including poster presenters) submitted extended abstracts of their presentations; these may be found in Appendices C to L, and are referenced in the text.

Finally, Chapter 11 will summarize the symposium and the recommendations resulting from the presentations and discussions.

2. OVERVIEW

Summary of the Opening Overview Session

by

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OVERVIEW OF INTERNATIONAL SCIENTIFIC EVIDENCE AND POLICY

An overview of the scientific evidence and policy implications of climate change, as summarized in the 1995 second assessment report of the Intergovernmental Panel on Climate Change (IPCC), was presented by Jim Bruce. Key scientific findings show that humans are having an effect on climate: the increase in greenhouse gases from fossil fuel combustion is changing the radiative forcing of the Earth, and thus driving climate change. Documented trends in Canada's climate include warming in central and western Canada, cooling in Atlantic Canada, and increasingly frequent storms that result in greater annual precipitation.

A major insight from the IPPC study is that, without intervention, climate change will occur and have far-reaching effects. Projected impacts include an increase in human health problems, illness, and death due to increased heat, extreme events (natural disasters), vector borne diseases, and changes in the distribution of tropical diseases. In the last decade, economic losses due to extreme events (storms, floods, and droughts) have increased dramatically. Death rates and damage to property will continue to climb, as flooding increases and sea level rises, especially with more people inhabiting coastal areas.

The causes and impacts of climate change involve significant inequalities between the developed and developing countries. Developed countries have the higher levels of emissions, but it is the developing countries that will be more negatively affected. The estimated costs of a 2.5°C warming, 1-1.5% GDP for the developed countries, jumps to 2-9% GDP for the developing countries. Vulnerability to climate change, as measured by ability to adapt to change and expected level of impact, are twice as high for developing countries and three times higher for small, developing island states than for developed countries.

The goals of the IPCC are to decrease greenhouse gas emissions by changing the economics of energy consumption and finding alternative energy sources. Possible scenarios range from no regrets, which would achieve a reduction in global emissions of 4-18% at little or no cost, to environmental double dividends, which would achieve the greatest reduction in emissions at the highest economic costs, but would be accompanied by many health and environmental benefits associated with reduced atmospheric pollution.

Canada is a particularly energy-inefficient country that has made little progress towards meeting its international obligations. The United Nations Framework Convention on Climate Change requires stabilizing the concentration of greenhouse gases at 350-700 ppm, requiring a 50% decrease in emissions. Canada is far from accomplishing its commitment towards this goal. Because the transport sector is the major contributor to our problem, more energy efficient vehicles and reduced operation of vehicles are urgently needed. Achieving large reductions in greenhouse gas emissions will require a higher level of cooperation among government, industry, academia, and the public, and ultimately, fundamental changes in the behaviour of Canadians.

THE CANADA COUNTRY STUDY

An overview of the Canada Country Study (CCS), an integrated study of climate change and its effects, was presented by Barrie Maxwell. (The full text of his paper may be found in Appendix C, Page 145.) Climate change research and impact assessment in Canada has developed over the past 15 years from studies focused on single sectors or components (e.g. sea ice, permafrost, wildlife movement, agriculture) to studies of integrated impacts (e.g. Mackenzie Basin and St. Lawrence River). The CCS is taking an integrated approach to examining the potential impact of climate change on the country as a whole, as well as on specific regions and sectors. Important issues to be addressed include the counterbalance between positive and negative effects of a changing climate, and possible ways to react, i.e. adapt our activities to mitigate the impacts of climate change.

The objective of Phase I of the CCS is to prepare an integrated assessment of present knowledge concerning climate change This information will be summarized in separate documents for each region (Pacific/Yukon, Prairie, Ontario, Quebec, Atlantic, and Arctic). In addition, one document will be devoted to the various sectors (agriculture, the built environment, fisheries, forestry, health, insurance industry, recreation and tourism, transportation, natural ecosystems, wildlife and biodiversity, water resources, and wetlands), and another to cross-cutting issues (changing landscapes, atmospheric issues, domestic trade and commerce, extra-territorial influences, extreme events, sustainability, and the subsistence economy vs. the wage economy). The final product suite will include regional and national plain language summaries. Phase II, which will address gaps and priorities, has a time frame of five years, but as yet no funding.

The results of this symposium will form the groundwork for the Atlantic Region portion of the CCS and serve to identify gaps and priorities most relevant to Atlantic Canada.

OVERVIEW OF CLIMATOLOGY

The scientific basis for concern over climate change, as summarized by the IPCC study, was presented by Pamela Kertland. Climate change has been documented and the increase in greenhouse gases (CO_2, CH_4, NOx) is the primary cause. As concluded in the IPCC report, "The balance of evidence suggests that there is a discernible human influence on global climate." Human activity has caused an increase in greenhouse gases over time; paleontological data show that atmospheric concentrations of greenhouse gases are now higher than at any time in the past 220,000 years.

The risks are significant and provide the rationale for action beyond "no-regrets." Even if we stabilize CO_2 emissions at year 2000 levels, climate will continue to change. The magnitude and distribution of change is uncertain, however, as changes in climate are not evenly distributed across the globe or seasons. For example, in Canada, temperatures increased in the west, especially in winter, while decreasing in the east. Greatest risks, however, appear to be associated with changes in the frequency and intensity of extreme events.

Global Circulation Models (GCMs) simulate changes in CO_2 and aerosols in the atmosphere in order to develop climate change scenarios. Results of simulations include differential warming across latitudes and centres of continents, changing patterns in precipitation, and rising sea level. Interestingly, these models do not predict the cooling observed in the Atlantic region, in part because they use a wide-spaced grid to model large-scale changes. Other improvements needed are the capability to model the physics of clouds and the detailed characteristics of ocean currents.

An overview of the climate of Atlantic Canada was presented by Teresa Caravan. (Her synthesis paper may be found on Page 11.) Large-scale influences on our climate include atmospheric circulation patterns, ocean currents, storm tracks, sea ice, and sea-surface temperatures: This region is influenced by prevailing westerlies (uneven heating of the surface causes air deflection to the east at 30ƒN) and series of high and low pressure systems. Warm (Gulf Stream) and cold (Labrador) ocean currents influence the region while their associated warm and cold air masses interact and create storms. Furthermore, the region is located along a major storm pathway extending from Cape Hatteras to the British Isles. In winter, the Gulf of St. Lawrence freezes over, making the climate of NB more continental than it would be otherwise. Sea surface temperatures are much cooler in winter (1-3°C) than in summer (16°C).

The Atlantic provinces fall into two world climate zones: (1) The Moist Continental Zone (NS, NB, PEI) has a large annual temperature range, with warm summers, cold winters, and ample precipitation that peaks in the summer. (2) The Boreal Forest Zone (NF, Labrador) has greater annual temperature ranges, short cold summers, long cold winters, and low annual precipitation with a summer peak. No location fits these descriptions perfectly, however, and climate varies with latitude, proximity to coasts, ocean currents, sea ice, etc. (e.g. the most severe climate records are for St. John's, NF).

Temperature and precipitation provide an incomplete picture of this region's climate. Storms, wind, and fog may be more localized but nonetheless important features of the Maritime climate. Winds are typically higher in winter and at coastal sites, but the highest winds are those associated with storms. The high precipitation of this region is largely due to storms, including tropical storms. Most of the Atlantic region experiences 30-60 days of fog (150 days in some parts of Newfoundland).

Sources of climate information include books (e.g. The Climate of Canada), atlases, State of the Environment reports, tourism-recreation guides, workshop proceedings (e.g. Climate and Weather of Newfoundland and Labrador), government documents (e.g. Canadian Climate Normals), and Meteorological Abstracts (e.g. those published in the 1990's). Much information is also available on the internet, such as the websites of Environment Canada and NOAA.

OBSERVING CLIMATE CHANGE

The rationalization of the national climate monitoring network, in particular its atmospheric monitoring capability, was described by Carr MacLeod. Faced with a budget decrease of $1.2 million, Environment Canada initiated a consultation and review to determine what climate information was needed and which existing stations could provide that information. Priorities included detection of climate change and variability, climate change and atmospheric deposition and impacts, international and provincial commitments, monitoring the climates of Canada, and weather forecasting. Budget reductions were achieved by closing 250 stations (half were of poor quality, half were in over-represented ecozones, the Boreal Plains and Mixed Wood Plains), increasing operational efficiencies, and decreasing data processing and quality assurance.

Climate change and variability monitoring across the 15 ecozones requires a minimum of 2000 stations. Weather forecasting requires a less dense network that reports more frequently than a climate network. It presently includes 581 automated SCRIBE stations (405 over land), 234 synoptic (primary) stations, and 50 hourly and 35 daily recording (secondary) stations. International agreements require, for example, 69 stations for the Global Climate Observing System (GCOS), 23 stations for the Columbia Treaty, 37 stations for Lake of the Woods). National research networks involved in Climate Change and Atmospheric Deposition Impact monitoring include the AEP, Reference Hydrometric Basin Network (172 basins), GEWEX, CAPMoN, National Ecological Monitoring and Assessment Network (EMAN; 72 stations at tentative research cooperatives).

The review process determined that a total 1,337 stations are needed to address specific requirements, and 600 more are needed to address broader requirements. This leaves a climate detection network of about 2000 stations, although Environment Canada would like to increase the total to 2200 stations. The idea is to build upon the present Reference Climate Change Network (254 stations) by amalgamating with the Historical Canadian Climate Database Network (131 stations). The result is a core of 300 key stations which would be maintained into the future, automating systems a timely fashion. This network would be supplemented by satellite stations that met specific criteria (i.e., within 50 km radius, >14 years in service).

The status of the Climate Change Network is that it is sparse and declining. Stations have decreased steadily from a peak of 2915 stations in 1991 to 2483 stations in 1996. A similar trend has occurred with the Supplementation Observation Networks (which monitor snow depth, ice coverage), but over a shorter period of time. One problem that remains is a lack of northern stations. The next step is to involve other government departments to extend the network, and to involve the Climate Advisory Committee to discuss further requirements for monitoring climate change.

An overview of the Global Ocean Observing System (GOOS) was presented by George Needler. Climate change is a global phenomenon and thus a system for obtaining large-scale measurements is crucial. Needed are regular, long-term, systematic, and cost-effective ocean measurements that are relevant to global climate systems and subject to continuous examination. Canada has a tradition of offshore measurements for research (e.g. Labrador Sea and Grand Banks) that could be continued as part of an oceans monitoring system.

GOOS has formulated a conceptual design of a long-term systematic observation system to monitor, describe, and understand the physical and biogeochemical processes that determine ocean circulation." Monitoring priorities include sea surface temperature (SST) and sea surface salinity (SSS), as data are especially lacking for the southern hemisphere; wind and wind stress, as this drives the ocean currents; El Nino Southern Oscillation (ENSO), as this can be predicted by the models; and sea level change, for which 50-60 stations globally require precision altimeters and tide gauges. Other measurements include: heat and freshwater flux, surface carbon fluxes, sea ice, upper ocean monitoring, ocean circulation and transport, and global inventories of heat, freshwater, and carbon. The global climate module of GOOS cuts across terrestrial, atmospheric, and cryosphere systems, and includes monitoring of the coastal zone, the health of oceans, marine services, and living marine resources.

Like most countries, Canada essentially lacks offshore observing systems. International efforts are focusing on the establishment of global monitoring networks such as the Global Climate Observing System (GCOS), the Global Terrestrial Observing System, (GTOS), and the Global Oceans Observing System (GOOS). These systems are sponsored by the United Nations (WMO, UNESCO, UNEP) but rely on the countries themselves to develop the monitoring capability and make the observations. It is clearly in Canada's interest to contribute to global climate and ocean monitoring systems.

OVERVIEW OF SOME POSSIBLE IMPACTS OF CLIMATE CHANGE

Socio-economic

A socio-economic overview of Atlantic Canada, with an emphasis on industries that are likely to be impacted by climate change, was presented by David Sawyer.(His paper may be found in Appendix C, Page 163.) Indicators of the socio-economic state of a region include the size of its population and labour force, its unemployment rate, and its per capita GDP. Unemployment rates for all Atlantic provinces are well above the Canadian average of 9.5%, with NB lowest at 11.5% and Newfoundland and Labrador highest at 18.3%. NB has the highest per capita GDP ($20,833) and Newfoundland and Labrador the lowest ($17,319), but all fall below the Canadian average of $26,347. NS has the largest population and labour force, PEI the smallest. Reliance is most heavy in NF and Labrador on fisheries(12.3% employment), in PEI on agriculture (10.4%), and in NB on forest and forest products (5.2%). Because of income and employment disparities, among provinces within the Maritimes as well as relative to Canada as a whole, climate change will have different effects on different regions and different provinces within the Atlantic Region.

The structure of an economy is based on the types of industry in a region. In goods-producing industries, the Atlantic provinces fall below the Canadian average (34.3% of the workforce), with the highest percent in NB (31.0%) and the lowest in Newfoundland and Labrador (26.2%). In comparison to the rest of Canada, the economy of the Atlantic provinces is more dependent on primary industries (agriculture, fisheries, and forestry) and associated services (processing of food, fish, and forest products). In the Maritimes, the percent of the workforce employed in these industries is well above the Canadian average of 7.2% (in NF and Labrador 16.5%, PEI 21.1%, NS 10.2%, NB 12.9%). Furthermore, the primary industries are especially important in rural areas and have a pervasive economic influence as seen in manufacturing trends. The significance is that the Atlantic Region economy is especially vulnerable to climate change, as primary industries depend on living resources.

Industry

An assessment of the potential impacts of climate change on industry was given by Robert Boutilier, with an emphasis on electrical energy. Climate change is of interest to a utility because it is necessary to plan for electricity, as it cannot be stored long-term. The utility must have sufficient capacity and availability to meet the demand at any one time; capacity is cost-intensive. Influences on load include the number and type of customer (e.g. in NS, 40% of energy use is residential, 30% commercial, 30% industrial), the number and type of end-uses, behavioural variances (how equipment is used, and how that might change), and external variances (e.g. economy, climate). Climate-sensitive loads include air conditioning, dehumidification, space heating (in NS, 210 days/year require heating); lighting (influenced by cloudy conditions), refrigeration, and cocoon effects (i.e. increased use of appliances during inclement weather).

Accurate forecasts are needed to plan properly. For example, an average increase of 1 degree C could lead to a reduction in space heating by 5%. The main factors to consider in forecasts are peak demands and energy requirements. Planning at an electrical utility is complex and must be done at a variety of time scales. Long-term (2-25 years) planning requires knowledge of the annual peak and annual energy requirements in order to plan for generation and transmission capacity and system design. Medium-term (1-24 months) planning requires knowledge of the monthly peak and energy requirements in order to plan for fuel and unit scheduling and plant maintenance. Short-term (next hour-next week) planning requires knowledge of the hourly demand to plan for efficient operation of the plant and for allocation of resources, especially for storm management.

Changes in the frequency or intensity of storms would clearly influence operations at a utility. Severe weather is important in short term decisions (resource scheduling and materials planning) as well as long term decisions (physical system design, transmission, distribution, power flow, stability and structures). The industry would benefit from long-term climate information as well as accurate and timely weather forecasts. Utilities need to continue to encourage energy efficiency, explore demand and supply technologies, and improve sensitivity analysis.

Transportation

The impacts of climate change on transportation policy and practices was discussed by John Pierce from Transport 2000, a pro-active organization that focuses on ways to lower greenhouse gas emissions by the transportation sector.(Pierce's paper may be found in Appendix C, Page 150) Of energy used in NS in 1989, 39% was used for transportation, as compared to 27% for residential use, and 17% for both agricultural, industrial, commercial and institutional uses. More than half (54%) of our petroleum is used in transportation. Alternatives for fueling vehicles are few, and even with very high energy efficiency we cannot eliminate CO_2 emissions--the transportation sector cannot be stopped, only changed.

Two obvious solutions are to shift as much travel as possible from air and car to bus and train, and to transport heavy products by rail instead of truck. A 10% shift from car to bus or rail would more than double traffic by these carriers and lead to more frequent and efficient travel and more attractive schedules. Trains and buses are almost three times more fuel-efficient than small cars. Efficiency increases more dramatically when considering the number of older and larger cars in use, and that cars carry, on average, only 1.5 people. We perceive that cars are increasing in efficiency, but this is slowing and does not outweigh the increases in vehicle registration and new licenses. The efficiency of trucks for hauling freight is much lower than that of rail transport of goods. A steel wheel on a steel rail of 1% grades gives, on average, a 3:1 advantage in fuel efficiency over tires on pavement of 5-10% grades. Despite these facts we tend to travel by the least energy efficient means (air for long distances, car for short-to-medium distances) and ship our products in the least efficient manner (truck 79% vs. rail 20%). The high subsidies for highways and highway travel and low subsidies for rails are in part responsible for this situation.

The effects of climate change on transportation will likely include both the positive (e.g. less ice and snow on roads, less ice in the Gulf of St. Lawrence, higher ocean levels allowing bigger ships to dock in ports, and improved conditions for shipping at Montreal and US east coast ports) and the negative (e.g. more snow in the eastern Maritimes and western NF due to an open gulf, more icebergs and hurricanes to threaten oil barges, and less traffic at ports in Atlantic Canada). In contrast, the effects of transportation on climate change are clearly negative but can be mitigated by a change in our travel behaviour. At work we receive free parking, but not free public transport passes. Our infrastructure is based on roads, and subsidies flow into highway construction when in reality the external cost of roads is >2 cents /tonne/km from a truck and only 0.5 cents for a train. Solutions include green taxes on fuel, higher parking fees and fewer parking spaces, encouraging efficiency through taxes, incentives and rebates, construction or designation of special bus and bike lanes, more support for public transportation, compact communities, full cost accounting, and integrated transportation policy.

CLOSING REMARKS

The first day's proceedings closed with a philosophical examination of the northern ("winter") cities by Sandy Robertson (see Appendix C, Page 157).Climate and weather affect everyone, especially those who live in north-temperate cities and experience winter in its full force. The northern cities that are most adapted to their climate were either built before electricity or have been designed with winter in mind. For example, instead of shutting out winter, their rooms and windows are concentrated on the south side, facing the sunlight; trees shelter houses and parks from wind, and block snow drifts; and festivals celebrate winter. By designing our cities, their buildings and transportation systems, and arranging our work, residential and recreational areas and activities with climate foremost in our minds, we can create cities that are not only functional and aesthetically pleasing but less susceptible to the impacts of climate change and variability.

3. CLIMATOLOGY

3.1: Synthesis paper

Climate of the Atlantic Region

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ABSTRACT

Knowledge of the present climate of the Atlantic Region, its variability over past decades and current trends enhances understanding of the impact of global warming on this district. Global atmospheric circulation patterns, ocean currents and sea ice extent are major influences on the current climate of this region due to its location on the eastern edge of North America. Local topography and sea surface temperature contribute to differences in climate within the region.

Temperature and precipitation measurements are most frequently used to describe the climate of a location. Additional data including air pressure, wind velocity, humidity, sunshine and cloudiness give more complete information.

Descriptions of the climate of the Atlantic Region can be found in several publications and in a number of government documents. Fewer detailed investigations of particular topics are available for this region.

LARGE SCALE INFLUENCES ON ATLANTIC CANADA'S CLIMATE

On a global scale, the Atlantic Region lies within the zone of prevailing westerly winds. This zone is characterized by the passage of a series of high and low pressure systems. Paths taken by these systems are further influenced by ocean currents and continental topography.

In the northern hemisphere, areas of low pressure develop when cold dry air originating over Northern Canada drifts southeastward and encounters warm moist air moving poleward from the Caribbean Sea. These systems are more intense during the winter months when differences in air mass temperatures are greater. Analyses of previous storm tracks reveal that many of these systems affect the Atlantic Region. Significant temperature differences in air masses affecting the district explain the large annual temperature ranges recorded at observing sites. An abundant supply of precipitation annually can be attributed to these storms with additional contributions from tropical storms and local convective activity in some areas.

EFFECTS OF THE NEARBY ATLANTIC OCEAN

Sea ice gradually spreads southward along the coast of Labrador, eastern Newfoundland, the Gulf of St. Lawrence and Cabot Strait during the winter months while unfrozen waters to the south provide a heat source for Nova Scotia and southern New Brunswick.

As the ice retreats in the spring, sea surface temperatures gradually increase, particularly in the Gulf of St. Lawrence. An exception is the eastern extremity of the Gulf which is influenced by the cold Labrador Current. This current maintains cool sea surface temperatures along the eastern coasts of Labrador and Newfoundland and has some effect on waters to the south of Nova Scotia. Warmer waters of the Gulf Stream extend farther northward during the summer months modifying surface temperatures south of Nova Scotia. Coastal cooling is less pronounced in areas adjacent to warmer waters of the Gulf of St. Lawrence than elsewhere in the region during the summer.

In addition to sea ice and ocean currents, high tides of the Bay of Fundy cause deeper water to be mixed with surface water maintaining relatively cool surface water temperatures in summer and warm temperatures in winter. (Dzikowski *et al.*, 1984).

Onshore winds produce a moderating effect on the climate of adjacent land areas throughout the year.

WORLD CLIMATE ZONES: CLASSIFYING THE ATLANTIC REGION

Daily temperature and precipitation measurements are taken at most stations belonging to the climate network. These values, as well as other factors such as vegetation, have been used to classify areas of the world into climatic zones. Strahler and Strahler [1994] describe Nova Scotia, Prince Edward Island and Southern New Brunswick as having a moist continental climate while Northern New Brunswick, Newfoundland and Labrador are classified within the boreal forest climate zone. The tundra climate covering much of Northern Canada includes the northerly tip of Labrador.

Goose Airport, Labrador, selected to represent the boreal forest climate zone, displays most characteristics of this zone including a large annual temperature range, short summer, long cold winter and a peak in precipitation during the summer. However, its annual precipitation amount is ample unlike other sites within this zone.

Because the world is represented by only 13 climate zones, these zones must ignore local discrepancies. For instance, an inland site for the Maritime Provinces (Fredericton, New Brunswick) was selected to represent a moist continental climate. Although Fredericton does display a large annual temperature range, its precipitation amounts are lower in summer than in winter, contrary to the definition given for this zone. Hence, further refinement of global classifications by analyses of regional data is required.

REGIONAL CLIMATE RECORDS

In accordance with international standards, the most recent set of 30 year normals published by the Canadian government for stations in the country having 20 years or more data is for the period of 1961-90. In addition to 30 year means, extreme values are given for the period of record for each station. Temperature and precipitation records are available for most sites. Although measured at fewer locations, records of air pressure, wind velocity, solar radiation, sunshine, cloudiness, fog, humidity, visibility and thunderstorms provide useful information for describing the climate more completely. Due to space limitations, these elements are not discussed here.

Temperature

During the winter season, warmest average temperatures are found in southwestern Nova Scotia and the Avalon Peninsula, Newfoundland with mean temperatures dipping a few degrees below freezing. Remaining areas of Newfoundland and Nova Scotia, plus Prince Edward Island and southern New Brunswick, are the next warmest followed by northern New Brunswick and southeastern Labrador. Labrador's northerly latitude contributes to its having the coldest temperatures in the region with means near minus 20°C inland.

Significant warming is reported during the summer months in the Atlantic Region. Central New Brunswick has the highest temperatures with means near 20°C followed by the rest of the Maritimes and central Newfoundland. Newfoundland's south coast, Avalon Peninsula and Northern Peninsula are the next warmest areas followed by Labrador. Areas in central Labrador have daytime maximums higher than coastal Newfoundland but nighttime minimums are cooler.

Precipitation

Frequent low pressure systems combined with an ocean nearby bring a generous supply of precipitation to the Atlantic Provinces. Southeast winds accompanying a storm pick up moisture from the sea giving southern coasts of Newfoundland (over 1700 mm) and Nova Scotia, plus the Fundy shore of New Brunswick, the greatest amounts of precipitation annually. Northern Newfoundland, northern Nova Scotia, Prince Edward Island and much of New Brunswick receive lesser amounts (but still in excess of 1000 mm).

Areas to the lee of higher terrain in northern New Brunswick and central Labrador receive greater amounts of precipitation during the summer months than in winter.

Although precipitation is almost exclusively liquid throughout the summer months in the region, rain, freezing rain and snow are common during the winter in southern areas. In fact, more rain than snow (i.e., water equivalent) occurs on average along the southern coasts of Newfoundland and Nova Scotia in the winter.

LITERATURE REVIEW

Descriptions of the climate of the Atlantic Region can be found in a few atlases and other books. Additional information is available in a number of workshop proceedings, government documents and occasionally in master's theses which usually focus on a particular location and topic. A review of the Meteorological and Geoastrophysical Abstracts for 1990 to September 1996 revealed that only two articles were published in the refereed journals included in this grouping that focused specifically on climatological studies within the Atlantic region. The number of publications increases when the search is expanded to include topics in the region such as agriculture, forestry and fisheries that use climatological data.

Workshop proceedings and government documents include a few studies that have been done using long-term data from specific sites in this region to determine trends. Results of such studies give some indication of actual changes occurring in the region and provide useful comparisons with sophisticated model predictions. Further study using additional long-term monitoring data could prove useful in answering many of the questions associated with the climate change issue in the Atlantic Region.

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3.2: Summary of other presentations and discussions on climatology

There were two papers that dealt with a comparison of regional climatic change with that occurring in the rest of Canada and worldwide. P. Lewis (Appendix D, Page 180) using data from 131 sites across Canada, found that, although there was a worldwide warming trend of 0.3 to 0.6C, and a similar warming of 1.1C in Canada overall, the Atlantic Region has shown a warming trend from 1985 to the mid 1950s, followed by a cooling trend into the 1990s. During the period 1948-1995, Atlantic Canada had shown a marked cooling of 0.7C with season trends as follows: winter (-2.2°C); spring (0.0°C); summer (+0.5°C); and autumn (-0.8°C). In the Maritime provinces during the period 1945-1993, Lewis found a increase in the mean daily minimum temperature of 0.3C, but a *decrease* in the daily maximum of 0.8C. Trends in precipitation were more difficult to determine; across Canada there has been an increase from 1948 to the mid 1980s, and a decrease thereafter. In contrast, Atlantic Canada has had an increase in precipitation amount since 1948. Lewis reported that cloud cover in the Atlantic Region had appeared to increase by 1% since 1953, but this change was not statistically significant. Lewis also reported: a decreasing trend in the number of days per year with a maximum temperature above 25°C; 2) an increasing trend in the number of days per year with a minimum temperature below -15°C; 3) an increasing trend in the number of daily precipitation events above 20mm and; 4) a very slightly increasing trend in the number of daily snowfall events above 15cm.

In response to questions, Lewis suggested that a possible reason for the difference between climatic trends in the Atlantic Region and the rest of Canada is that the warming effect of greenhouse gases might be overcome (at least temporarily) by the cooling effect of aerosols from upwind source regions. Lewis also stared that calculated trends will depend very much on the starting year for the time series, and that the spatial resolution of Global Circulation Models (GCMs) is still too coarse to reliably predict regional climatic change, although that situation might change in the not-too-distant future.

The paper by R. Morgan and R. Pocklington (Appendix D, Page 184) supported that of Lewis in that it concluded that, following an analysis of data between 1900 and 1995, the climate has been cooling since about 1950. They found that the temperature for Atlantic Canada, as well as the east coast of North America from Labrador to the Gulf of Mexico, may be resolved into quasi-decadal trends. By examining heating degree days (mean temperature < 18C) and cooling degree days (mean temperature >25C), they concluded that there has been an increase in demand for heating energy to off-set the regional cooling. The number of growing degree days (mean temperature > 5C) have remained fairly constant, however.

Morgan and Pockington concluded that the term “global warming” was misleading and should be discouraged. Proxy data (from ice cores, tree rings, isotope analysis, etc.) indicate that there have been three trends of about 200 years periodicity that have occurred during this millennium, with temperature rises that have been just as dramatic as those being experienced presently. This would indicate that there may be contributors to climatic change other than greenhouse gases that may be negating the warming effect, at least temporarily. These other factors accompanying increases in

CO_2, such as aerosols and acidic precipitation, have their own detrimental effects which should not be ignored.

In their poster presentation, R. Pocklington and R. Morgan (Appendix L, Page 329) examine in more detail the apparent cooling in the Atlantic Region during the latter half of this century. Their paper contains time series of temperature trends at a number of stations in the North Atlantic region. The authors conclude that surface air temperatures around the northern North Atlantic are currently close to (or below) their long-term means, and below the values reached in the warmest decades of this century. In northwest Europe, the warmest decade in the record at a majority of long-term stations came before the 1990s, in many cases before this century. They maintain that the thesis of global warming is poorly supported by their analysis of time-series of surface air temperatures in the North Atlantic region.

Several papers dealt with the linkages between climatic change, large scale atmospheric indicators, and other aspects of the environment such as ice. A. Shabbar postulated that much of the variability in the surface air temperature in a region including Greenland, Labrador and the Atlantic coat could be explained by the circulation around the Canadian Polar Trough at a pressure level of 50 kPa., as expressed by the Baffin West Atlantic (BWA) Index. The BWA Index was related to the temperature with a correlation coefficient of 0.85. Shabbar reported that he had detected two distinct periods of temperature change during the period 1945-1995: one before 1970 and one afterward. The difference was statistically significant and the nature of the variability was different in the two periods: interannual before 1970 and decadal after 1970. The cause is as yet unknown; Shabbar suggested that the answer may lie in the ocean.

Two papers discussed the connection between regional climatic change and the North Atlantic Oscillation (NAO), defined as the pressure difference between the Icelandic Low and the Azores High during the months of December, January and February. B. Topliss (Appendix D, Page 208) examined the linkage between the NAO and climatic variability in North America and Europe through the use of spatial probability maps. These maps were constructed from the correlation between gridded air temperature anomolies and the NAO Index. Generally speaking, Labrador and eastern Greenland will have a negative correlation to the NAO; those in the Mediterranean and Northern Africa will have a positive correlation. There are certain regions, including Nova Scotia on the North American side, sandwiched between these areas of positive and negative correlation. Topliss found that the normal NAO correlation pattern with temperature was disrupted at the start of this century and during the third decade, due to temperature "jumps" and anomalous circulation patterns. For example, a strong westerly circulation in the 1920s brought on a warming in the waters off the United Kingdom, resulting in increase herring catches.

Topliss concluded by stating that some climatic process needs to be identified linking environmental signals in Europe, Atlantic Canada and the Black Sea, areas which lie between the positive and negative phases of the NAO correlation. She proposes a system which has the same annual variation as the NAO but which persists over the winter and spring seasons and may even have isolated residual effects in summer, namely an association with the period of hot, dry summers in the United Kingdom.

K. Drinkwater linked the North Atlantic Oscillation with fluctuations in air and sea water temperature, and windstress, off Newfoundland and Labrador. Drinkwater reported a negative correlation of 0.75 between the NAO and wind stress off Labrador; when the Icelandic Low is strong, there are strong northwesterly winds, large wind stress and low air temperatures.

S. Prinsenberg *et al* (Appendix D, Page 195) discussed the linkage between the North Atlantic Oscillation and sea ice cover. Water column conditions over shelf areas enhances ice conditions relative to those found offshore. Over the continental shelf, vertical water stratification associated with the low salinity water from the Arctic Ocean inhibits deepening of the surface layer. Cold air will cool the surface water layer to the freezing point initiating local ice growth by mid-December. Offshore in the Labrador sea, the less stratified waters continue to mix to deeper layers due to surface cooling so that the surface temperatures do not drop below 2 to 3°C and ice does not form. In January and February, the predominant strong northwesterly winds advect ice southwards faster than ice melts at the ice edge resulting in a southwards advancing ice edge. The pack ice reaches its most southernmost extent by mid-March and usually has a narrow tongue of ice extending eastward along the northern flank of the Grand Bank. By April, northwesterly winds decrease while the atmospheric heat flux increases. Ice starts to melt faster than it is advected southwards, resulting in a northwards retreating ice edge. By the end of June, the Newfoundland shelf is normally ice free.

During winters with high positive NAO indices, NW winds along the Labrador and Baffin Bay coasts increases causing severe ice conditions, for example, in the early 1970s and 1990s and the mid-1980s. However during some years, the strong winds do not reach as far south as the Newfoundland shelf even though abnormal low temperatures do occur causing severe ice conditions (i.e. mid-1980s. Prinsenberg stated that both winds and temperature effects are important since the NW winds and cold air temperatures are in phase. Prinsenberg concluded by stating that ice extent variability can be forecast to 80% of the variance two months in advance using wind and air temperatures.

B. Petrie discussed the factors affecting the temperature and salinity on the Scotian Shelf and the Gulf of Maine. He maintained that the Labrador Current was the major factor. The Labrador Current moves southward and splits by the Tail of the Grand Banks; some is entrained in the Gulf Stream and is advected towards Europe while the remainder travels westward toward the Scotian Shelf. It is joined by the outflow from the Gulf of St. Lawrence and travels down toward George's Bank and the Gulf of Maine. Petrie stated that one approach to examining climatic variability was to pick a site and observe the change with time of water temperature and salinity, as was done for Emerald Basin. The observations showed that there was a cooling and freshening from the 1950s to the mid-1960s, then a sharp warming and increase in salinity until the 1970s. Since then temperatures have remained at or above normal. Similar changes were observed on the Halifax Section and at Boothbay Harbor, Maine. These temporal changes could be linked to an increase in the strength of the Labrador Current in the early 1950s to mid-1960s, bringing in cooler and fresher water. This increase had also occurred in the mid-1930s and 1940s. During questions, Petrie expressed the opinion that the North Atlantic Oscillation was a bit overused in explaining climatic variability in coastal waters.

J. Bobanovic described his work with two hindcast models for predicting wind-driven currents on the Canadian Atlantic Shelf. He compared a large scale regional model (Cape Chidley to the Gulf of Maine) with a finer-scale model which focuses only on the Gulf of St. Lawrence. Both models were barotropic and linear, and they used depth-averaged temperatures with open, radiative boundaries. The models are driven by wind and pressure fields. Preliminary predictions of storm surge with the large scale model were reasonably good In response to questions, Bobanovic stated that the model does not include ice cover. Tidal information was removed from the model. It is intended to include free waves in the near future.

Climate researchers require access to long temporal datasets, updated continuously and collected on a broad regional or global scale. These data must have well documented quality standards and, in some cases, be limited by programme objectives to specific datasets and derived products. J. Gagnon (Appendix D, Page 173) described a data management model proposed for the Atlantic Coastal Zone Monitoring Programme, which makes use of the Internet to provide direct access to active collections and associated historical datasets, with the ability to share this information globally. Gagnon also presented an overview of three active databases managed by the Marine Environmental Data System (MEDS), which may be of interest to climate researchers in general. These are: 1) physical and chemical profile data; 2) tides and water level time series data and; 3) drifting buoy data.

In their poster presentation, C. Mason and B. Topliss (Appendix L, Page 321) described the use of weekly global 18 km gridded multichannel sea-surface temperatures (MCSST) derived from the daytime NOAA Advanced Very High Resolution Radiometer (AVHRR). These data are available from the Physical Oceanography Archive Center of the Jet Propulsion Laboratory. The data are available as a global set (2048x1024 pixels) and covers the period October 1981 to present. Each data file contains a weekly map of gridded SST with a spatial resolution approximately 18 km by 18 km at the equator. Time series of monthly temperature measurements have been obtained from the MCSST product and compared with the coincident ship measurements. There is no apparent difference between the two data sets. The authors intend to examine the night time MCSST data set to determine if the temperature measurements are as accurate as the day time values. There may be a problem with the night time values because there will be no data for cloud cover. If these values are useable, this may further increase the number of available measurements. It appears, however, that the MCSST data appears to constitute a time series of monthly temperature measurements for the Scotian Shelf which is equivalent in accuracy to the much smaller data set of ship measurements.

4. FISHERIES AND PLANKTON

4.1 Synthesis paper

Impacts of Climate Variability on Atlantic Canadian Fish and Shellfish Stocks

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INTRODUCTION

Frank *et al.* (1988, 1990) were the first to examine the response of fish and shellfish stocks in Atlantic Canada to possible climate change scenarios. Their approach was to use published relationships between environment and fish to predict the response of fish stocks to the possible atmospheric CO_2-induced climate changes in the physical oceanography of the northwest Atlantic region suggested by Wright *et al.* (1986). Frank and co-workers noted that lack of understanding of the linkages between environmental changes and fish stocks, and the dangers of extrapolating beyond the original conditions used to formulate such linkages, produced the largest uncertainty in forecasting the response to possible future climate changes. This statement continues to hold, although our understanding has increased and new linkages have been established. While GCMs (general circulation models) have improved in the years since the late 1980s, predictions of CO_2-induced climate change on a regionally basis are not yet considered to be reliable, including those for the Atlantic Region of Canada. In the absence of such regional climate change information, I have focused upon reviewing the major linkages between fisheries and the environment, providing examples of the fisheries response to past climate variations in Atlantic Canada. It includes several examples of linkages established since the Frank *et al.* (1990) study but is not intended to be a fully comprehensive review of environmental effects on fisheries, a job clearly beyond the scope of the present study.

Fish and shellfish respond directly to climate fluctuations as well as to changes in their biological environment (predators, prey, species interactions, disease) and to fishing pressures. While this multi-forcing sometimes makes it difficult to establish unequivocal linkages between changes in the physical environment and the response of fish or shellfish stocks, some effects are clear (see reviews by Cushing and Dickson, 1976; Bakun *et al.*, 1982; Cushing 1982; Sissenwine, 1984; Shepherd *et al.*, 1984; Sharp, 1987). These include affects on the growth and reproduction of individual fish, as well as the distribution and abundance of fish populations. Within this paper the term fish refers to both finfish (vertebrates) and shellfish (invertebrates) unless otherwise stated. The influence on abundance occurs principally through effects on recruitment (how many young survive long enough to potentially enter the fishery) but in some cases may also be due to direct mortality of adult fish. How does the environment affect fish? This occurs through four main processes; direct physiological effects, diseases, food and predators (Shepard *et al.* 1984). Physiological effects include those metabolic processes influenced by temperature and salinity. Fish often seek optimal temperature or salinity regimes or avoid sub-optimal conditions. Ocean climate changes can thus lead to distributional changes. If caught in sup-optimal conditions, performance is reduced leading to starvation or increased predation. Certain environmental conditions are more conducive to diseases than others. For example, warm waters can trigger disease outbreaks; likewise, cold temperatures can limit them. The environment affects feeding rates and competition, as well as the abundance, quality, size, timing, spatial distribution, and concentration of food. It also affects predation through influences on the abundance and distribution of predators.

Fish are influenced not only by temperature and salinity conditions but also by mixing and transport processes. For example, mixing can affect primary production through promoting nutrient replenishment of the surface layers and influence the encounter rate between larvae and prey organisms. Also, ichthyoplankton (fish eggs and larvae) can be dispersed by the currents, which may carry them into or away from areas of good food production, into or out of optimal temperature or salinity conditions, and perhaps ultimately determine whether they are lost to the original population. The remainder of the paper provides some examples of these effects within Atlantic Canadian waters.

ENVIRONMENT/FISHERIES LINKAGES: SOME EXAMPLES

Growth

Environmental conditions have a marked effect on the growth of many fish species. For example, mean bottom temperatures account for 90% of the observed (10-fold) difference in growth rates between different Atlantic cod (*Gadus morhua*) stocks in the North Atlantic (Brander, 1994, 1995). Warmer temperatures lead to faster growth rates. Regional studies have shown similar results (Fleming, 1960; Shackell *et al.*, 1995). In the northwest Atlantic, the largest cod are found on Georges Bank with a 4 year old fish being, on average, five times bigger than one off Labrador and Newfoundland. Temperature not only accounts for differences in growth rates between cod stocks but also year-to-year changes in growth rates within a stock. Thus, sea temperature declines since the mid-1980s are responsible for approximately 50% of the recent observed decrease in size-at-age of Atlantic cod on the northeastern Scotian Shelf (Campana, 1995) and off Newfoundland (de Cárdenas, 1996; Shelton *et al.*, 1996). This is particularly important given that 50-75% of the declines in the spawning stock biomass of the Newfoundland, Gulf of St. Lawrence and northeastern Scotian Shelf cod stocks during this period were caused by reduced weight-at-age (Sinclair, 1996). Fifty percent of the decline in recent years of weight-at-age of the 4 to 8 year old northern cod can be accounted for by the weight at age 3 indicating size at an early age affects future fish production (Krohn and Kerr, 1996). Since 1979, the weight of northern cod older than 4 years have been lower than expected based on predictions from weight at age 3 suggesting the growth environment for these older fish has also worsened (Krohn and Kerr, 1996).

Temperature-dependent growth rates are not restricted to cod. Cold bottom temperatures resulted in decreased growth rates of adult American plaice (*Hippoglossoides platessoides*) on the Grand Bank during the 1980s (Brodie, 1987), and reduced length-at-age and weight-at-age for ages 3 and 4 capelin (*Mallous villosus*) off Newfoundland during the 1990s have been shown to be a direct response to cold ocean temperatures (Nakashima, 1996). Fifty percent of the interannual variations of growth of herring (*Clupea harengus harengus*) ages 3-7 in St. Mary's and Placentia bays were accounted for by the March to December water temperatures (Winters *et al.*, 1986). Growth rates of larvae have also been found to be temperature dependent for many species in the northwest Atlantic including Atlantic cod, haddock (*Melanogrammus aeglefinus*) and winter flounder (*Pseudopleuronectes americanus*) (Morse, 1989).

Reduced growth rates at lower temperatures are, in part, due to changes in feeding rates. Laboratory experiments by McKenzie (1934, 1938) found that Atlantic cod from the Bay of Fundy and Scotian Shelf ate well at temperatures within their normal tolerance range but ceased feeding at very high (>17°C) or very low temperatures (<0°C). He also noted that at low temperatures cod had difficulty swallowing and the size of the food particles consumed decreased as the cod were unable to open their mouths as wide as in warmer water (McKenzie, 1938). Kohler (1964) found feeding rates for Atlantic cod increased with temperature over the range 4° to 13°C, a result consistent with that of McKenzie (1934, 1938). Reduced feeding with subsequent weight loss at low temperatures for adult American plaice from the Grand Banks has also been measured in the laboratory by Morgan (1992). Besides lower feeding rates, reduced growth may also arise through delayed spawning (see below), initially causing a short growing season, and subsequently smaller size latter in life.

Spawning and Reproduction

In addition to growth, the environment affects the reproductive cycle of fish and shellfish. For example, the age of sexually maturity of certain fish species is determined by ambient temperatures. Atlantic cod off Labrador and the northern Grand Banks mature at age 7 and in the northern Gulf of St. Lawrence and the eastern Scotian Shelf at age 6 while in the warmer waters off southwest Nova Scotia and on Georges Bank they mature at 3.5 and 2 years, respectively (Myers *et al.*, 1996a).

Spawning times too are influenced by temperature. Cold temperatures typically result in delayed spawning through slow gonad development as has been observed in Atlantic cod on the northern Grand Bank (Hutchings and Myers, 1994a). While warm temperatures promote gonad development resulting in earlier spawning, the relationship between temperature at the spawning site and time of spawning depends on local hydrography and fish distribution. In contrast to the positive relationship between local temperatures and time of spawning on the northern Grand Banks, cold temperatures lead to earlier spawning of cod off southern Newfoundland (Hutchings and Myers, 1994a). However, these fish reside in warm offshore waters and move onto St. Pierre Bank prior to spawning. In very cold years on the Bank, they appear to delay migration onto the Bank thereby remaining in the warm offshore waters longer, resulting in faster gonad development and an earlier readiness to spawn.

Temperature-dependent spawning again is not limited to cod. In the early 1990s, extremely low temperatures during spring off Newfoundland delayed capelin spawning by over a month which lead to slow growth rates and poor condition (Nakashima, 1996). Marak and Livingston (1970) found a 1.5° to 2°C temperature change produced a difference in spawning time of haddock on Georges Bank by a month with earlier spawning and a longer duration in warm years. From studies in the Baie des Chaleurs within the Gulf of St. Lawrence, spawning of the giant scallop (*Placopecten magellanicus*) has been shown to be associated with rapid temperature changes caused by wind-induced upwelling

(Bonardelli *et al.*, 1996). It therefore follows that interannual variations in timing of spawning likely depends upon wind forcing.

Miller *et al.* (1995) found that 52% and 70% of the seasonal variance of egg and larval size at hatch, respectively, of Atlantic cod on the Scotian Shelf are temperature dependent over the range 2° to 14°C with size decreasing as temperature increases. Similar dependence of egg size on temperature was found by Ware (1977) for Atlantic mackerel (*Scomber scombrus*) in the Gulf of St. Lawrence. This is believed to be in part an ecological advantage in order to match available prey size at the time of hatching as the latter is temperature dependent (Ware, 1977).

Incubation times of cod eggs are also temperature dependent. Page and Frank (1989) found they varied from 8 to 42 d at 14° to 1°C, respectively, for Atlantic cod on the Scotian Shelf. Thus eggs in colder water are more vulnerable to predation due to longer exposure time and may therefore experience lower survival.

Distribution and Migration

Temperature is one of the primary factors, together with food availability and suitable spawning grounds, in determining the large-scale distribution pattern of fish and shellfish. Because most fish species or stocks tend to prefer a specific temperature range (Coutant, 1977; Scott, 1982), long-term changes in temperature can lead to expansion or contraction of the distribution range of certain species. These are generally most evident near their northern or southern boundaries; warming results in a distributional shift northward and cooling draws species southward.

Capelin, a cold-water pelagic species and the major food source of Atlantic cod off Newfoundland and Labrador, spread southward as far as the Bay of Fundy when temperatures declined south of Newfoundland in the mid-1960s and retracted northward as temperatures rose in the 1970s (Tibbo and Humphreys, 1966; Colton, 1972; Frank, *et al.*, 1996). During cooling in the later half of the 1980s and into the 1990s, capelin again extended their range, eastward to Flemish Cap and southward onto the northeastern Scotian Shelf off Nova Scotia (Frank *et al.*, 1996; Nakashima, 1996). For example, small quantities of capelin began to appear in the groundfish trawl surveys on the Scotian Shelf in the mid-1980s and since then numbers have increased dramatically (Frank *et al.*, 1996). Initially only adult capelin were caught but in recent years juveniles have appeared, suggesting capelin are successfully spawning.

This recent shift appears to be part of a larger scale ecosystem change. While capelin were spreading onto the Scotian Shelf, Arctic cod (*Boreogadus saida*) were moving southward. Another small cold-water pelagic fish, its primary grounds have traditionally been the Labrador Shelf stretching southward to northern Newfoundland. Recently these fish have pushed southward to the Grand Banks and into the Gulf of St. Lawrence in large numbers. This southward movement was suggested by Gomes *et al.* (1995) and substantiated from annual autumn ground surveys off Newfoundland through the 1990s (Lilly *et al.*, 1994; K. Zwanenburg and G. Howell, Bedford Institute of Oceanography, personal communication). Recent southward shifts in the distribution of groundfish species off Newfoundland and Labrador have also been documented; Atlantic cod by deYoung and Rose (1993), Taggart *et al.* (1994) and Rose *et al.* (1994), and of fish assemblages consisting of both commercial (e.g. Greenland halibut (*Reinhardtius hippoglossoides*) and American plaice) and non-commercial species by Gomes *et al.* (1995).

Changes in distribution were also observed during the warming trend in the 1940s in the Gulf of Maine which produced a northward shift in abundance and distribution of Atlantic mackerel, American lobster (*Homarus americanus*), yellowtail flounder (*Limanda ferruginea*), Atlantic menhaden (Brevoortia tyrannus), and whiting (*Merluccius bilinearis*) as well as the range extension of more southern species such as the green crab (*Carcinus maenas*) (Taylor *et al.*, 1957). In contrast, during the cooling trend in the Gulf of Maine from 1953-1967, American plaice extended their range southward while butterfish (*Peprilus triancanthus*) retracted southward to their more traditional distributional range prior to the warm 1950s (Colton, 1972). Mountain and Murawski (1992) have documented north-south shifts in distribution as a function of temperature within the Gulf of Maine. The weighted-mean catch for 14 out of 30 stocks investigated from groundfish surveys conducted during 1968 to 1989 was found to increase northward with increasing temperature. This relationship was found to be strongest for Atlantic mackerel, Atlantic herring and silver hake (*Merluccius bilinearis*).

Many species that migrate appear to key on environmental conditions. For example, Atlantic mackerel migrate from their overwintering grounds off the Middle Atlantic Bight across the Gulf of Maine along the Atlantic coast of Nova Scotia and into the Gulf of St. Lawrence. Their arrival at any location along their route requires temperatures warmer than 7° to 8°C (Sette 1950). Similarly, the north-south migrations of American shad along the Atlantic coast of North America are regulated by the seasonal movement of waters in the 13°-18°C range (Leggett and Whitney, 1972). The timing and geographical distribution of Atlantic salmon (*Salma salar*) along the Newfoundland and Labrador coasts are dependent upon the arrival of the 4°C water (Narayanan *et al.*, 1995). April sea surface temperatures and ice conditions in the southern Gulf of St. Lawrence determines the average arrival time of Atlantic herring on their spawning grounds (Lauzier and Tibbo, 1965; Messieh, 1986). Ice conditions also appear to control the arrival time in spring of Atlantic cod onto the Magdalen Shallows in the Gulf of St. Lawrence (Sinclair and Currie, 1994). This is in contrast to their return migration in the autumn to the deep waters in the Laurentian Channel south of Cabot Strait which appears to be unrelated to environmental conditions.

Abundance and Recruitment

Understanding recruitment variability has been the number one issue in fisheries science this century. Evidence of changes in fish abundance in the absence of fishing suggests the likelihood of environmental causes. Since the advent of intensive fishing, it has become increasing difficult to sort out the relative importance of fishing versus environment as the cause of recruitment variability. Still, recruitment levels have frequently been associated with variations in temperature during the first years of life of the fish (Drinkwater and Myers, 1987). The recruitment levels of Atlantic cod off West Greenland, Labrador and Newfoundland have generally been high when ocean temperatures are warm and decrease when temperatures are cold (Taggart *et al.*, 1994), but the warm periods were also those in which the spawning stock biomass were high and thus temperature as the main cause of recruitment decline can not be confirmed. During the last 10 years of extremely cold temperatures in the northern regions, recruitment from Labrador to the Grand Bank has been poor. At the same time, as previously mentioned, cod moved further southward. A recent hypothesis suggests these two features are related; in cold years, spawning tends to occur at southerly locations where larval retention and hence survival is poor (deYoung and Rose, 1993). Other studies have suggested that the collapse of the cod stocks was not caused by a low larval survival index (recruitment/spawning stock biomass) and attributes the poor state of the fish stocks to overfishing (Myers *et al.*, 1996b). In the Gulf of St. Lawrence, the survival index of Atlantic cod is weakly related to the freshwater runoff from the St. Lawrence River system (Chouinard and Frechet, 1994). High survival occurs only when runoff is above normal although years of high runoff do not always lead to high survival, implying other factors are also important. The discharge is not considered to have a direct effect on the cod but may be a proxy for food resources through influences on nutrient levels, phytoplankton production or zooplankton abundance.

Atlantic salmon, unlike their Pacific cousins, are multi-year spawners. Most of those that spawn in the rivers of eastern Canada in summer, later migrate to the Labrador Sea where they overwinter (Reddin and Shearer, 1987). The young salmon, or "smolts", also travel to the Labrador Sea where they reside until ready to return to the rivers. There is large variability in the numbers of salmon returning to the rivers of eastern Canada each year. The similarity in the interannual variability from different rivers over widely separated regions suggests that the numbers of returning salmon are most likely determined in the marine environment. A wintertime index of the areal extent of sea surface temperatures (4°-8°C) in the Labrador Sea conducive for salmon has been developed which shows a high positive correlation with the number of salmon returning to North America during the following spring and summer (Friedland *et al.*, 1993; Reddin and Friedland, 1993). This winter index is now used to predict prefishery abundance of salmon entering the rivers during the following late spring or summer. It is one of few examples where environment is used to predict fish abundance for fisheries assessment purposes.

American lobster landings in Canada and the United States increased steadily during the 1980s and into the 1990s to all time historic highs in most regions. This is due primarily to higher recruitment rather than increased fishing effort (Drinkwater *et al.*, 1996). Relationships between temperature and lobster landings had been established in several areas (i.e. from the Gulf of Maine to the Gulf of St. Lawrence) prior to the large increase in landings showing higher landings during warm temperatures. This suggested that perhaps the recent high landings may have been due to a large scale warming trend. However, examine of the data showed no such warming and using recent temperature data, the temperature-landing relationships were unable to predict any significant rise in landings during the 1980s and 1990s (Drinkwater *et al.*, 1996). This is an example of a "failed" relationship, one in which a linear regression between an environmental variable and fish or shellfish abundance was established only to find that it was unable to explain the observed abundance in later years. These can arise because abundance is usually controlled by more than one variable. There may be one dominant variable for a period of time but then later another variable or variables become dominant.

While most of the examples mentioned above have involved changes in temperature, there is also a transport-related effect on recruitment. Eggs and larvae are affected by currents. The 1987 haddock year class on eastern Georges Bank, which appeared to have been spawned normally in early spring, was located almost entirely in the Middle Atlantic Bight by June. This unusually large southwestward displacement was the result of an enhanced transport of water from the bank (Polochek *et al.*, 1992). Recent improvements in numerical models of the currents over the continental shelves have allowed scientists to study the potential drift patterns of eggs and larvae (Werner *et al.*, 1993; Lough *et al.*, 1994). Advection into unfavourable sites leads to reduced recruitment if the fish die or if they can not make it back to the parent stock to reproduce (Sinclair, 1988). One example of transport related effects on recruitment involves Gulf Stream rings off northeastern United States and eastern Canada. Large meanders in the Gulf Stream will sometimes pinch off and separate from the stream to form Gulf Stream rings or eddies. Eddies on the north side of the stream rotate clockwise and tend to trap warm Sargasso Sea water in their center giving rise to the terminology "warm-core" rings. Those rings that approach the shelf often entrain large amounts of shelf water offshore, transporting it off the shelf into the adjacent deeper slope water region. Greater numbers of Gulf Stream rings close to the continental shelf during the spawning or larval periods has been shown to lead to reduced recruitment in 15 of 17 groundfish stocks, including Atlantic cod, redfish, haddock, pollock and yellowtail flounder (Myers and Drinkwater, 1989). The leading hypothesis is that rings entrain shelf waters laden with eggs and larvae, transporting them off the shelf where they may die because they cannot find appropriate habitat. Death can also occur if they encounter temperatures that are too high, as observed in the waters off Georges Bank by Colton (1959).

Catchability and Availability

Climate can also affect the fishery through influences upon availability and catchability. Availability is how many fish there are for the fishermen to catch and catchability is how difficult it is for the fishermen to catch them. Availability and catchability depend not only upon the total abundance of fish but upon when and how they are distributed. For example, if migrating fish such as herring are abundant but do not arrive on the fishing grounds during the time the fishery is permitted to fish, then the availability is low. Also, if fish are abundant but widely distributed such that concentrations are low, then catchability is also likely to be low. Similarly, if the fish are not very abundant but highly concentrated then catch rates in those areas containing fish are good. The environment can affect catchability, e.g. when temperatures are low, lobster are known to move slowly, reducing the potential for encountering lobster traps, and hence cause reduced catchability (McLeese and Wilder, 1958). The landings in cod traps off Newfoundland have also been shown to depend upon temperature variability (Templeman, 1966). If the traps are located in waters that are too cold, catches are low. Only when the temperatures are warm enough do catches increase. Similar results were observed in cod traps from Quebec off the north shore of the Gulf of St. Lawrence (Rose and Leggett, 1988).

Catch rates in the groundfish surveys conducted by the Canadian Government have also been shown to be influenced by environment conditions. For example, the abundance of age 4 Atlantic cod on the eastern Scotian Shelf caught in the annual spring surveys is greater during years when a larger proportion of ocean bottom is covered by CIL waters, i.e. temperatures less the 5°C and salinities of 32-33.5‰ (Smith *et al.*, 1991). This may result from cod seeking preferred conditions or an inability to avoid the trawls due to reduced swimming speeds at lower temperatures (Smith and Page, 1996).

Aquaculture

Aquaculture is rapidly expanding in Atlantic Canada and is projected to continue this pace into the future. Climate variability is important to this relatively new industry for Atlantic Canada. Decreasing temperatures may cause low minimum temperatures through the year, possibly causing mass mortalities, especially on the east coast of Canada. Long-term temperature trends will affect what species of fish or shellfish are suitable, whether there is a possibility of expansion or contraction of suitable aquaculture sites. General warming may allow aquaculture sites to expand into regions previously unavailable because either sea temperatures were too cold or there was a presence of sea ice. Growth rates of the fish or shellfish and their food requirements are temperature dependent. Aquaculturists are also interested in predictions of wind mixing which contributes to flushing (i.e. the exchange of water between the aquaculture site and the surrounding waters). Low flushing can lead to decreased oxygen, greater potential for the spread of diseases and, in the case of filter feeders such as muscles, reduced food availability.

SUMMARY

This paper has provided several examples of the affects of environment and environmental variability on fish stocks and aquaculture. As stated by Frank *et al.* (1990), taking the step to then predict the response of local marine organisms to possible climate change scenarios becomes a highly speculative exercise. However, observations of changes to the fish stocks due to climate variability in the past allow us to predict some general responses. Climate change (and here we will not deal with the amplitude nor sign of the change at this point) can be expected to result in distributional shifts in species with the most obvious changes occurring near the northern or southern boundaries of their range. Migration patterns will shift causing changes in arrival times along the migration route. Growth rates are expected to vary with the amplitude and direction being species dependent. Recruitment success could be affected due to changes in time of spawning, fecundity rates, survival rate of larvae, and food availability. Although not discussed within this paper, another possibility associated with climate change is a change in stratification (due to differences in heating, freshwater, and vertical mixing rates) which may lead to changes in the ratio of pelagic to groundfish abundance (Frank *et al.*, 1990). If stratification increased, more of the production is expected to be recycled within the upper layers of the oceans and less reach the bottom. Under such a scenario higher pelagic production and lower groundfish production would be expected.

Qualitative predictions of the consequences of climate change on the fish resources of Atlantic Canada will require good regional atmospheric and oceanic models of the response of the ocean to climate change, improved knowledge of the life histories of those species for which predictions are required and further understanding of the role of environment, species interactions and fishing play in determining the variability of growth, reproduction, distribution and abundance of fish stocks. This multi-forcing and numerous past examples of "failed" environment-fish relationships indicate the difficulty fisheries scientists face in providing reliable predictions of the fish response to climate change.

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4.2 Summary of other papers and discussion on fisheries and plankton

Three papers dealt with proxy indicators of climate change. P. Mudie stressed the need to use paleoclimate records since instrumental observations go back only 100 years or so. She discussed the use of foraminifera in sea bed cores; these microfossils can be used to extract oxygen isotopes to indicate temperature. In addition, their shells spiral in one direction in temperatures from 7C to 10C, and in the other direction above 10C. One result of the work with dinoflagellates is that there has not been much change in temperature in the past 10,000 years, but there was a warm period 6000 years ago, long before the use of fossil fuels.

C. Shafer's paper dealt with the use of benthic foraminifera in Chezzetcook Inlet on the Eastern Shore of Nova Scotia to study the effects of the Little Ice Age in the 16th century. (This paper was not presented verbally at the symposium but is shown in Appendix E, Page 220.) At this time, conditions at the sampling site apparently changed from "open bay" to "estuarine"; this change may be related to an increase in freshwater flux to the estuary (caused by an increase in precipitation), or a decrease in tidal flushing caused by changes in the geometry of the bay mouth. Which factor is the more important is an open question.

J.-C. Therriault and J. Plourde (Appendix E, Page 226) attempted to develop an environmental index to predict climate changes in the Gulf of St. Lawrence and its effect upon primary production. A phytoplankton bloom following a mixing event for whatever reason (wind, tide, etc.) always leads to enhanced primary production which supports, on the long run, food chains leading to the production of important commercial fish stocks. The authors developed an index based upon a multiple regression analysis of the temperature profile in the top 205 metres of the water to predict nitrate concentration in the mixed layer. This index was well-correlated with winter air temperature and particularly with ice volume in the Gulf of St. Lawrence. Their work may be interpreted as saying that a succession of cold and warm years can have profound consequences on the global productivity of the marine ecosystem by significantly affecting the global trophic structure and the efficiency of organic matter transfer to fish stocks. For example, it can be hypothesized that during cold years the fishery stocks that are directly linked to the benthic production (i.e. shrimps) will be favored because of a massive sedimentation of organic matter when the large diatom cells have exhausted the nutrient pool in the surface mixed layer. During warm years, little or no nutrient enrichment is occurring in the mixed layer and the organic matter is probably mostly recycled within the pelagic zone (the microbial loop). These warmer conditions associated with fundamental changes in the trophic structure of the plankton community may then create favorable conditions for other fishery stocks (i.e. redfish).

F. Page and S. Robinson (Appendix E, Page 215) discussed the effect of climate variability on aquaculture, which takes place in the marine coastal environment. Aquaculture is well-established and is growing every year. For example, salmon aquaculture in southwestern New Brunswick is worth 120 million dollars per year and employs 1500 people. Many environmental factors such as temperature, salinity, waves, etc. will have an effect on one or more of the following three aspects of aquaculture: physiology of the fish stock; aquaculture operation; or the quality of the product. For example, each species such as salmon have an optimum water temperature range for successful aquaculture. Aquaculture species cannot migrate and are, therefore, vulnerable to environmental change. In southwestern New Brunswick, winter temperatures can drop below 0.0°C in some microenvironments. This has resulted in significant salmon kills, dollar loss and media attention in the past. In addition, because the industry is growing, it is being expanded into areas with marginal conditions for successful operation. Therefore climatic variability, for whatever reason, can put aquaculture in marginal areas at risk. In response to questions, Page said that it was possible for aquaculture operators to get insurance; the premiums are determined on the basis of the history of the aquaculture site. Page stated that sites closer to shore are at greater risk, because of shallow water and lower salinity.

B. Dwyer of the Fogo Island Cooperative gave a talk on the sociological and economic effects of the groundfish closures on the 10 fishing communities on Fogo Island (population 3300) on the northeastern coast of Newfoundland. The groundfish closure brought about considerable shock, anger, fear, uncertainty and feelings of betrayal among the population. The was an out-migration of younger people seeking retraining and education; most are not expected to return. Although those who have remained have survived economically, when the government subsidies terminate there may be an inability to maintain debts or to invest in new equipment to harvest other species. From the point of view of climate change, a lesson to be learned from the collapse of the cod stocks (for whatever reason) is that the socioeconomic impact of an environmental crisis might be to involve fishermen in the decision making process and the gathering of information (such as environmental monitoring) leading to the decisions.

5. COASTAL ZONE

5.1 Synthesis paper

Climate Change Impacts in the Coastal Zone of Atlantic Canada

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ABSTRACT

Climate warming is predicted to cause an increase in global sea level, as well as changes in storm characteristics, ocean wave climate, sea-ice cover, and ecological zonation. These may have a significant impact on coastal stability, flood and storm hazards, and socio-economic activity or investment in the coastal zone. The Atlantic coast of Canada is already adjusting to rising relative sea levels (reflecting a combination of crustal subsidence and sea-level rise [SLR]). Accelerated SLR, combined with a possible increase in storm activity, can be expected to increase coastal erosion, flood hazards, storm damage, and associated property loss over coming decades if existing scenarios for climate change are valid. The prediction of impacts is complicated both by limited understanding of possible changes in storm climatology and by limitations in our ability to predict coastal response. There is a need for recognition of sea-level rise and climate change issues in municipal planning strategies and zoning regulations. Adaptive measures that allow retreat or accommodation to environmental change at the coast will reduce the risk of damage and ultimately reduce costs. Improved prediction of climate-change impacts in the coastal zone will require a better understanding of coastal response at storm-event scale and at longer time scales, both of which require sustained funding for long-term monitoring of water levels, waves, and coastal change.

INTRODUCTION

Climate change scenarios and impacts in the coastal zone

Increasing concentrations of greenhouse gases in the atmosphere are widely believed to be influencing the earth's radiation balance in such a way as to cause global warming (IPCC, 1990). Increased temperatures may lead to thermal expansion of the ocean, melting of glaciers, and other outcomes contributing to an increase in ocean volume. The best estimate of global sea-level rise [SLR] under the IS92a scenario is about +0.5 m by 2100 (Wigley and Raper, 1992; IPCC, 1995).

Changes in atmospheric composition may also lead to increased storm intensity (Emanuel, 1987), possible changes in storm tracks and frequency (Broccoli and Manabe, 1990; Haarsma *et al.*, 1992), and changes in other factors relevant to coastal stability, such as surface winds, ocean waves, storm surges, and ice conditions.

Although the impact of each factor may be predictable to a certain extent, it is difficult to forecast the combined effects, given the large uncertainty that still prevails in various estimates of change. Mikolajewicz *et al.* (1990) showed that sea-level changes resulting from thermal expansion in the ocean will vary geographically, such that some regions may experience negative or negligible change, while others will be subjected to larger increases in mean sea level. Further complication is introduced by natural sources of variability in the climate system, such as El Niño and the Southern Oscillation (e.g. Diaz and Pulwarty, 1993), the North Atlantic Oscillation (e.g. Maul and Hanson, 1991), secular variation in tropical and extratropical storm occurrence and ocean wave climate (e.g. Hayden, 1981; Dolan *et al.*, 1988; Bacon and Carter, 1993), arctic and sub-arctic sea-ice extent (e.g. Mysak *et al.*, 1990; Hill and Jones, 1990), and other factors.

Global sea-level rise

Detecting the various contributions to secular trends in mean sea level is an ongoing challenge (Gornitz, 1995). Direct human influence may be a factor (Sahagian *et al.*, 1994; Gornitz *et al.*, 1994), but the reality of a human-induced greenhouse effect remains controversial. Global sea level appears to be rising at a rate between 0.1 and 0.2 m/century (Warrick and Oerlemans, 1990), with some estimates slightly higher. There is widespread evidence to suggest a recent increase in the rate of sea-level rise (e.g. Carrera and Vanícek, 1988; Peltier and Tushingham, 1989; Gornitz and Seeber, 1990; Varekamp *et al.*, 1992), part of which may be attributable to greenhouse warming. However, saltmarsh deposits and other coastal systems contain evidence for natural fluctuations in sea level at time scales of the order of 100 years (e.g. van de Plassche, 1991; Tanner, 1995; Shaw *et al.*, 1997), implying that accelerated SLR observed over the past century may be partly or wholly natural in origin.

Issues considered in this review

In this brief review, we consider the potential impacts of future climate variability and trends under two major categories:

- effects of accelerated sea-level rise;
- effects of variable storminess;

and conclude with a brief consideration of ice effects and socio-economic implications. Other effects may be anticipated, including changes in ocean and estuarine circulation, water temperature, precipitation, wind regime, and associated ecological changes that may have far-reaching effects on the marine and coastal environment.

ACCELERATED SEA-LEVEL RISE

General issues

The potential impacts of higher mean water level in the coastal zone extend far beyond the effects of direct flooding. A rise in mean sea level has a direct impact across the tidal spectrum, affecting the joint probability distribution of tides and storm surges or storm-wave runup. Tidal amplification may also be a factor (Gehrels *et al.*, 1995). Quite apart from any changes in tidal range, inlet hydraulics or estuarine circulation, altered flood frequency has important implications for saltmarsh dynamics and ecology. Perhaps the most important (and widely overlooked) impact of higher mean sea level is its effect on wave energy at the coast. Deeper water in the nearshore allows larger waves to approach the shore before breaking. Larger waves arriving higher on the beach produce higher runup and shear stress, increasing the frequency of overtopping on coastal landforms and structures and greatly enhancing the potential for coastal erosion.

Relative sea level (the position of the water line with respect to reference points on land) has been changing systematically throughout southeastern Canada for thousands of years, due to the interplay between crustal loading (by ice or water) and the level of the global ocean. In some cases, these changes have resulted in shoreline movements of tens of kilometres or more (Shaw *et al.*, 1993). Along the coast of Labrador, relative sea level has been falling for the past 9000 years (Andrews, 1989), while much of Newfoundland and parts of the Maritime Provinces experienced falling sea levels in the early Holocene (a term used to describe the past 10 000 years of postglacial time) before relative sea level began to rise again (e.g. Scott and Medioli, 1980; Stea *et al.*, 1992; Shaw and Forbes, 1995). Rising relative sea levels have prevailed in most parts of Atlantic Canada south of the Gulf of St. Lawrence and Strait of Belle Isle for the past few thousand years. In the Halifax area, relative sea level has risen at least 40 m in the past 10 000 years (Shaw *et al.*, 1993; Stea *et al.*, 1994). Tide-gauge data from Halifax indicate a rising trend of 0.36 m/century since 1920 (Shaw and Forbes, 1990). A large part of this change is attributable to crustal subsidence (Grant, 1975) but as much as a third may be due to the global rise in sea level. The latter will be superimposed on any crustal motion, leading to an acceleration of the existing sea-level rise in the Maritimes and Newfoundland.

Observed and anticipated effects

Coastal flooding

Low-lying coastal lands are subject to inundation under high tides and storm surges. The frequency of such flooding and the landward limits of flooding will increase with a rise in mean relative sea level. Related effects may include saline groundwater intrusion, backwater flooding in coastal streams, and changes in saltmarsh zonation. Areas susceptible to flooding occur throughout the region, some of the most extensive being around the margins of drowned-valley estuaries in Prince Edward Island (e.g. Hillsborough Bay, where wide intertidal flats and marshes are up to 1 km wide), along the Gulf coast of New Brunswick and Nova Scotia (e.g. the Tantramar Marsh region in the provincial boundary area), and locally elsewhere (e.g. parts of St. George's Bay on the west coast of Newfoundland).

The salt marsh coast of the Bay of Fundy is highly vulnerable to future sea-level rise. An extensive system of dykes, initiated in the late 1630s and maintained and extended over the intervening years, now encloses 85% of the former marsh area (Nova Scotia Department of Agriculture and Marketing, 1987). Whereas natural marsh surfaces might keep pace with rising relative sea levels, the elevation of enclosed lands behind the dykes has lagged behind rising sea level. Mean sea level has risen by 1.3 m since 1630 and 0.44 m since 1869 (Shaw *et al.*, 1997), necessitating ongoing expenditures to compensate for subsidence and maintain the dykes at high enough levels to prevent flooding. Accelerated SLR will increase the cost of dyke maintenance. The greatest concern, however, is the risk of overtopping and inundation associated with storm surges superimposed on high tides.

Accelerated SLR is sometimes seen as a threat to coastal marshland, assuming that the rate of marsh growth does not keep pace with rising tide levels. The presence of relict marsh deposits on the present continental shelf (e.g. Forbes *et al.*, 1989; Shaw *et al.*, 1993) indicates that long-term submergence over hundreds of years can lead to abandonment. The maintenance of marsh area then depends on the rate of marsh expansion, which is a complex function of terrain, sediment supply, recruitment and other factors. Under some circumstances, as at some sites along the Eastern Shore of Nova Scotia, marsh expansion may occur even under rapidly rising sea level (Scott, 1980; Carter *et al.*, 1992; Nichol and Boyd, 1992). Where high rates of erosion at the outer coast are supplying large volumes of sediment to the estuary, rapid accretion on marsh surfaces may enable a transformation to freshwater marsh, producing a vertical sequence contrary to the normal transgressive sequence of marine incursion over terrestrial deposits (Carter *et al.*, 1989; Jennings *et al.*, 1993).

Flooding of urban property, utility infrastructure, and port facilities has been recognised as a potential impact of future sea-level rise at a number of major ports and urban centres in the region. Some communities are already vulnerable to flooding during high astronomical tides and storm surges, sometimes exacerbated by high runoff. The town of Placentia, in southern Newfoundland, is a case in point (ShawMont Martec Ltd, 1985; Forbes *et al.*, 1989). This community, occupying a gravel beach-ridge plain on an otherwise rugged coast, has a long history of flooding. Recent residential, commercial, and institutional development on the strandplain have increased the value of property at risk. The proposed development of a new nickel smelter at nearby Argentia will place added demand on this 'prime' coastal real estate.

In a detailed study to evaluate the impact of a 1 m rise of sea level at Charlottetown (Lane and Associates Ltd, 1988), it was found that some of the highest-value property in the downtown core and significant parts of the sewage system would be flooded. This points to the need for recognition of sea-level and climate-change issues in building codes and municipal planning guidelines.

Coastal erosion

Wave action at the toe of a coastal cliff is one of the primary factors determining the rate of shoreline recession (e.g. Robinson, 1977; Sunamura, 1977). Toe erosion and undercutting exert a critical control on the cliff profile and its overall stability. As noted earlier, higher water levels promote higher wave energy at the shoreline by shifting the locus of wave breaking higher up the profile. Numerous studies, particularly in the Great Lakes, have demonstrated an empirical link between lake levels and erosion rates on cohesive till bluffs (e.g. Amin and Davidson-Arnott, 1995), consistent with theoretical expectations.

Many factors can influence the coastal response to rising sea level. Erosion of boulder-rich glacial deposits, common in Atlantic Canada, can lead to accumulation of protective boulder lags at the cliff base and across the nearshore, reducing wave energy and erosion rates (Forbes and Syvitski, 1995). Coastal progradation can occur where sediment supply exceeds the quantity required to maintain shoreline stability. It can even be argued that accelerated SLR may increase sediment supply from eroding coastal segments, leading to more rapid shoreline progradation at down-drift or bayhead sediment sinks (Forbes *et al.*, 1995b). Changing sediment budgets can lead to closure of tidal inlets or changes in inlet configuration (Armon and McCann, 1979; Reinson, 1980), causing localised erosion and flooding.

On sandy coasts, simple geometrical models have been used to predict erosion as a function of relative sea-level rise (Bruun, 1962). However, the assumptions underlying Bruun's model, including a closed sediment budget and preservation of an equilibrium nearshore profile, are rarely satisfied. The trajectory of a shoreline under rising sea level depends on a number of factors, including sediment supply and accommodation space (Cant, 1991). Nevertheless, a long-term rise in sea level generally produces regional submergence, tending to promote erosion along susceptible coasts. In a Canada-wide assessment of coastal sensitivity to sea-level rise, Shaw *et al.* (1994) identified parts of Atlantic Canada, particularly in the southern Gulf of St. Lawrence, as among the most susceptible to greater instability under accelerated SLR (cf. Owens and Bowen, 1977).

Numerous studies have documented processes and rates of coastal erosion and landward shoreline migration along the Gulf coasts of New Brunswick (e.g. Ganong, 1908; Airphoto Analysis Associates Consultants Ltd, 1975; Reinson, 1980), Prince Edward Island (e.g. Forward, 1960; Armon and McCann, 1979; LRIS, 1988), Nova Scotia (e.g. Bowen *et al.*, 1975; Taylor *et al.*, 1985; Shaw *et al.*, 1993), and Newfoundland (e.g. Forbes *et al.*, 1995a). Severe localised erosion is also documented at numerous sites in the Bay of Fundy (e.g. Atlantic Air Survey, 1976) and along the Atlantic coasts of Nova Scotia (e.g. Bowen *et al.*, 1975; Taylor *et al.*, 1985, 1995; Shaw *et al.*, 1993; Covill *et al.*, 1995) and Newfoundland (Shaw and Forbes, 1992; Liverman *et al.*, 1994).

In summary, it is anticipated that rising sea levels will tend to threaten shoreline stability in many parts of the region. Although some areas will experience shoreline accretion, erosion will be a greater problem in many places. Property losses may become significant if this hazard is not recognised in development planning and regulation.

VARIABLE STORMINESS

General issues

The challenge in determining probable impacts of changing storm climate in the coastal zone lies *both* in the specification of storm climatology (frequency, intensity, storm paths) and in predicting the coastal response. Many processes on wave-dominated shores occur at scales of hours to weeks and are associated with storm-scale variation in the nearshore wave field. The shore-zone response is reasonably well understood at this scale, involving many aspects of sand beach morphodynamics (e.g. Bowen, 1980; Wright and Short, 1984), although some components such as washover channels and nearshore bars may develop and persist for longer time intervals (e.g. Hale and Greenwood, 1980; Boczar-Karakiewicz *et al.*, 1995). The larger-scale system response to decadal or interdecadal variance in storm climate is less well specified, in part because there are few sufficiently long and detailed records of coastal behaviour (see, however, Wijnberg, 1995). It is not always clear to what extent changes are driven by extreme events, by secular changes in climate, or by internal feedback within the coastal system (Forbes and Liverman, 1996). Long-term cyclic behaviour has been demonstrated in some systems, where observations at time intervals of a few weeks over 10 years or more may be necessary to resolve the range of stationary variance (e.g. Clarke and Eliot, 1988; Short and Hall, 1993). The response of a given coastal system, particularly gravel-dominated ones, may depend critically on the antecedent condition of the shore and its susceptibility to erosion or overtopping (Forbes *et al.*, 1995b, 1997).

Proxy indicators of varying storminess in the recent geological record of eastern Canada include variations in the number, thickness, and texture of sandy storm layers in coastal and shelf basins (Kontopoulos and Piper, 1982; Piper *et al.*, 1983). Storms may also be recorded in backbarrier ponds and marshes (Liu and Fearn, 1993; Devoy *et al.*, 1996), although this source has not been exploited in eastern Canada (and care may be needed to avoid possible confusion with tsunami deposits). General historical accounts provide evidence for variations in storminess, such as a lull in the incidence of hurricanes at Bermuda in the mid-1700s (Emanuel, 1995), or the occurrence of extreme events such as the Saxby Gale (Desplanque, 1974).

The observational record of tropical storms in the western North Atlantic extends back to 1871 (Neumann *et al.*, 1981) and shows marked variation in the annual frequency, as well as in the frequency of storms penetrating as far north as the Canadian Maritimes. Similarly, extratropical storm tracks and storm intensity vary from year to year (e.g. Brown *et al.*, 1986; Dolan and Davis, 1992). The instrumental record of wave climate in the North Atlantic, though still limited, is beginning to show some evidence of interdecadal trends (Neu, 1984; Jónsson, 1994).

Funding pressures are threatening the already sparse networks for measurement of water levels and waves in eastern Canada, yet the data provided by long-term monitoring programs are essential for an understanding of environmental forcing and coastal response under variable or changing climate.

Observed and anticipated effects

Storm-surge flooding

Overtopping of dykes and extensive flooding of low-lying areas around the Bay of Fundy can occur when a northeast-tracking low-pressure system and associated storm surge moves up the bay in phase with the tidal wave (Shaw *et al.*, 1997). This occurred during the notorious Saxby Gale of 5 October 1869, which caused extensive flooding, and again on 10 January 1997, when very high tides caused severe damage to facilities up to 100 years old at Hall's Harbour and extensive flooding along the Nova Scotia coast (Delaney, 1997). The recurrence intervals for such events are poorly defined and the effect of global warming on surge probability is uncertain. It is clear, however, that higher mean sea levels will increase the frequency of flooding at any given level, assuming no shoreline adjustment or change in surge probability.

Coastal erosion

Recent work on interdecadal variance in coastal recession rates along the Atlantic coast of Nova Scotia (e.g. Orford *et al.*, 1992; Orford and Carter, 1995; Forbes *et al.*, 1997) has shown that phases of instability on susceptible barrier beaches can be related to a low-pass filtered index of positive water-level residuals in the Halifax tide-gauge record. This is taken as a surrogate for storm-surge frequency at a decadal scale and shows high values in the late 1920s and early 1930s, low values through the 1940s and early 1950s, and high values again after 1954. Photogrammetric analysis shows landward migration of barrier beaches at rates as high as 14 m/a (Covill *et al.*, 1995) at times of combined rapid sea-level rise and high storm-surge frequency (Forbes *et al.*, 1997). Some systems show a delayed response resulting from local site conditions that impede erosion; others show an enhanced response when highly erodible material is exposed in the nearshore; while yet others remain stable under all but the most extreme events because they have developed robust high structures through several decades or centuries of self-organisation (Forbes *et al.*, 1995b). The high barriers may be susceptible to rapid downcutting and washover when stability thresholds are exceeded in exceptional storms.

The Geological Survey of Canada [GSC] and collaborating provincial agencies have established an extensive network of monitoring sites to determine rates and processes of coastal erosion, the impact of individual storm events, and trends or long-term cycles in coastal stability in the Atlantic Provinces and elsewhere. The results are beginning to indicate significant trends in some areas. Taylor *et al.* (1995) showed that some sites on the Nova Scotia coast experienced dune growth and cliff stability during the early to mid 1980s, whereas erosion of dunes and more rapid cliff retreat were evident in the early 1990s.

Storm impacts vary considerably from site to site, depending on the morphodynamic status of individual coastal cells, the duration and intensity of the storm, the incident wave characteristics, and other factors such as the interval between storms. Extreme events can leave an imprint lasting many years, such as large-scale swash cusps (95 m in wavelength) formed on the beach at Holyrood Pond (St. Mary's Bay) in southeast Newfoundland during a storm in March 1985 (Forbes *et al.*, 1995b). Such features may then control washover processes and other aspects of beach response during subsequent large wave runup events. In another example, massive translation of a gravel barrier at Story Head on the Eastern Shore of Nova Scotia, involving 16 to 20 m of movement during a single storm event in late December 1995, may have been facilitated by a smaller storm 10 days earlier with very high water levels (Taylor *et al.*, 1997). The same study has also shown that the most damaging storms are those that coincide with storm surges at high water, or storms of long duration (several tidal cycles) coinciding with spring tides.

Coastal erosion can be a major cause of concern where valuable land, residential structures, and other capital investments are threatened by cliff retreat (e.g. Eyles *et al.*, 1985). Cliff erosion may be effected primarily by removal of material at the cliff base, a process largely controlled by wave energy (which varies as the square of the wave height) and water level (enhanced by high tide, storm surge, wave setup or runup), or it may involve slumping and gullying, processes dominated by lithological and geotechnical properties of the soil and by runoff and groundwater conditions. The latter can lead to rapid headward erosion and property loss, as documented at Romaines in western Newfoundland (Forbes *et al.*, 1995a). Weather conditions favouring one type of erosion (wind, storm surge, waves) may differ from those contributing to the other (heavy precipitation), further complicating the prediction of climate change impacts.

OTHER ISSUES

Sea ice and shore ice

Sea ice is an important factor affecting coastal stability in parts of Atlantic Canada, particularly the Gulf of St. Lawrence and northeast Newfoundland (Forbes and Taylor, 1994). Possible increases in open-water fetch during the winter storm season, resulting from higher sea-surface temperatures and reduced extent or duration of winter sea ice, could increase mean wave energy and contribute to coastal erosion losses. This effect has been predicted for a doubled CO_2 scenario in the Beaufort Sea (Solomon and Forbes, 1994).

Ice-foot development is an important phenomenon on shores in Atlantic Canada, not only in the Gulf of St. Lawrence (Owens, 1976), but in the Bay of Fundy (Knight and Dalrymple, 1976) and on the outer Atlantic coast as well (Taylor *et al.*, 1997). While the effects of an ice foot and nearshore ice complex may include contributions to sediment transport (by ice rafting) and nearshore scour (by development of a reflective natural seawall and seaward displacement of wave breaking), the ice foot commonly serves a protective role on beaches in this region (Taylor *et al.*, 1997). Therefore, less common or persistent ice-foot development under warmer conditions might contribute to shore erosion in a minor way.

Socio-economic interactions and management implications

Socio-economic responses to climate change may exacerbate certain impacts. Under a scenario of global warming, for example, we might anticipate increasing recreational use of coastal lands in eastern Canada, leading to greater risk associated with expansion of shore-zone development and the growth of property values. Demand for coastal real estate in Atlantic Canada is already on the rise, with upward pressure on prices. Similar trends along heavily developed coasts in the USA, southern Europe, and elsewhere have led to rapid growth in the value of buildings and other capital investment within the coastal zone (Carter, 1988). Under these circumstances, the financial risk associated with a given physical hazard (e.g. coastal erosion or flooding) is greatly increased. On a global scale, natural disasters have produced property losses averaging US$1 billion per week in recent years; this is two to three times the rate of loss in the 1980s (Carlowicz, 1996). The challenge of coastal management under more hazardous natural conditions is to minimise the risk to property, human safety, and environmental damage.

Three adaptive responses to sea-level rise have been distinguished in reports of the Intergovernmental Panel on Climate Change (IPCC, 1990, 1992). These are retreat, accommodation, and protection. Retreat may take the form of establishing setback requirements for new construction, allowing wetland migration, or relocating activities. Accommodation may involve modified building codes, acceptance of development compromises, and other adjustments to reduce vulnerability. Protection requires significant capital investment in seawalls, dykes, landfill, beach nourishment, or artificial wetlands, all of which will require ongoing maintenance and upgrading, as experience with the dyke system in the Bay of Fundy demonstrates. This option is only viable where the value of protected property justifies the cost (and protection may fail under extreme conditions). In most circumstances, costs and hazards can be reduced by appropriate planning strategies that favour retreat or accommodation.

SUMMARY

Relative sea level is rising now along most parts of the coast in Atlantic Canada. Accelerated sea-level rise over the past century may be a response to global climate change or it may represent medium-term (century-scale) natural variance in the rate of sea-level rise. There is evidence to suggest that global sea level has been rising at a rate between 0.1 and 0.2 m/century. The current IPCC consensus suggests a further increase of about 0.5 m by 2100. This will be added to vertical crustal movement (subsidence at rates as high as 0.2 to 0.3 m/century) in many parts of Atlantic Canada. The result will be an enhanced flood risk in some areas and accelerated coastal erosion in others. Appropriate zoning regulations and other adaptive measures that support strategies of retreat or accommodation will reduce the risk of property loss or damage by limiting vulnerability to flood and erosion hazards.

Variations in storminess, including possible increases in storm frequency or intensity, can be expected to cause enhanced erosion in some places and may affect the risk of storm-surge flooding and dyke overtopping in the Bay of Fundy. Changing winter ice conditions may also be important, increasing exposure to winter storm waves, among other effects. The impact of a given weather event is a function of storm characteristics and timing, coastal setting, and vulnerability of landforms or structures in the coastal zone. Differences in coastal response depend on the specific erosion processes, the coastal geology, and the morphological status of a site. The latter may reflect the impact of a previous storm and the time available for recovery since that event. Susceptible coastal landforms such as low gravel barriers may retreat as much as 20 m or more in single major storms, while higher barriers nearby remain stable. The high barriers may also be vulnerable if thresholds of stability are exceeded under changing climate conditions. Rapid cliff recession is also observed where protective boulder shoals are absent and where slumping or retrogressive flows and gullying occur. Long-term monitoring of the coast shows evidence for interdecadal variation in erosion rates, related to changes in the rate of relative sea-level rise and storm-surge frequency. Improved prediction of climate-change impacts in the coastal zone will require a better understanding of coastal response at storm-event scale and at longer time scales, both of which require sustained funding for long-term monitoring of water levels, waves, and coastal change.

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5.2 Summary of other papers and discussion on the coastal zone

The paper by J. Shaw *et al* (Appendix F, Page 245) examined the sensitivity of coastlines in the Atlantic Region to climate change. This was done through a sensitivity index based upon factors such as relief, geology, sea level trend and tidal range. Although the analysis indicated that only 3% of the Canadian coastline is highly sensitive to climate change, most of the sensitive areas are found in the Atlantic Region. In Newfoundland there were three sensitive areas: Cape Freels, the coast of St. George's Bay and the southwest Burin coast. In Nova Scotia, the sensitive areas are: the Atlantic coast with its coastal bluffs, estuaries and salt marshes and ; the salt marches at the upper end of the Bay of Fundy. In the latter area, the Acadians first dyked and drained parts of the marshes in the late 1630s and today about 85 % of the former marsh lies behind dykes constructed at various dates. As sea level continues to rise (it has risen by 1.3 m since the Acadians arrived), the dykelands are at progressively lower levels in a relative sense. If sea level rises more rapidly due to global climate change, then the cost of dyke maintenance will obviously increase. Even more important than the financial consideration, however, is the hazard posed by a major storm, which could overtop the dykes and inundate the lowlands behind them.

Apart from the Fundy marshlands (discussed above), the most sensitive coasts in New Brunswick fringe the Gulf of St. Lawrence. Barrier islands and spits extend across shallow, drowned embayments to form the longest barrier coast in Canada. The anticipated impacts include all the changes that accompany migration of a barrier coast: overwashing during storm surges, migration, opening and closing of channels. In many areas freshwater bogs are common in the coastal zone, mostly along the mainland coast behind the barrier islands. Further inundation and erosion of these bogs and adjacent woodlands are to be expected.

The coasts of Prince Edward Island, except for some parts of the Northumberland Strait coast, are highly sensitive to impact from sea-level rise. The coastline is highly variable in character and includes bedrock cliffs, sandy barriers, coastal dunes, salt marshes, estuaries, and intertidal flats. Parts of the Gulf coast lie at the heart of the PEI tourist industry, and could undergo even higher rates of coastal change than at present. Accelerated coastal retreat could increase the costs of maintaining a tourist infrastructure.

Shaw suggests the following directions for research:

1. With regard to the Bay of Fundy, an important objective must be to determine the probability of the dykes being overwhelmed by the coincidence of a storm surge and high tides.

2. We need to enhance our ability to predict the changes that would occur on wave-dominated coasts in the next century if accelerated sea-level rise were to occur.

3. The Coastal Zone Management Subgroup of the IPCC recommends that coastal nations adapt three strategies to cope with global sea-level rise: 1) retreat (abandon structures in developed areas and ensure that new developments are set back from the shore); 2) protect (defend vulnerable areas, especially population centres, economic activities, natural resources); and 3) accommodate (strike a balance between preservation and development).

4. In its 1992 report, the Coastal Zone Management Subgroup of IPCC described a common methodology for assessing vulnerability to sea-level rise. This methodology differs from that adopted for the Canadian study in that it is focused on socio-economic impacts. Whether or not a similar approach should be adopted for all or parts of the Canadian coast, and how it would be integrated with coastal zone management, are matters for future consideration. The study of the vulnerability of the Fundy lowlands described above would undoubtedly consider socio-economic impacts.

In response to questions, Shaw stated that salt marches could adapt to sea level rises as rapid as 60-70 cm/century.

R.Taylor *et al* (Appendix F, Page 253) described, with the aid of colour slides, the response of various shorelines to several storm events that took place during the 1990s. He stated that beaches were the final line of defense of the land against the sea; gravel barriers could be 3-6 m high and 20-70 m broad at the base. The primary mechanism for beach migration is storm events; important factors are the combination of storm duration, wave height and stage of the tide. The effect of a given storm can be reduced during neap tides and increased during spring tides. Brash ice can absorb the energy of waves and thereby reduce the effect of the storm. The frequency of storms is also important; frequent storms give less chance for recovery. Low-crested beaches recover more quickly. Beaches can recover by combing up from behind sediment that had been deposited there by the storm. In response to questions, Taylor stated that we may lose our outer beaches to today's storms; tomorrow our children will enjoy new beaches that used to be today's inner beaches.

R. Hendry *et al* (Appendix F, Page 241) described the development of a technique to use satellite altimetry by the joint U.S./French TOPEX/POSEIDON (T/P) satellite to monitor sea level in Canadian coastal waters. Sea level height is gauged by measuring the travel time of a microwave pulse sent by the satellite and reflected back to the satellite from the surface of the ocean. T/P offers an impressive system accuracy for height measurements of approximately 3 cm. Every 10 days, TOPEX/POSEIDON gives measurements along discrete ground tracks separated by approximately 200 km at 45N latitude. The altimeter footprint varies from approximately 2 to 10 km diameter as a function of sea state, with larger values associated with higher wave heights. Operational products are smoothed to approximately 10 km resolution in the along-track direction to improve the signal to noise ratio and reduce the data volume.

Measurements are not possible very close to shore because of contamination by the strong reflection of the radar pulse from the nearby land surface. Tides generally show greater amplitudes and smaller spatial scales in coastal regions than offshore, and consequently tidal aliasing of altimetric measurements poses a greater problem for coastal applications. Therefore, accurate and highly-resolved regional tidal models are required to use altimetry in coastal regions. Finally the seasonal march of sea ice down the Labrador and Newfoundland shelf hinders the use of altimetric measurements during part of the year, and optimal processing strategies must be derived to use available measurements.

Hendry stated that they plan to map sea levels in eastern Canadian waters using presently available TOPEX/POSEIDON altimetric data. They will compare the resulting estimates of mean sea level and seasonal and interannual variations in sea level with *in situ* measurements from coastal tide gauges and offshore data to test the effectiveness of this approach for monitoring future sea level changes in Canadian coastal waters. In response to questions, Hendry replied that the height of the satellite is measured with an accuracy of 1-2 cm by laser techniques. The technology cannot be used in the Arctic because ir requires an ice-free surface; in any vent the T/P satellite flies only to 70N.

6. ECOSYSTEM SCIENCE AND WATER RESOURCES

6.1 Synthesis paper

Climate change sensitivities of Atlantic Canada's Hydrological and Ecological Systems

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INTRODUCTION

Atlantic Canada ecosystems and hydrological regimes are defined by cool, wet, temperate conditions in New Brunswick, Nova Scotia, Prince Edward Island and the Island of Newfoundland, and by colder drier conditions in Labrador. The three Maritime Provinces are located in the Atlantic Maritime Ecozone and the Island of Newfoundland and southern Labrador are in the Boreal Ecozone. Central Labrador is in the Taiga and northern Labrador is in the southern Arctic and Arctic Cordillera Ecozones. The main characteristics of the zones are listed in Table 1.

Table 1. General description of Atlantic Canada ecozones (from Eaton *et al.* 1994).

Ecozone	Climate	Primary ground cover
Atlantic Maritime	moderate, cool-moist maritime influence	productive forests
Boreal Shield	cold arctic air masses, modified near the coast	poor forests
Taiga Shield	cold winters, cool summers, short summers	tundra, permafrost
Southern Arctic	cold year round, little precipitation	rolling plains
Arctic Cordillera	very cold, glaciers	coastal mountains

The work summarized in this section is the result of ongoing or recent hydrological, geochemical and ecological studies analyzing the impacts of climate on avian, freshwater and wetland systems in the region. There are a large number of relevant topics which are not dealt with in this report which is more an indication of the current state of knowledge than an indication of importance. Topics not covered due to insufficient information include freshwater fisheries, mammalian wildlife populations as well as non-commercial plant species. Forests and marine ecosystems are covered in other sections of this report.

WATER RESOURCES

General

Persistent change or increased variability in climate will affect the present characteristics of the water resource. Precipitation and temperature are the principal driving forces behind the hydrological cycle and anticipated changes in climate are expected to significantly alter Canada's water resources. To this end, it is important that the various climate/hydrologic mechanisms at play and their interdependent reactions be understood. Proper monitoring of key elements over the long term is vital to increasing our understanding of these processes so that preventative or adaptive measures may be taken to reduce the impact on society.

The amplification of the temperature trend signal through the hydrology cycle could be dramatic. The timing of the change could also be gradual or stepwise (Nuttle, 1993). Increased variation seen as seasonal time shifts or rapid swings in seasonal climate variables could change the normal characteristics of the water cycle, creating havoc for human or ecosystem users of the resource. For example, increased winter precipitation would impact both the winter and spring runoff depending on the temperatures. This could produce increased winter runoff if supplied as rain or increased spring runoff is stored in the winter snowpack. The timing of these precipitation/temperature combinations will dictate the severity of the runoff event. The result would include both beneficial and catastrophic impacts depending upon the sensitivity of individual species of the ecosystem to change, their interdependence and the ability of natural and anthropogenic systems to adapt or mitigate that change.

Habitat loss is a major concern especially in the Atlantic Region as there may be no alternatives for some species. Climate and hydrology play a major role in the health of freshwater ecosystems. The timing and magnitude of specific hydrologic events such as freeze-up/break-up, the severity of the spring freshet or the duration of the low flow period is vital to the life cycle of many species. Though little of these potential impacts are discussed in this report, a more thorough discussion of ecological impacts of freshwater ecosystems can be found in McKnight *et al.* (1996).

On the human side of the ecosystem, the accumulation of long term flow and climate data have been invaluable in aiding the safe and economical design of dams, bridges, water supplies and other infrastructure whose design and integrity are influenced by the extremes of the hydrologic cycle. Significant changes in the hydrologic cycle may impact on the safe and long term economic use of some capital projects. Without a clear indication of the size and timing of the trend it will be difficult to convince developers to justify additional design costs to mitigate the predicted change.

Ice in Rivers

In the Atlantic Region, the preliminary screening of existing data revealed an interesting source of information previously not included in normal hydrological analyses. A remark "Backwater due to ice" which is appended to the daily flow values, alerts the user that ice conditions existed and that data is estimated using different procedures than those used for open water conditions. In using the ice data, two approaches were initially examined. The first was to consider the period from the first day of ice to the last, while the second only considered the number of days with ice. In the more northerly regions of New Brunswick, Newfoundland and Labrador where the ice cover is established and generally remains consistent, the approaches were essentially the same. Most of Nova Scotia, PEI, southern New Brunswick and Newfoundland have streams which may or may not freeze over or which may have several freeze/break-up episodes each winter, particularly in watersheds near the coast with a southerly exposure to the ocean.

Preliminary analyses of these data showed that there were some definite trends over the last 40 years. Stations in Nova Scotia (Figure 1.) and on the Island of Newfoundland showed that the number of days with ice in the river has increased since 1952 (when the data became part of the record). Preliminary comparisons of ice data with winter season temperatures showed that there was a cause and effect relationship between the temperature and ice, but for whatever reason it did not explain it completely.

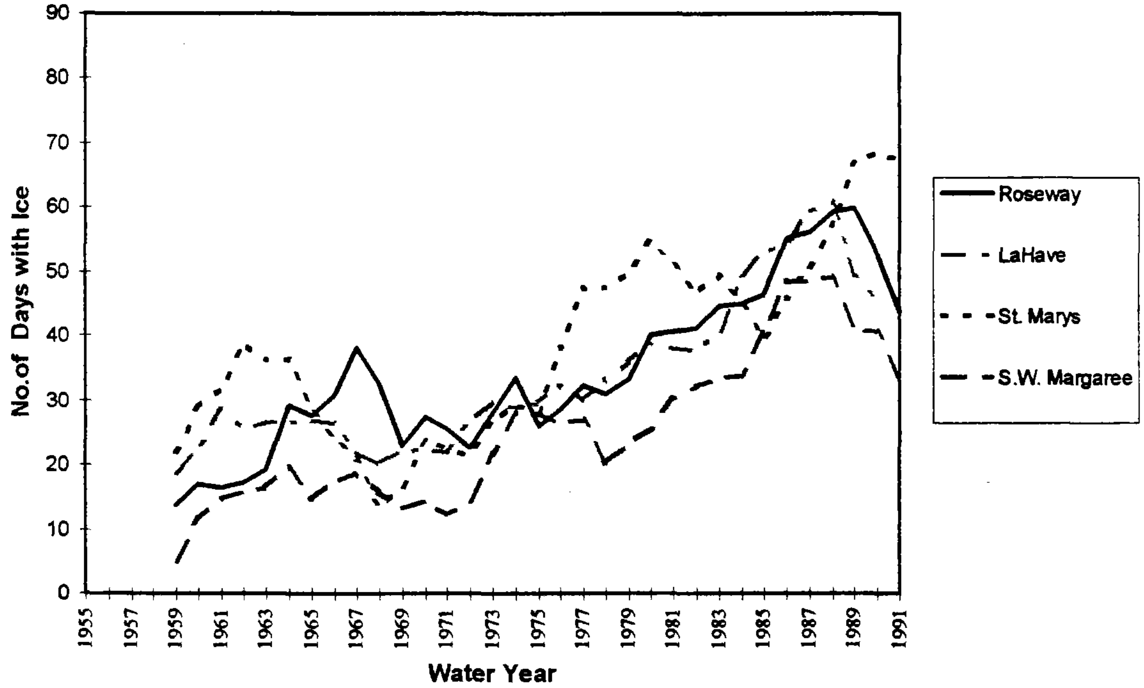

Figure 1. Ice Trends in Select Nova Scotia Rivers - 5 Year moving Averages

Runoff

Simplistically, runoff is a function of the watershed characteristics, which are essentially the physical structure of the watershed and the vegetation, in conjunction with the climate. The amount of runoff from a watershed is usually expressed as an average depth (i.e. millimeters) over the area of the watershed which enables us to make comparisons between watersheds as well as compare the output with the input (precipitation measured in the area). A given amount of precipitation will produce a different total runoff depending on the season, vegetation and the soil moisture condition.

By looking at the changes in runoff on an annual, seasonal, or shorter duration basis, it is possible to detect signals of change. Changes may include the magnitude and timing of seasonal events; trends in the number and severity of events per season and persistent trends or a change in the normal variability,

Trends may be the result of either a long term natural cyclic variation, climate change or a combination of both. To the ecosystem, the reason for the change may not be as important as the change itself. A more important fact is whether the anticipated effect of climate change will exacerbate or mitigate a cyclic trend, how long the trend will last and what are the implications for the entire ecosystem. Most of all, it is vital to apply this model to those susceptible species which may be on the edge of their habitat range. By understanding these systems there may be environmental management decisions that could reduce the impact on these species. Preliminary analysis techniques have been used on the river ice data and on some annual and seasonal runoff data. In the case of the river ice data, trends were plotted for all existing data using a standard period from 1969-1992.

The results show three distinct hydrological areas: northern and eastern New Brunswick and Prince Edward Island, where there appears to be a mild signal showing less ice in the rivers; southern New Brunswick and central Nova Scotia where there appears to be no change; and southern, eastern and northern Cape Breton (Nova Scotia), as well as most of Newfoundland where there appears to be a significant trend towards more days with ice.

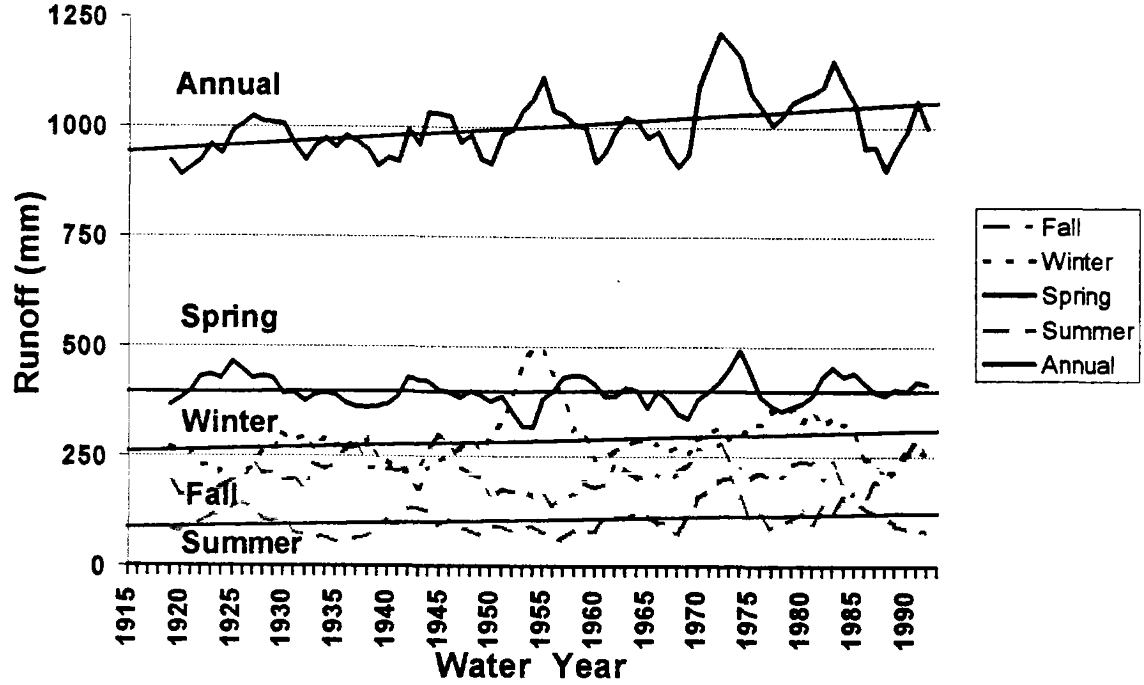

Figure 2. Seasonal and Annual Runoff as 5 - Year Moving Averages for the St. Marys River, N.S.

Using Figure 2 as an example, the runoff data shows a long period of level or slightly increased runoff in the St. Mary's River, Nova Scotia until 1970 when there is a dramatic increase in the runoff followed by increased variability. The pivotal point of 1970 appears to be a starting point for some sort of change (Karl, 1996). The effect of the 1952 warm winter anomaly (Richards and Russell, 1995), is also quite pronounced. When the last 25 years are viewed in isolation there appears to be a dramatic decrease in runoff in Nova Scotia streams especially during the winter. What appears to be a trend from 1970 toward lower winter runoff is also the same period of longer ice seasons in rivers and a full cause effect relationship is being determined.

EFFECTS OF CLIMATE ON RIVER ICE JAMS

General

Ice jamming in Canadian rivers has a multitude of socio-economic impacts such as flooding, damage to private property and infrastructure, interference with navigation, and inhibition of hydropower generation. When a jam is in place, the water level has to rise dramatically to enable conveyance of the river flow while accommodating the keel of the jam and the additional resistance produced by the very rough jam underside. The release of an ice jam is also a matter of concern. A large volume of water comes suddenly out of storage, creating a *surge*. Ice-jam surges are characterized by very rapid stage increases downstream (order of a metre in minutes) and very high flow velocities (5 m/s is not uncommon). Bank erosion, bed scour, and very high suspended sediment loads often accompany ice-jam surges.

The average tangible cost of ice jamming to the Canadian economy is estimated at $60 million per year (Gerard and Davar, 1995). A much greater amount is attributed to missed hydro-power generation opportunities due to inadequate understanding of river ice processes (Raban, 1995). Atlantic Canada is one of the most-seriously affected regions (Environment Canada, 1985; Kindervater, 1977, 1980, 1985). In New Brunswick, for example, ice jams cause a third of all flood events but are responsible for two-thirds of all flood damages (Humes and Dublin, 1988).

The strong relationship between river ice and aquatic ecosystems has only recently been emphasized (Prowse and Gridley, 1993). Ice jams and the surges that follow their release, have many detrimental impacts on aquatic life. Habitat loss due to bed and bank scour, fish mortality due to stranding on the floodplains, very high concentrations of fines, abrupt water quality changes, long range transport of pollutants, deposition of fine sediment and degradation of spawning habitat, are but a few examples. Ice jams also have positive ecological effects, such as the replenishment of floodplain habitat with nutrients and sediment for the sustenance of many aquatic, terrestrial and avian species, during the spring flood (e.g. see Peace-Athabasca Delta Project, 1973; Marsh and Hey, 1989).

Ice Processes and *their Links to Climate*

River ice studies show that the onset and severity of a breakup event, and the ensuing ice jams, are controlled by: the water levels during the preceding freeze-up; the thickness of the ice cover at the end of winter; the weather conditions during the breakup period; and the volume and rapidity of the spring runoff (Beltaos, 1995). The freeze-up level and the winter ice thickness determine threshold values of river flow for ice movement (onset of breakup) and ice clearing (end of breakup). If the runoff is slow, the onset of breakup will be delayed and the ice subjected to significant thermal deterioration. In extreme situations, the ice cover disintegrates in place and the breakup is *overmature* or *thermal*, characterized by minimal, if any, jamming. The opposite extreme is the *premature* or *mechanical* breakup which has the greatest potential for ice-jam damages. Here, the runoff is very rapid, usually due to rainfall combined with snowmelt. The breakup onset threshold is attained quickly, allowing little opportunity for ice deterioration.

Where the winter ice cover is set in motion, it rapidly breaks down into small floes that are eventually arrested by segments of still-intact ice cover. Major jams form, release, and re-form downstream, until the clearing threshold is reached and the breakup event is completed. Premature breakups are rare where the runoff is produced by snowmelt. They are most common in relatively temperate regions and often triggered by mid-winter thaws. Such *winter breakups* can be very dangerous, not only while they are in progress but even later on: when the cold winter weather resumes, ice jams that are still in place freeze over, resulting in higher freeze-up levels and thicker ice covers, thus enhancing the potential for more jamming during the next breakup event.

This brief discussion shows that the factors controlling the onset and severity of ice jams, viz. the flow hydrograph between fall and spring, and the thickness of the winter ice cover, are climate-related. Subtle changes in weather conditions can produce very different hydrographs, thus modifying the river ice regime. For instance, a slight temperature difference can produce a winter breakup by transforming a common snow storm into a rainfall event. Reduced ice thickness would imply easier ice clearance and lesser ice volumes that may be available to form ice jams, but the reduction would have to be more than subtle before noticeable moderation of ice jamming occurs.

Evidence of Changing River Ice Regimes and *Impacts of Various Scenarios*

The sensitivity of river ice processes to climate has been demonstrated by a limited number of studies in Canada and abroad. Zachrisson (1989) reported that earlier and more severe breakups are occurring in the river Torneälven (Sweden-Finland boundary), likely due to rising April temperatures. However, clear-cutting of forested areas and removal of numerous log-driving dams were also cited as factors. In rivers of Russia, Belorussia, and Ukraine, ice forms later than in the past, by as much as 21 days in 100 years (Ginzburg *et al*, 1992), in response to concomitant warming trends. Corresponding advances of up to 11 days in 100 years were reported for breakup dates by Soldatova (1993).

In Canada, Williams (1970) and Rannie (1983) reported earlier breakups in the Saint John River (NB) and the Red River (Man.), respectively, by about 15 days since the last century. These trends are consistent with Burn's (1994) findings, showing that the snowmelt peak flows generally arrive earlier, at an average rate of 0.25 days/year, in rivers of west-central Canada. Brimley (1996) considered the duration of the ice season in Atlantic Canada, as revealed by hydrometric gauge records (Water Survey of Canada) in the past 45 years or so. The results highlight the strong spatial variability of the Atlantic region's climate, and are consistent with, though not entirely explained by, local winter temperature trends.

The above studies deal with the length of the ice-cover season and do not specifically address ice-jam processes and their severity. This question could be investigated by examination and analysis of unpublished hydrometric gauge data, namely the continuously recorded time series of river stage. Beltaos *et al* (1990) provide guidelines for interpreting such data.

Considerable warming and changes in precipitation patterns are predicted by General Circulation Models (GCMs), under the well-known 2xCO_2 scenario. If these changes materialize, our understanding of river ice processes suggests that the ice regime may be modified in different ways over different parts of the country. In temperate regions such as SW Ontario, and parts of British Columbia and Atlantic Canada, the brief and capricious river ice cover may disappear completely, or become more intermittent. This should be good news on the socio-economic front, but could be disruptive to aquatic species that depend on the ice cover for winter survival.

A large part of Canada, on the other hand, including northern B.C., the Prairies, most of Ontario and Quebec, and northern parts of the Atlantic Region, experiences long river ice seasons, mostly devoid of winter breakups. This is certainly the case with west-central Canada. Ontario, Quebec, and northern New Brunswick do experience the occasional winter breakup, seemingly more often in recent years. [A case in point is the upper Saint John River (USGS gauge data, Fort Kent), where 3 of the 7 winter breakups of the past 70 years occurred during 1995 and 1996. A fourth event (December 1990) was followed by one of the most severe spring breakups on record (see also Beltaos and Ismail, 1996). No winter breakups have occurred between 1927 and 1957]. A common change that may occur in this part of Canada is the occurrence of winter breakups, either as a new phenomenon in some areas, or a more common one in other areas. Ice thickness will be reduced somewhat, though not enough to alleviate the risk of ice jamming.

In northern Canada, the winters are so cold that, even with the predicted warming, winter breakups should be very rare, if they appear at all. Less frequent jamming and flooding may occur in some areas, leading to long-term decline in floodplain habitat replenishment, as explained earlier. Longer open-water seasons in northern rivers could result in significantly increased exposure of aquatic species to UV-B radiation.

Beyond such broad predictions of possible changes, , it is not possible at present to identify specific areas and communities that may be vulnerable to climatic change, or to anticipate the magnitude of economic and ecological impacts. This is due to: (a) uncertainties introduced by the coarse grids of GCMs and their weakness in predicting amounts and types of precipitation; and (b) the relative "youth" of river ice science.

Research Needs

The preceding discussion has been a preliminary attempt to identify some of the changes in the ice-jam regime of Canadian rivers that may be expected under the global warming scenario. The emphasis should be on the word "preliminary" because neither GCMs nor river ice science are sufficiently advanced. However, GCM sophistication and computer power are increasing, and it is likely that many of the weaknesses of the GCMs will be rectified in the next decade. To take advantage of such progress, river ice science must also advance to the point that it can furnish quantitative predictions, given climatic inputs and channel morphology.

This cannot be accomplished satisfactorily at present because there is still considerable reliance on empirical formulae and methods. Such methods often assume that several climatic variables - except air temperature - do not change much from year to year, thus providing approximate relationships between ice-related parameters and simple thermal indices. This approach is not reliable in the climate-change context, and there is a need to develop physically-based models, by improving the basic understanding of river ice processes. A parallel effort needs to be made toward predicting what may happen to river ecosystems. Inter-disciplinary studies, combining biological, chemical, and physical expertise would have the best chance of success. At the same time, it is important to continue monitoring the status of the ice regime and assess how it may be changing. A comprehensive study of hydrometric station data to investigate hydrologic and ice-jam processes would be a starting point toward eventual identification of areas that may be of concern (see also Beltaos *et al*, 1990).

Summary

River ice jams have major social, economic and ecological impacts in the Atlantic Region. River ice processes in general, and ice breakup and jamming in particular, are highly sensitive to climatic inputs. The limited available evidence indicates that changes are taking place and they are consistent with concomitant temperature trends. A preliminary attempt to formulate future scenarios has indicated that there are several concerns pertaining to changing ice-jam regime, both of socio-economic and ecological nature. How serious the possible impacts might be, and exactly in what areas, cannot be determined at present, because neither the GCMs nor river ice science are sufficiently advanced. Research needs for the latter include assessment of current indicators of change using hydrometric gauge data, improved basic knowledge of breakup and ice jam phenomena to reduce empiricism, and inter-disciplinary studies of the links between river ice and stream ecology.

ATLANTIC CANADA WETLANDS AND CLIMATE

Introduction

Wetlands are areas where water tables are at or near the surface long enough to be noticeable to plants and animals. They can be very small, from a few hundred square meters or very large, covering hundreds of square kilometers as is the case in southern Labrador. They occupy 2% of the land area in New Brunswick, 17% of Newfoundland and Labrador, 3% of Nova Scotia and 1% of Prince Edward Island (National Wetlands Working Group, 1988). Despite the somewhat low coverage, they are very important in controlling water abundances and quality as well as are important ecosystems for waterfowl and plants.

There are a number of wetland classifications used in Canada and elsewhere, but what drives these classifications are three things: nutrients, temperature, and precipitation, the last two being modified by climate. Atlantic Canada wetlands fall in three general regions which overlap somewhat with the Ecozone classification. The Temperate wetland region is most important in the lower St. John River Valley and is defined by relatively warm summers, mild winters and moderately high amounts of precipitation. Most of the region has wetlands classified as Boreal which are influenced by cold winters, warm summers and in coastal regions, relatively high precipitation. Southern Newfoundland and northern Labrador wetlands are classified as Subarctic and are subjected to intensively cold winters and warm summers with relatively low precipitation levels. Each of these wetland groups has a well defined plant and animal assemblage which could be changed by changes in climate. They are important as waterfowl habitat and have an important role to play in landscape and geochemical cycles.

Wetlands are important to the global carbon cycle. The Northern Hemisphere with its large amount of wetlands is potentially one of the strong controls to the global atmospheric CO_2 cycling. CO_2 is taken up by the plants which eventually die, some of the organic matter is converted to peat, some of it goes back into the atmosphere as CO_2 and methane, and some of it leaves in drainage water in the form of dissolved organic carbon. The last sink is also an ecologically significant component of the water chemistry.

Consumptive uses of wetlands are varied. The peat industry for example drains wetlands and uses the dried organic matter for making horticultural products. Wetlands are also being used to clean up mining wastes because the organic acids that are generated in the wetland organic material, are good complexers of metals. Further, in small communities wetlands are used to purify municipal effluents.

Because they are defined by the location of seasonal and permanent water tables, wetlands are closely linked to climate. Balances between precipitation and temperature which control total water input and outputs are critical in determining the very existence of wetlands. Changes in the evapotranspiration balance leading to lower water tables may thus cause the disappearance of wetlands along with the ability of basins to absorb water and increase flood risks in certain areas. For examples, Clair and Ehrman (1996) used historical climate and hydrology information from 15 wetland influenced rivers in Atlantic Canada and developed predictions of water discharge from the region based on a number of climate scenarios (Table 2). They found that a regional temperature increase of 3° would lead to a decrease of 29% of regional discharge with a 20% decrease of precipitation, a 10% decrease with no change in precipitation and a 9.5% increase with a 20% increase in precipitation. These numbers suggest that water levels might change significantly with shifts in climate but how these translate into actual wetland distributions has not yet been determined and remains an important unknown in attempting to understand the implications of climate change.

Water levels and flows through wetlands also control their carbon content and fluxes (Gorham 1991). Clair and Ehrman (1996) show that aquatic dissolved organic carbon fluxes are closely linked to water flow through the basins. Moore (1994) also shows that water levels control the level of methane and CO_2 emissions from wetlands. Recent work (Dalva and Moore, unpub.) shows that gas fluxes from Nova Scotia wetlands fall within values measured elsewhere in Canada. These show that methane emissions under waterlogged conditions range from -23 to 1153 $mg/m^2/day$, while CO_2 fluxes are more important under drying conditions with values ranging from 0.2 to 23 $g/m^2/day$. Shifts in water tables due to a changing climate will change the relative importance of the gases and their impact on the global atmospheric carbon cycle.

EFFECTS OF CLIMATE ON MIGRATORY BIRDS IN ATLANTIC CANADA

Indirect Effects of Climate

Changes in habitat

Birds, like other organisms, live in habitats to which they are adapted and the distribution of these habitats in determined by interactions between climate (especially rainfall and temperature) and soils. Globally, continentally and regionally, the effects of changing climate on avifaunas will likely be mediated through changes in the distribution of ecoclimatic zones, which are reasonably predictable on a very broad scale. An important consequence of changes in distribution of ecoclimatic regions is that species will come into contact with other species from which they are currently separated geographically.

Biotic communities are not fixed associations, but shifting assemblages of species brought together by a common tolerance for combinations of environmental conditions (Pease *et al.* 1989). The most important changes to terrestrial habitats, however, are likely to be caused by changes in land-use by humans. Atlantic-region terrestrial ecosystems are dominated by forestry and agriculture which will respond to global changes of all kinds, especially economic and trade-related, in addition to climate, and these responses will likely dwarf any responses due directly to changing climate.

Changes in distribution

Boundaries of winter ranges of terrestrial birds will likely shift northwards with warmer winters; the northern boundaries of many species of songbird coincide with January isotherms reflecting daily energy requirements of about 2.5 times Basal Metabolic Rate (Root 1998 a, b). However, these direct effects of temperature are manifest only within the range of suitable habitat for any particular species, so that changes in habitat distribution will likely remain more important than temperature *per se* in determining winter distribution of most species. Equivalent relationships between climate and distribution presumably operate in summer as well as winter, but these relationships have not been described in Canada. The 'energy theory' of species distributions developed by Brown (1981) and Wright (1983), which relates abundance and distribution of species to available solar energy (Turner *et al.* 1988), suggests that climatic changes could affect bird distributions directly, in addition to changes mediated through changes in distribution of habitat.

Among marine birds, changes in range will likely follow changes in the distribution of prey such as capelin, arctic cod, herring, sand-lance etc., which in turn will accompany changes in water-temperature and salinity (Brown 1991). Compression of the boreal marine ecozone can be expected as the cold Labrador current becomes cooler from increased inflow of glacial melt as the Greenland ice-caps melts, at the same time that warm waters of the Gulf Stream move further north (Brown 1991). Colonies of Thick-billed Murres and other arctic seabirds currently occur chiefly near polynyas and coasts where ice melts early, and are likely to change localities if these water-masses change in distribution.

Sea-level rises will likely cause abandonment of Funk Island, which currently supports enormous colonies but is only 15m above sea-level and already vulnerable to significant losses from summer storms (Brown 1991). Other shoreline habitats support breeding pairs of two endangered bird species - Roseate Terns and Piping Plovers - which will have to move to new locations as their present sites are inundated or washed away.

Migration routes

Habitat requirements on migration may be just as specific as those for breeding and wintering. Rising sea level is likely to inundate coastal staging grounds which are essential for shorebirds and waterfowl migrating between arctic breeding grounds and southern winter quarters. The most obvious examples in this region are the saltwater marshes connecting New Brunswick and Nova Scotia, and the mudflats at the head of the Bay of Fundy. The former are staging grounds for large numbers of migrating waterfowl, while the latter make up a critical stopover in July and August for shorebirds, especially most of the Semi-palmated Sandpipers *Calidris pusilla* in the world (Hicklin 1987). A rise is sea-level of 1 m will likely cause a 1.7% increase in tidal range in the Bay of Fundy (Greenberg 1986), with significant but unpredictable effects on these mudflats and marshes.

Direct Effects of Climate

Timing of breeding

Most birds breed as early as they can; accordingly, changes in the timing of warm spring temperatures are likely to bring breeding seasons forward. In many species, too, breeding success is correlated with the timing of breeding and early breeders do better than later breeders (Perrins and Birkhead 1983).

Understanding of effects of climate on breeding phenology is best developed for arctic-nesting waterfowl, whose breeding is normally initiated at or shortly after snow-melt; late melt delays breeding and often lowers breeding productivity as well, either for energetic reasons (e.g. Barry 1962, Davies and Cooke 1983, Ryder 1967) or through increased predation (Byrkjedal 1980). In extreme cases, it may lead geese to move to entirely new areas (McCormick 1988) or to abandon breeding altogether.

In Atlantic terrestrial ecosystems we know very little about the relation between climate and breeding phenology; in general at these latitudes breeding is probably initiated chiefly by changes in daylength (the 'proximate' factor in evolutionary terms) in such a way that the time of maximum energy demand coincides with increased food supplies (evolution's 'ultimate' factor) (Perrins and Birkhead 1983). In a changing climate the temporal relationship between daylength and food production will likely change, requiring adaptive changes by the bird populations.

Breeding success

Beyond general correlations between 'bad' (i.e. wet and cold) summer weather, and lower bird productivity, the influence of climate on breeding success has not been explored in Atlantic Canada. 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. Climate fluctuations in the north-west Atlantic over the last few hundred years, and their effects on fish and seabird populations, have been reviewed by Dunbar (1985), Dunbar and Thompson (1979), and Brown (1991).

Timing and success of migration

Migration is clearly timed 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 (17 C) isotherm (Lincoln 1979). In general, weather systems - rather than actual temperatures - probably govern the timing of migration. Peak waterfowl migration in fall usually follows 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).

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

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 (e.g. Henny *et al.* 1982), and summer storms can kill shorebirds on their breeding grounds (e.g. Morrison 1975) and greatly reduce breeding success among bird groups as varied as songbirds and seabirds (pers. obs.). Observations of such extreme events are essentially anecdotal, and it is uncertain what role they may play in determining population persistence in the long term; however if, as is widely predicted, they become more frequent during climatic change, more attention will need to be paid to their possible impacts.

Discussion

The current state of knowledge of climate /wildlife interactions is fragmented and poorly understood; it is not yet organized as a coherent field of research. Currently we can estimate general sensitivities of birds to climate change, in the very broad fashion outlined here, but we have very limited knowledge of the sensitivities of particular species.

Examination of three General Circulation Models (GCM's) (Taylor and Taylor 1996) suggests that despite the last few decades cooling trend, the portion of Atlantic Canada most likely to be affected by climate warming is central and northern Labrador, especially during the winter and spring periods. Because of the moderating effect of the oceans, the remaining regions whose climate is likely to change slightly are not as likely to how large changes.

However, measures currently available (e.g. monthly temperature means, precipitation totals) in the climatological record are of limited value in assessing ecological impacts of climate change. Estimates of precipitation on finer geographic and temporal scales, are needed to predict effects of climate change on biodiversity in general, including birds.

For historical and geographical reasons, universities and research institutions, as well as most of the region's population, are located in the southern, more climatically hospitable part of the region. This has caused a situation where most of the knowledge of hydrological and ecological conditions and processes is concentrated on the one third of the region which is least likely to be affected by climate change. Future research on climate change or climate variability impacts should be initiated in Labrador as this is the area most likely impacted by a changing atmospheric energy balance.

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6.2 Summary of other papers, and discussion on ecosystem science and water resources

H. Vaughan (Appendix G, Page 271) in his paper on the potential ecosystem effects of climate change, stresses that ecosystems may be able to cope with small, gradual changes but it is not known if they can deal with large scale, rapid changes or increases in variability and the frequency and severity of extreme events. He feels that the latter poses the greater threat. As an example of how interlinked different components of an ecosystem are to each other and to the climate, Vaughan cited the example of the Edmonton merlins. One year in Edmonton there was a late frost which froze the Saskatoon flowers, resulting in no Saskatoon berries. The local birds ate the Mountain Ash berries instead. When the cedar waxwings arrived on their way north, they did not stop because their accustomed food, the Mountain Ash berries, were depleted. As a result, the Edmonton merlins, which rely upon the cedar waxwings for food, suffered a population decline.

R. Miller suggests in his paper (submitted but not presented at the symposium, shown in Appendix L, Page 324) that efforts should continue to exploit proxy climatic records that are archived in terrestrial and marine sediments. These would include stratigraphic interpretation, radiocarbon chronology, pollen and arthopod records. The Younger Dryas event which took place about 14,000 to 10,000 years BP would be a good analogue for studying ecosystem change in the face of future rapid climatic change; temperatures during the Younger Dryas decreased by 5 to 7C in as little as a decade.

7. AGRICULTURE

7.1: Synthesis paper

A Review of Impacts of Climate Variability and Change on Agriculture in Atlantic Canada

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ABSTRACT:

Climate is one of the most fundamental natural resources needed for agricultural production. Along with soils, climate to a large extent determines the types of crops that can be successfully produced in the Atlantic region, where these crops can best be grown and the management practices that are used. A review of existing literature will be presented to highlight climate variability and change and the various impacts these have on agricultural production and management practices in the region.

Spatial variation in climate ranging from the micro-scale (on-farm) level to the broader meso- to macro-scale has a significant influence on crop selection and management. Temporal variability has greatest impact on the yield and quality of crops being produced in a given year and hence also directly impacts on farm profits. Relative to these factors, long term climatic change over the last 100 years or more has had much lesser impact on agriculture, although projected changes in future climate could become a significant factor in agricultural production in the region.

INTRODUCTION

The agricultural sector is particularly sensitive to climate change and variability because of its direct dependence on the weather/climate. Along with soils, climate, to a large extent, determines the types of crops that can be grown in the Atlantic region, where these are best produced, the yield and quality that is achievable with present-day technology and the types of management practices used. Some crops, such as grain corn, soybeans, winter wheat, tree fruits and grapes are presently marginal in many parts of the region but can be successfully produced where the climate is favourable. These types of crops are likely to be particularly sensitive to any climate change that may occur. Yearly variability in climate is large and has a very significant impact on crop yields and quality, and on the losses that are experienced due to such hazards as drought, frost, excess moisture and wind. The agricultural industry is continually challenged to minimize the negative impacts of climatic extremes that periodically occur. However, agriculture in the region may be considered as a 'success' story, achieving impressive gains in production over the years under what is often an inhospitable climate. In 1994, the region produced over 1.5 million metric tonnes of potatoes with a farm value of over $275 million (Statistics Canada, 1995). Farm cash receipts for all agricultural commodities totalled close to $1 billion in 1995 (Statistics Canada, 1996).

Climatic change could have a significant impact (either positive or negative) on the ability of the agricultural industry to compete with other regions, particularly if the frequency of occurrence of extreme conditions such as droughts, early fall frosts and excess moisture increases. Any impacts on the agricultural sector could have important spin-offs, since agriculture is a significant part of the regional economic activity. However, it is generally felt that the industry can adapt to gradual changes in climate that may occur over the next few decades or more.

This presentation will examine some of the current variability (both spatial and temporal) and long term trends in climate in the region, and highlight some of the impacts of these on agriculture. Other factors that could overwhelm the climatic impacts, and mitigation measures that can be taken to lessen the negative effects and take advantage of the positive changes that may occur will also be considered briefly.

CURRENT CLIMATE VARIABILITY AND IMPACTS

Spatial Variability and Impacts

Spatial climatic variations in the Atlantic region have considerable impact on agriculture, affecting such things as yield, quality, maturity and winter survival of crops and influencing management practices such as seeding and harvesting dates, pest and disease control measures, drainage and irrigation, crop selection and fertilizer inputs. Numerous descriptions of variations at the macro- to meso-scale level have been made, but interpretations of how these variations impact on agricultural production and management are frequently lacking. At this scale, the influence of large water bodies, major changes in relief (elevation) and latitude are fairly well identified.

Classification schemes developed in the early 1900's by Koppen and by Thornthwaite tended to be too broad (global) to be of practical use to agriculture in the region. Putnam (1940) published a detailed description of climate in the region, dividing the three Maritime provinces into eleven climatic zones. Other agroclimatic studies followed, including the Canada Land Inventory report by Chapman and Brown (1966) and the Agroclimatic Atlas of Canada (Agriculture Canada, 1976). Banfield (1981) provided a detailed description of the climate of Newfoundland relevant to agriculture. Dzikowski, *et al.* (1984) also prepared a detailed description of climate specifically for agriculture. These publications present spatial variations in average climatic variables of importance to agriculture such as heat units, frost-free period, growing season length, moisture deficits, potential evapotranspiration and precipitation. Other studies have focused on variations in a single variable such as annual water surpluses (Sanderson and Phillips (1967) or growing degree-days (Gordon and Bootsma, 1993). Some have focused on specific impacts of spatial differences in climate on crop production/management practices, such as cutting management of forage crops (Bootsma, 1984), optimum seeding period of winter wheat (Bootsma and Suzuki, 1986), field workdays available for spring and fall tillage (Baier, *et al.*, 1978: Dyer, 1980) and for harvesting small grains cereals (Dyer and Bootsma, 1979).

It is beyond the scope of this presentation to describe all of the spatial variations in climate that exist and their impact on agriculture. Some of the most important differences are related to temperature (heat units), soil moisture, growing season length, frost occurrence and severity of winter conditions. A few examples follow.

Spatial differences in heat units (CHU) available for corn and soybean production (Bootsma *et al.*, 1992) have significant impact on the production potential of these crops. Average CHU in the three Maritime provinces range from a high of about 2800 in the Annapolis valley to less than 1700 in northern New Brunswick. With present-day available hybrids, grain corn has good potential in areas with >2500 CHU, is marginal in 2300-2500 heat unit areas, and is generally not feasible in areas with <2300 CHU. Silage corn is generally not feasible in areas with <2100 CHU. These limits may be streched as improved early-maturing corn becomes available through breeding. Thus the availability of heat units has very significant impact on which crop species, varieties and/or hybrids producers choose to grow and on the productivity of their farms.

Growing degree-days above 5°C (GDD) vary from less than 1000 to over 1800 in parts of the Annapolis and lower Saint John River valleys (Gordon and Bootsma, 1993: Dzikowski *et al.* 1984). Differences in GDD particularly impact the potential on long season crops such as spring wheat, potatoes and forages. GDD in combination with growing season length affects the number of cuts that can be taken of various forage crops (Bootsma, 1984), thereby impacting on their productivity. Providing that adequate winter survival is achievable, areas with less than 1300 GDD generally have potential for only one cut of alfalfa, while up to three cuts may be possible in regions with more than 1800 GDD. Spatial variation in autumn temperatures result in differences in the time of the optimum period for seeding winter wheat. This period ranges from Sep. 10-25 in the Annapolis valley to the latter part of August in northern New Brunswick (Bootsma and Suzuki, 1986).

Spatial variations in winter climates have significant impact on survival (and hence the suitability) of overwintering crops such as winter wheat, clover, alfalfa, strawberries, tree fruits and ornamental trees and shrubs. Blackburn (1984) rated the susceptibility of winter injury to apples from low in the Annapolis valley to high in many areas of New Brunswick. The Annapolis valley probably has one of the most favourable climates for tree fruits in the region because of a combination of low susceptibility to winter damage and a long warm growing season (relative to other areas in the region) promoting good maturity and yield, while many other areas of the region which lack these characteristics are either marginally or not at all suited for tree fruit production. Significant differences exist in winter hardiness zones for ornamental trees and shrubs, with the area least susceptible to damage being the southwest tip of Nova Scotia and the severest region in north-central New Brunswick (Ouellet and Sherk, 1967).

Significant climate-induced differences in soil moisture deficits and spring field workdays occur in the region. Estimates for well-drained sandy loam soils at St. John's, Charlottetown and Kentville, respectively, indicate there are on average about 16, 24 and 31 days suitable for tillage and planting between April 1 and June 2, and 35, 75 and 110 mm of seasonal water deficits (Coligado *et al.*, 1968; Bootsma and Boisvert, 1987). These differences impact farm management decisions such as machinery size, labour requirements, irrigation and drainage system design. Regional differences in climate impact the need for and potential benefit of irrigation. Bootsma *et al.* (1996), using a crop growth model, estimated that average alfalfa yields would only increase by 0.5 t/ha at St. John's, but as much as 4 t/ha at Charlottetown using irrigation.

Significant variations in climate also can occur over short distances or the topo or farm scale. Nighttime minimum temperature and wind are particularly affected by topography and shelter. Surveys conducted in P.E.I. indicated that on-farm minimum temperatures during clear calm nights can vary by 6°C or more between hilltops and valley bottoms with elevation differences of as little as 35 m (Bootsma, 1976, 1980). As a result, the average date of the first fall frost can differ by 4 weeks or more on the same farm. This has important implications for a variety of frost sensitive crops such as tender fruits and vegetables, corn, potatoes, tobacco, blueberries and tree fruits, affecting field suitability for these crops and impacting on management decisions such as planting dates, harvesting dates and whether or not active frost prevention methods are needed. Crop damage inflicted by unusually early fall frost is generally greatest in low-lying fields which experience lower nighttime minimum temperatures than surrounding areas. Significant gradients in minimum temperature during some freeze situations may also be experienced on land influenced by large bodies of water such as the Northumberland Strait and the Bay of Fundy.

Temporal Variability and Impacts

Temporal variability in climate exerts perhaps even greater impact on agriculture than the spatial differences that are encountered in the Atlantic region. Variations that likely have the greatest impact on agriculture include excess moisture, unusually late spring or early fall frosts, drought, unusually severe storms, unfavourable overwintering conditions and exceptionally cool growing season weather. Yearly variability is perhaps the most difficult attribute of the climate that producers must cope with, having very significant impacts on crop yield, quality, field losses and on cost of production and economic returns.

Treidl (1978) provided statistics on variability (e.g. coefficient of variation, standard deviation, extremes) for a number of climatic variables of importance to agriculture. Information on spring and fall frost dates is generally presented for a range of probability levels, indicating the variability (Hornstein, 1961; Coligado *et al.*, 1968; Environment Canada, 1982). We evaluated variability in dates of last spring and first fall frost (0°C), GDD above 5°C, and May to September total precipitation (P) at four locations (Table 1). If variables are normally distributed, then about 5% of years will be more than ± 2 standard deviations from the mean value. Thus variations in spring and fall frost dates of 5 or 6 weeks are not uncommon. Heat units vary by more than 450 GDD and precipitation fluctuations of 350 mm are fairly common (extreme differences in growing season precipitation at Kentville is 477 mm!).

Excessively wet spring conditions can result in delayed planting dates, reduce yields, increase susceptibility to disease and increased risk of frost damage in the fall due to later maturity. The number of days suitable for field work between April 1 and June 2 can vary by more than 200% from year to year, ranging, for example, from less than 16 to over 35 days at Charlottetown (Table 2). This variability makes it difficult for growers to schedule field work activity and labour requirements and make the most appropriate machinery size selection for their operation. Excess moisture during the growing season can result in significantly increased disease pressure, particularly of foliar type fungal diseases such as potato blight. Quality of hay is particularly sensitive to weather conditions during field curing and losses in quality can be high during abnormally wet years. Wet conditions during the fall can result in serious field losses of crops by delaying the harvest, particularly when accompanied by early frosts. In 1974, such conditions resulted in losses in potatoes estimated to exceed $4 million in P.E.I. alone (The Guardian, Nov. 8, 1994). Unusually severe storms with heavy rain and wind can result in severe lodging of cereals and too much humidity at harvest can cause grain to sprout. Other negative impacts of excessive rainfall include leaching of soil nutrients (especially nitrogen) and chemicals into the ground water and increased erosion.

Unusually late spring or early fall frosts can have severe impact on agriculture, with the effects ranging from a partial loss of crop yield and/or quality to total loss of the crop. Crop insurance statistics from New Brunswick indicate that for the 1975-1984 period, 19% of indemnities for apples and 22.4% for strawberries were due to frost (Smith, 1987). In 1980 it was estimated that approximately 450 metric tonnes of tobacco with a farm value of over $1 million were lost because of frost on a single night (Province of P.E.I., 1981).

Although problems of drought are possibly less frequent than those associated with too much moisture, periods of moisture stress that significantly impact crop yields do occur. From 1980-1985, over 44% of crop insurance payouts (exceeding $4.4 million) to potato growers in New Brunswick were drought related (Smith, 1987). In 1975, exceptionally dry weather reduced average potato yields by about 15% on P.E.I. (Statistics Canada). At prices and acreages of the '90's, a drought of this severity could reduce the total farm value of the crop in P.E.I. alone by over $20 million (although in real life the situation is more complex since price may be influenced by supply).

Yearly variability in available moisture affects the amount of irrigation water needed and how the crop responds. Water supply is adequate in many years, but seasonal deficits typically exceed 120 to 150 mm at 5% probability (1 year in 20) on well-drained loam soils at many locations (Coligado *et al.*, 1968). Irrigation increased potato yields in field trials on P.E.I. by more than 8 t/ha in 3 out of 7 years from 1988-1994, while in the other 4 years there was no significant increase (White and Sanderson, 1995). Yields were increased by more than 60% in 1994, an exceptionally dry year.

Variability in overwintering conditions can have severe impact on the survival of crops such as alfalfa, clover, winter wheat, strawberries and tree fruits. Frequent freeze/thaw cycles and extreme cold during periods with little or no snow cover can be particularly hard on these crops. In 1972 almost the entire strawberry crop was wiped out in P.E.I. and severe damage was inflicted of alfalfa, clover, orchard grass and winter wheat (Suzuki, 1972). Total strawberry production in the Maritimes was reduced by about 60% from the previous year, or by a farm value of almost $1 million (Statistics Canada). Surveys from historical records (Suzuki *et al.*, 1975) indicate that climate variability results in winter injury ranging from little to none in some years to severe in others (Table 3).

From these examples it is clear that large temporal variability in climate has a very significant impact on agriculture in the region, influencing crop production, final yield and economic returns to producers. These impacts have spin-off effects on service industries and on the economy of the region as a whole, since agriculture is a very significant part of the regional economy.

CLIMATE CHANGE AND IMPACTS

Past Changes in Climate

For this presentation we will primarily consider climatic changes over the last 100 years or so, since changes over a longer time are generally beyond the planning time frame that is useful for agriculture. There is evidence that the climate has changed significantly since the period of the 'little ice age' from around 1400-1900 A.D. (Environment Canada, 1995). The year 1816 has been labelled as 'the year without a summer', and personal diaries indicate occurrences in the 1800's when buckwheat was frozen in the middle of July on P.E.I. However, it is debatable whether the warming which has occurred since then was due to the enhanced greenhouse effect or due to other causes.

Changes in both average climate and in variability can occur. The Atlantic region has apparently not followed the national warming trend of about 1°C during the last 100 years. Trends indicate that there was slight gradual warming from around 1900 to the 1950's, cooling from the '50's to the 1970's and a levelling off in the '80's (Phillips, 1990; Berry, 1991; Gullett and Skinner, 1992; Bootsma, 1994). Morgan *et al.* (1993) observed a remarkable similarity between air temperature trends and sea surface temperatures in the North Atlantic, but indicated that definite cause and effect relationships had not yet been established. Lack of increase in daily minimum temperature may be partly due to lack of change in cloud cover in the region, since there seems to be evidence that increased cloud in other parts of north America has raised nighttime minimum temperatures and reduced day/night temperature range (Karl *et al.*, 1993; Environment Canada, 1995). Overall, the temperature changes are relatively insignificant and likely have had little or no impact on agriculture compared to that of climatic variability.

Precipitation seems to have increased and become more variable over the past 100 years (Danard, 1990; Phillips, 1990; Bootsma, 1994). This may have impacted agriculture through reduced drought stress but may have increased problems in coping with excess moisture. Increased variability may have resulted in greater fluctuations in crop yields in recent decades, although no data are presented to support this. While long term changes in precipitation are statistically significant, they are still relatively small in comparison to the yearly variability that growers must contend with.

We recently examined long term trends in selected climatic variables at 8 locations (Table 4) in the region, using linear regression and correlation analyses. No attempt was made to test for or remove inhomogeneities in the data, although in a few cases stations were relocated to another site or alternate nearby stations were used for part of the period of record. Missing data were estimated using adjusted values from nearby stations. Results indicate that May to September precipitation increased significantly at most locations (Table 5), confirming the trends observed by others. GDD showed no positive correlation with time at six locations, confirming the lack of overall warming trend. Several locations had significant trends in frost-free period, although this variable is quite sensitive to minor changes in station elevation or exposure.

Correlations between 5-year moving standard deviations and time indicate significant increases in variability in precipitation but not in GDD at most locations (Table 6). Spring and fall frosts appear to have become more variable over time at some locations, but less at others.

Long term trends in yearly values of May-Sept. precipitation and GDD, and their standard deviations, are shown for four locations in Figures 1 and 2. Linear regression trends are shown where these are statistically significant. These figures clearly show the extent to which climate variability overwhelms any long term gradual changes.

Impacts of Climate Change

From the foregoing analyses, we can conclude that climate change over the past 100 years has had relatively little impact on agriculture compared to the variability, with the possible exception of precipitation which appears to have increased and become more variable. Changes over the longer term (centuries) likely have had significant impact, but these are beyond the planning time frame of agriculture.

Few studies have investigated the potential impacts of possible future changes in climate in the Atlantic region. Bootsma *et al.* (1984) examined the possible effects of warmer/cooler and wetter/drier conditions on crop yields by processing hypothetical scenarios through a crop growth model. Results for the Annapolis valley suggested that a rise in temperature with no change in precipitation would tend to reduce yields due to higher moisture stress. Estimated yields tended to increase slightly if precipitation increased and decrease with lower precipitation with no temperature change. The study had several weaknesses common to many studies of this nature: i) the direct effects of rising CO_2 concentrations on crop growth, although likely to be quite significant, were not considered; ii) no attempts were made to consider adaptation to change using different or new crop species or varieties; iii) there was no indication of which scenario is most likely to occur (predictions of this are still very uncertain in our opinion); iv) reliability of the model for predicting impacts of change on yield was uncertain.

Stewart and Muma (1990) looked at the possible impacts of climate change under a $2XCO_2$ scenario, based partly on outputs from three General Circulation Models (GCM's). They concluded that the potential for corn, soybeans and winter wheat would increase significantly in the region mostly as a result of warming, and expected that the P/PE ratio would reduce slightly towards more optimum conditions for crop production. However, higher temperatures would tend to shorten the growth period of many crops which could reduce yields unless there was a shift to longer season varieties. They also concluded that a 1 to 2°C cooling would eliminate many crops from the region, including corn, soybeans, spring wheat, many specialty crops and tree fruits.

The sensitivity of potato yields in P.E.I. to climatic variables was studied by Gordon and Asiedu (1990) by using a multiple linear regression model developed from yield data from the 1911-1987 period. Results indicated that above normal temperatures in spring were associated with higher yields, while yields tended to decrease with departures in summer temperatures either above or below normal values. Cautions must be exercised in interpreting the results, however, as regression coefficients do not necessarily explain cause and effect relationships. Their model also contained time trends which indicated that the impact of technological improvements on potato yields was far greater than that of climate over that period.

While the above studies may give some general indications of agriculture's sensitivity to a warmer and a wetter or drier climate, none of them consider the direct effects that continually rising concentrations of CO_2 in the earth's atmosphere may have. CO_2 is one of the principal 'greenhouse' gases in the atmosphere which is expected to cause global warming. Concentrations have increased by more than 25% since the start of the industrial revolution (Environment Canada, 1996). While often looked at as a pollutant, it should be noted that additional CO_2 acts as fertilizer to the plant and a doubling of its concentration is likely to have a beneficial effect on growth and yield. Increased concentrations of CO_2 particularly promote more rapid photosynthetic rates in what are known as C_3 plants ('inefficient' species), such as soybeans, small grains cereals, most grass species and alfalfa, but less so in C_4 plants ('efficient' species) such as corn (Warrick, 1988). In both types of crops the extra CO_2 is also expected to increase water use efficiency by reducing plant transpiration rates. Some studies have suggested that yields of some crops could be enhanced by as much as 50% with a doubling of CO_2 concentrations.

Climatic changes that may occur in the future could have significant impact on agriculture in the Atlantic region. Rising CO_2 concentrations accompanied by a warming trend would be beneficial to agriculture, particularly if new crop varieties that are better adapted to any changed conditions are selected. Warming could be expected to improve the competitiveness of the agricultural industry by expansion of production in corn, soybeans, tree fruits and specialty crops. Change to wetter or drier conditions could have both positive and negative impacts. Increased moisture supply would reduce yield reductions due to drought, but likely result in increased disease pressure (particularly from foliar-type fungal diseases such as potato blight, which thrive in wet weather), increase the leaching of nutrients and chemicals to the ground water, reduce the number of days suitable for field work and result in greater soil erosion. A change to drier conditions would have the opposite effect. Milder winters could significantly impact the survival of many crops such as alfalfa, clover, winter wheat, strawberries, tree fruits and grapes, and improve the potential of these crops in many areas. However, negative effects on survival could be experienced in some areas where warming results in less reliable snow cover.

The agricultural industry should, in general, be able to adjust relatively well to any long term gradual changes in climate that may occur, taking advantage of any improvement in conditions while minimizing the negative impacts of less favourable climate. Variability and extremes in climate that will occur will likely have greater impact and be more difficult for producers to cope with. In general, any progress that can be made in reduce the negative impacts of climatic extremes should help the industry to cope with any long term climate changes that may occur.

Some Possible Overriding Factors

Because of the expected gradual nature of any climatic change, it is quite likely that a number of other factors will have overriding impact on agriculture and on people's lives in the future. It is not our intent to predict which factors will be most important. However, some of the following are likely candidates (not necessarily in order of importance):

i) Soil degradation and its impacts on long term sustainability of agricultural production.
ii) Environmental and food safety issues are becoming increasingly important public concerns.
iii) Impacts of global economy, interest rates, etc.
iv) Supply/demand for food and their impact on prices.
v) Changes in costs of production (e.g. energy, fertilizer, chemicals, labour).
vi) Further developments in farm mechanization (in the past this has drastically reduced the percentage of the population involved in primary agricultural production).
vii) Consolidation of farms into larger units.
viii) Political changes, free trade (e.g. NAFTA).
ix) Appearance of new weeds, pests and/or diseases or mutated strains of present diseases (e.g. potato blight) for which present control measures are less effective.
x) Government stabilization and subsidy programs, crop insurance.

Climate change could influence the extent that some of these factors impact on the agricultural industry. For example, the impact of unfavourable commodity prices, interest rates and energy costs would likely be greater if these were combined with climatic conditions less favourable to agriculture, putting additional strain on the economic well-being of individual farm units.

Mitigating Factors

There are measures that could be implemented that would reduce the negative impacts of climate change and take advantage of any improvements in the climate that may occur. A few examples follow:

i) Increased use of irrigation and wider adoption of soil management practices and crop rotations which build up soil organic matter levels would make agriculture more resilient to the effects of drought.
ii) Wider adoption of drainage practices and erosion control methods such as cover crops, grassed waterways, contour plowing and reduced tillage would help to offset negative effects of higher rainfall.
iii) Increased adoption of active and passive frost prevention methods. (Active methods include those used at the time frost occurs, such as sprinkling irrigation, covering, wind machines or helicopters; passive methods are taken well before frost occurs, such as crop selection, field selection, planting/harvesting schedules and windbreak management).
iv) Increased efficiency in field tillage, planting and harvesting operations through improvements in machinery, adoption of minimum or zero tillage, appropriate machinery size selection. Negative effects of reductions in available field work caused by climate change could be offset by some of these measures.
v) Develop new crop varieties that are better adapted to existing or changed climate or climatic extremes and improved agro-chemicals and/or management practices to control weeds, pests and

diseases. Probably the bulk of present day research efforts by both industry and government are focused on these areas.

CONCLUSIONS

The agricultural sector of the economy is heavily dependent on climatic conditions for successful crop production and is therefore highly vulnerable to climate change. Nevertheless, it is generally felt that agriculture can readily adapt to the kinds of changes that have occurred over the last 100 years or so. If continued rise in 'greenhouse gas' concentrations in the earth's atmosphere lead to some warming without drastic change in precipitation, the region would likely stand to benefit through increased agricultural productivity. Spatial and temporal variability in the climate have greater impact on agriculture than is likely to be experienced as a result of climate change in the next few decades. The continual challenge is for agriculture to become more resilient to climatic extremes that periodically occur and, in so doing, should be in a good position to cope with climatic changes that may be experienced in the Atlantic region in the future.

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Table 1. Statistics on selected agroclimatic variables at four locations in the Atlantic region.

Station/Province/ Period of record	Variable*	Mean value	Standard deviation	Extreme values	
				low/earliest	high/latest
Fredericton CDA, N.B. 1921-1994	SF	May 17	9.3	Apr. 25	June 14
	FF	Sep. 28	8.4	Sep. 11	Oct. 21
	GDD	1714	112	1451	1930
	PREC	439	91	230	648
Kentville CDA, N.S. 1914-1994	SF	May 20	10.8	Apr. 25	June 15
	FF	Oct. 2	11.8	Sep. 9	Nov. 2
	GDD	1781	119	1459	1999
	PREC	402	94	219	696
Charlottetown CDA, P.E.I. 1889-1991	SF	May 15	9.7	Apr. 26	June 10
	FF	Oct. 15	9.7	Sep. 12	Nov. 11
	GDD	1680	121	1412	1955
	PREC	416	84	212	640
Deer Lake, Nfld. 1934-1994	SF	June 9	12.3	May 8	July 9
	FF	Sep. 15	16.7	July 19	Oct. 20
	GDD	1222	124	954	1482
	PREC	434	84	264	671

* SF =Date of last occurrence of 0°C or lower in spring; FF =Date of first occurrence of 0°C or lower in fall; GDD = Growing degree-days above 5°C accumulated over the length of the growing season; PREC =Total precipitation, May-Sept. (mm).

Table 2. Estimated minimum number of field work-days from April 1 - June 2 for well-drained sandy loam soil at three probability levels and four locations (from Baier *et al.*, 1978).

Location	Probability level		
	10 %	50 %	90%
Fredericton, N.B.	42	32	24
Kentville, N.S.	38	31	22
Charlottetown, P.E.I.	35	24	16
St. John's, Nfld.	34	16	9

Table 3. Frequencies of winter injury to clover, alfalfa, winter wheat and strawberry plants in P.E.I. (from Suzuki *et al.*, 1975).

Crop	Little or no injury	Considerable to severe injury	No. of years surveyed
Clover	1/1.9	1/4.7	75
Alfalfa	1/2.2	1/4.7	28
Winter wheat	1/3.3	1/3.3	10
Strawberries	1/3.1	1/4.9	34

Table 4. Climatic stations used in long term trend analyses.

Location	Station name	AES #	Elevation (m)	Period of record used
Grand Falls, N.B.	Grand Falls	8101900	152	1921-1965
	Grand Falls Drummond	8101904	229	1965-1992
Fredericton, N.B.	Fredericton CDA	8101600	40	1921-1994
Sussex, N.B.	Sussex	8105200	21	1900-1994
Nappan, N.S.	Nappan CDA	8203700	20	1916-1994
Kentville, N.S.	Kentville CDA	8202800	49*	1914-1994
Charlottetown, P.E.I.	Charlottetown	8300298	12	1889-1910
	Charlottetown, CDA	8300400	23	1910-1991
Deer Lake, Nfld.	Deer Lake	8401500	11	1934-1994
St. John's, Nfld.	St. John's	8403500	38	1935-1941
	St. John's Torbay A	8403900	140	1942-1950
	St. John's West CDA	8403600	114	1951-1994

* Kentville CDA was at 30 m elevation prior to April, 1960.

Table 5. Correlation coefficients (r) between selected agroclimatic variables and year at eight locations in the Atlantic region.

Variable	Location and period of record							
	Grand Falls N.B. 1921-1992	Fredericton N.B. 1921-1994	Sussex N.B. 1900-1994	Kentville N.S. 1914-1994	Nappan N.S. 1916-1994	Charlottetown P.E.I. 1889-1991	Deer Lake Nfld. 1934-1994	St. John's Nfld. 1935-1994
FAI	-.38**	-.27*	-.18	-.19	-.24*			
SF	-.45**			-.32**				
SF-2	-.26**					.17		
FF			.21*	.31**		-.22*		
FF-2						-.32**		
FFP	.39**		.24*	.42**		-.18		
FFP-2	.23			.23*	-.25*	-.33**		
GDD			.20*	.39**				
CHU			.30**	.41**				
GSS				-.24*				
GSE	-.26*							
GSL				.26*				
PE	-.36**	-.25*		-.26*			-.35**	
PREC	.47**	.23*	.28**	.21	.36**	.24*	.27*	
JAN								
JUL								
SNOW	.19		.32*	.35**		.21*	.58**	-.32*

**Significant at P=.01; *Significant at P=.05; Coefficients without asterisks significant at P=.10; Coefficients not shown were not significant at P=.10. FAI =Forage aridity index; SF =Last spring frost, 0°C; FF =Fisrt fall frost, 0°C; SF-2 =Last spring frost, -2°C; FF-2 =First fall frost, -2°C; FFP =Frost free period, 0°C; FFP-2 =Frost free period, -2°C; GDD = Growing degree-days >5°C: CHU =Corn heat units; GSS =Growing season start; GSE =Growing season end; GSL =Growing season length; PE = Potential evapotraspiration; PREC = May to Sept. precipitation; JAN = January mean air temperature; JUL=July mean air temperature; SNOW = Total snowfall, Oct. to March. (For more detailed explanation of variables, see Bootsma, 1994).

Table 6. Correlation coefficients (r) between 5-year moving standard deviations of selected agroclimatic variables and year at eight locations in the Atlantic region.

Location	SF	FF	GDD	PREC
Grand Falls	-.30*		-.35**	
Fredericton	.42**	.53**		
Sussex	.25*	-.46**		.25*
Kentville		.35**		
Nappan	.43**	.43**	.31**	.25*
Charlottetown	.30**	-.56**		.52**
Deer Lake	-.35**			.52**
St. John's		-.36**		-.44**

7.2 Summary of other papers and discussion on agriculture

R. Shaw and B. Döös (Appendix H, Page 275) presented a spreadsheet model which could be used to examine the balance between demand for crop commodites from human consumption, animal feed, etc., and production which depends upon a combination of cultivated area and yield, among other factors. Human consumption will change due to population increases and changes in diet (for example, a shift to more meat) while production could be affected by environmental factors including climate change. The model has been used to examine for ten world regions the effects of various scenarios of atmospheric change , including climatic change, tropospheric ozone, and increased UV-B radiation from the depletion of the stratospheric ozone layer. Because reliable predictions of climatic change on a regional (as opposed to global) scale are still some time away, the authors suggest that the spreadsheet model could be used to carry out sensitivity analyses of the relative importance of uncertainties in predictions of various elements of climatic change. Policies could then be designed that would be as robust as possible with respect to the most sensitive parameters.

There were three papers that dealt with changes in the *radiative* climate to which agricultural crops are exposed - an increase in UV-B radiation due to a depletion of the stratospheric ozone layer. Y. Papadopoulos reported on an examination, using greenhouses, of the effect of depleted UV-B radiation, ambient levels and levels elevated by 2 and 3 times on the growth of timothy grass and alfalfa. Plant heights were measured every two weeks and dry matter yield was monitored. He reported that it was not possible to detect any significant effect upon growth of the differing UV-B levels during the year of seeding. Further studies are being carried out to see if there are any cumulative effects. In response to a question, Papadopoulos stated that studies in Ontario had found that broad-leafed plants (soybean) were somewhat sensitive to increased UV-B radiation.

R. Gordon described a field evaluation of a UV-B exclusion system used to study the sensitivity of plants to increased UV-B radiation. Two materials, used in open-ended greenhouses, were examined: cellulose diacetate which allows radiation of wavelength 280-320 nm to pass through, and polyester which filters out that band of radiation. Gordon reported that photodegradation of the filtering materials was observed, and that there was a significant shading effect (about 20%) from the framework of the greenhouses. These factors must be taken into account when interpreting the results of experiments.

R. Bush reported on the search for proteins in plants that would serve as markers to indicate a tolerance to increased UV-B radiation. These substances would serve as "sunscreens". The plant material was ground up and put on a gel. Thus far no substance has been found that acts to block UV-B radiation, but work is continuing.

8. FORESTRY

8.1: Synthesis paper

Climate Change, Potential Impacts and Forestry Research in the Atlantic Region of Canada: A Synthesis

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INTRODUCTION

Increasing levels of carbon dioxide (30% since 1750) and other greenhouse gasses (Methane 145% and NO_2 15% since 1750) are expected to alter climate (Houghton, *et al,* 1990). Doubling CO_2 concentrations in the atmosphere may be achieved by the year 2056 (Jenkins and Derwint 1990). Mean annual global increases of air temperature of 0.5 °C in the last century are evident. Mean temperature in Canada has risen 1.1 °C nationally and 1.7 °C regionally in the past century (Gullett and Skinner 1992) and temperature increases are expected to be greater in winter than in summer (McElroy 1994). These temperature increases are also expected to be greater at higher latitudes and are expected to approach 3-4 °C in parts of Canada (Hansen, *et al,* 1988) with some projections for doubled CO_2 concentrations as high as +8-12 °C in the winter (Hengeveld, 1991). Recent modelling results (Santer, *et al* 1996, work cited in Kerr 1995) have tentatively implicated greenhouse effect in climate warming since 1950, using both climate forcing by greenhouse gasses and aerosol cooling by the reflective haze in the northern hemisphere. Of relevance to Atlantic Canada, is the significant increasing trends in mean annual temperatures of the North Eastern forest region (Ontario to Labrador coast) over the last 100 years (increase of 0.5 °C). The Maritimes (PEI, NFL, NB and NS), however, shows no significant trend with a small rise of 0.4 °C (Gullett and Skinner 1992), with most of the warming projected for the winter and spring and a cooling influence in the autumn (Hengeveld, 1991). With these competing influences together with the effects of aerosol cooling, it may not be unreasonable to postulate changes in seasonality, increased climate variability and more extreme weather events. This scenario is likely to have more serious consequences to forest health than a small rise in mean temperature both in terms of wide spread tree decline phenomena (Auclair, 1987: Cox and Malcolm, 1997) and insect outbreaks (Flemming and Volney, 1995). In addition if this climatic instability leads to increased incidence and severity of storms due to increased vigour of the hydrological cycle we may expect more large scale blowdown in the forests of Atlantic Canada.

FOREST RESPONSES

The forest of Atlantic Canada can respond to these changes in climate by alterations in: 1) growth rates; 2) forest extent; 3) carbon sink-source relationships; 4) species composition; and 5) disturbance regimes.

Growth rates

Climatic factors may influence growth rates and carbon sinks: predicted temperature changes indicate warmer winters and springs but cooler summers for most of the Maritimes (Hengeveld, 1991). This may increase growth rates of conifers if the length of growing season significantly increases due to the warmer springs. Warmer soils also means faster nutrient cycle and more nutrients. Modelled responses (Joyce *et al,* 1995) suggests mean increase in productivity in the northeast US of 33.4% for spruce-fir and 25.2% for Maple-beech-birch. These results however, were highly variable for the projected period of 75 years. Certainly, earlier springs would have to be accompanied by an extension of frost free days here in Atlantic Canada, as late frosts or early extended thaws would be more damaging to the hardwood species with early phenology if refreezing occurred after dehardening of buds and roots. Such early species would be those of birch, aspen and maple (Auclair 1987, Cox and Malcolm 1997).

The amount of light or photosynthetically active radiation (PAR) would be dependent on cloud cover, fog, and haze. Cloud cover is likely to increase generally due to increased energy in the hydrological cycle, however, it is at present uncertain what the changes will be in the Atlantic region. Enhanced UV-B exposure due to the depletion of the stratospheric ozone layer may also be a factor affecting tree growth. Although the majority of plant species that have been tested to date were agricultural plants, trees appear to run a higher risk of accumulating UV-B damage over their far longer lifetimes (De Gruijl 1995). More subtle changes, such as a delay in flowering, changes in leaf structure and metabolism, as verified in field studies (SCOPE, 1993), and in laboratory studies (Gordon 1995: Gordon *et al* 1995), may have far-reaching consequences as these may change competitive relationships, which can in turn, cause shifts in plant populations and in biodiversity.

Projected changes in precipitation indicate little change for the Maritimes perhaps a little dryer towards northern Newfoundland (Bergeron and Flannigan, 1995). Better water use efficiency due to increased CO_2 concentrations will aid in offsetting this deficit.

Forest extent

Changes in forest extent in the due to melting permafrost is not an issue in the Maritimes but changes in tree line at altitude may occur. Extensions of agricultural land in the central and northern New Brunswick and southern Nova Scotia may be a factor (Hengeveld, 1991)..

Carbon sink-source relationships

Gains in carbon storage due to higher productivity will be offset in some part by increased decomposition rates in the soils and peat. Transient losses in the mature forest due to disturbances may account for additional loss in carbon storage. Sink strength of the young forest could be negated by other stresses such as air pollution, especially tropospheric ozone (Cox and Malcolm 1996), acid rain and acid fog (Cox *et al* 1995). The importance of a more accurate assessment of the carbon cycle of temperate deciduous and mixed forests present in the Atlantic region is given by Lavigne *et al* (Appendix J, Page 309).

Forest sector response is driven by market forces and competition for exports. Higher inventories due to higher biomass production, at least in some conifers, may lead to lower stumpage rates and higher harvest here. Strategies should be developed both nationally and internationally that allow maximization of carbon storage from our mature forest either as biomass or forest products in the light of possible increasing forest disturbances and a need for salvage operations. These activities, however, should not detract from efforts that maximize the growth and production of our carbon sink, our young forest.

Species composition

Changes in species composition in the long term may be affected by slow changes in biome distributions in the Maritimes. There is some expectation, for a move to a more temperate mixed forest, with some loss of boreal characteristics (Rizzo 1990 cited in Hengeveld 1991). In the short term, transient behaviour of our forests will depend on the adaptability of each species population in the current forest and the regional manifestation of climatic change. Current research in the region is underway to determine the limits of adaptation of black spruce to drought (Major and Johnsen 1996) and to photoperiod and CO_2 enrichment (Johnsen and Seiler 1996). The response of sugar maple to snow removal and frost penetration of soil and roots have been investigated (Bertrand *et al* 1994) together with the responses of birches to winter thaw duration and frequency (Cox and Malcolm 1997). Responses of two birch species to marine fog frequencies have also been investigated (Cox *et al* 1995: Hughes and Cox 1994).

Rate of migration from refugia can be estimated and modelled from pollen records. The conservation of refugia and habitats of rare species assemblages is necessary to maintain species diversity and the provision of potential pre-adapted populations. The environment for seedling establishment can be projected using GCMs using climate surfaces of specific variables (Flannigan and Woodward 1993). There is a need to interpolate the GCM's output on to the three dimensional landscape to determine spatial shifts in habitat requirements of specific species (Bourque, Appendix J, Page 281). Changes in succession due to changed competition under higher CO_2 and nutrients needs to be incorporated within gap dynamics models used at present to predict species composition.

Disturbance regimes

Forest disturbances usually refer to catastrophic events which trigger a change from a renewal phase to a release phase of a successional cycle. Li and Apps (1995) have suggested that understanding disturbance regimes in the forest is a prerequisite to modelling and understanding forest dynamics, and that this requires spatial models, without which no realistic simulation can match the natural species abundance and composition.

The main types of disturbance in the Atlantic Region likely to respond to climate change are fire, insect outbreaks, climate related decline phenomena, storm damage (blow downs), browser population (deer) and human population migration (associated forest harvesting).

Fire: Fire burns an average 1-2 Million ha each year in Canada. Mean annual burns in New Brunswick's Acadia forest up to 1975 were 1200 ha. Relevance of this to the Maritimes under climatic change is indicated in Changes in the simulated Fire Weather Index (FWI) using the AES General circulation model under 1 times CO_2 and 2 times CO_2 scenarios, carried out by Bergeron and Flannigan (1995). This computer simulation indicated that changes in FWI are variable over eastern Canada. The predicted changes in FWI would vary from being reduced in the southeast boreal in southern Quebec, with only slight increases in the southern Maritimes, increasing slightly more over Cape Breton and east Newfoundland. The uncertainty in these predictions, however, are increased by other disturbances such as blowdown, insect outbreaks, and declines, which affect fuel quality and fire risk.

Insect outbreaks: Major contributors to disturbance regimes in the Maritimes forest are insects, outbreaks of which, exert a large influence on forest productivity. In Canada, on average 51 million m^3 of wood are lost per year to insect damage, and represents one third of the harvest volume (Hall and Moody 1994).

The Balsam Woolly Adelgid was introduced from Europe just prior to 1900 by 1930 was found in Nova Scotia, PEI, Fundy Coast, by 1934 had spread south to New Brunswick, Maine and most of Vermont. By 1950 it was in New Hampshire and had moved more slowly north into parts of Cape Breton and Newfoundland. There was a serious outbreak in Nova Scotia from 1970-71; 67% of the fir were affected from Barrington to Shelburne. This insect seems to be controlled in its northward extension due to intolerance of dormant adelgids of temperatures <-34 °C. (Bryant 1995; Johnson 1986). It is likely that this insect would present a serious problem if the winter temperature of the Boreal forest increased.

Another introduced insect vector of beech bark disease (parasitic bark fungus *Nectria coccineea*) the beech scale insect was introduced to Halifax in 1890. This insect carried the disease slowly into Nova Scotia's hardwood forests west to New Brunswick, Quebec, New England and to New York by 1970 and is responsible for the removal of beech as a dominant tree in the Eastern North American forest. By 1970 there was evidence that beech escaped the disease at altitude and in the northern parts of their range, indicating that this insect too, may be limited by climate (Johnson 1986) and thus, may respond to a warmer winters under climatic warming.

It has also been suggested (Flemming and Volney, 1995) that, in the northern limits of the spruce budworm, that ends of outbreaks may be associated with late spring frosts that destroy the early foliage. As climate warms, fewer late frosts may increase the length and severity of outbreaks in these northern areas. Defoliators populations such as the spruce budworm may also respond to climate change in another way, as their population cycle may be controlled by two univoltine parasitoids (Royama, 1992). This control which is reliant on the synchrony between the host larval stage and the parasites adult stage may be broken in warm springs if larval development outpaces that of its parasitoids' (Flemming and Volney, 1995)

Climate related decline phenomena: An important example of a decline phenomenon linked to climate was the birch decline of the 1930's in eastern North America. This resulted in an estimated stem volume loss of 1400 Million m^3 of yellow and white birch over an area of 490,000 km^2 (Pomerleau 1991). Winter thaws have been implicated in this decline (Braathe 1957 and 1995: Cox and Malcolm 1997). Auclair (1987) has discussed the role of winter thaw in the other hardwood species. Thaws have also been proposed as the cause of dieback in all but a few hardy commercial apple cultivars in New Brunswick (Coleman 1992). Studies by Pomerleau (1991) have linked root depth of birch to degree of decline. In addition, using snow removal studies, he was able to link thaws and deep soil frosts with decline. This effect of soil freezing was also noted by Bertrand *et al* (1994) using snow exclusion from the ground under sugar maples.

Freeze induced damage was noted by Sperry *et al* (1988) who observed seasonal occurrence of xylem embolisms in sugar maple, which reached a maximum of 84% in February. The authors also suggested that recovery from this injury was driven by spring-time root pressure.

Extensive xylem cavitation was also documented in birches showing crown dieback in New Brunswick (Greenidge 1951) but at the time, was not attributed to winter thaw freeze cycles. Auclair (1993) has noted that the long time between winter cavitation and the development of symptoms has made it more difficult to recognize the cause of the injury. Results from winter thaw simulations, using paper birch and yellow birch, (Cox and Malcolm 1997 and in Appendix J, Page 289) indicate that combinations of accumulated winter cavitation and root damage caused by thaw duration that allow dehardening of roots prior to refreeze are key factors in birch dieback. In addition it was shown that yellow birch was more sensitive to thaw durations than paper birch.

Storms and large scale blow-downs: The Atlantic Region lies exposed to ocean storms and hurricanes which cause large amounts of damage and influence cutting practices (Johnson 1986). Major events causing forest damage which influenced cutting practices are shown in Table 1. This table shows an increasing effort in the salvage of blowdown in recent times, due to a shortage of wood supply, and jobs. Government subsidies for salvage and the fast and organized response of the forest industries to the large Christmas Mountain blowdown in 1994 proved responsible for maintaining the carbon storage of this forest as forest products. Good forest management of the salvaged areas will insure sustainability of the forest and return the areas to a strong carbon sink. Storm damage (blowdowns) may possibly increase in severity and frequency with global warming due to a more intense hydrological cycle. The effects of increased forest disturbances as described above serve to open the canopy and may exacerbate blowdown situations, as will the move towards more softwood plantations.

Browser populations: Warmer winters, less snow accumulation may lead to extensions of overwintering areas for deer which means more available food and decreased predation. These effects can, in turn, lead to higher population levels which can impact regeneration and lower species diversity.

Uncertainties

There is little research and much uncertainty concerning multiple effects of climatic factors and other stresses such as air pollution i.e. SO_2, NH_4, No_x and O_3, together with deposition of acidifying substances and heavy metals. The effects of enhanced UV-B exposure needs consideration. There is a need to determine which of these stressors may predispose trees to climatic effects. For example ozone is known to change carbon allocation in forest trees favouring above ground biomass at the expense of roots. This effect may leave trees more vulnerable to drought, nutrient deficiency, blowdown and reduce capabilities of some hardwoods to recover from winter cavitation injury. The long term effects of population migration (associated forest clearing and harvesting) due to extension of farmable land and industrial development are also uncertain these will be added to by movements of people due sea level rise .

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TABLE 1.

MAJOR STORM BLOW-DOWN IN THE MARITIMES FOREST

Year	Date	Name	Location of Maximum Impact	Forest Losses	Notes
1869	Oct 5	Saxby Gale	South NB - North NS	Whole tracks of forest were uprooted	Large tidal wave covered Tantramar marsh
1873	Aug 24	August Gale	North NS - Cape Breton	extensive forest damage	
1953	Sept 7	Carol	North Shore NS	Blow down in patches Halifax - Yarmouth	Most blowdown in partially cut stands within 30 miles from ocean coast
1953	Dec 1	Unnamed storm	North Shore NS	Moderate damage to trees	Most damage accounted for with Edna
1954	Sept 11	Edna	Central NB Woodstock-Chatham	Massive blowdown of forest. 700 million board feet in NS. 300,000 cords salvaged	Bark beetle outbreak followed this disturbance
1974	Oct 20	Unnamed storm	Annapolis Valley, NS	Heavy forest damage reported	No salvage reported
1976	Feb 2-3	Ground Hog Day Storm	NS Bay of Fundy, South NB	Heavy losses due to tree breakage Some forest damage	Extensive flooding $4M paid by NS Gov. for salvage operations (first known assistance for salvage).
1976	Mar 2-3	Unnamed Storm			
1994	Nov 7	Christmas Mountains Blow Down	Central East NB	>30 million trees blown down = $100M. 2,015,000 m^3 of wood salvaged	44% rebate on stumpage as incentive to salvage by NB Gov. Most fir >80y old.

8.2: Summary of other papers and discussion on forestry

There were two other papers dealing with climate-related forest damage. R. Cox and J. Malcom (Appendix J, Page 289) described an investigation of dieback of paper and yellow birch due to winter thaw conditions. The authors conclude by suggesting that dieback in paper birch would be greatest in winters when there were large numbers of thaw/freeze events, which would maximize development of xylem embolisms, followed by a prolonged thaw, which would maximize damage to the roots, thus preventing refilling of the cavitated xylem. Such prolonged thaws prior to a -5 °C frost and their distribution have been linked them to birch dieback. These events may become more frequent and occur over wider areas under climate warming, a scenario which generally increases risk to northern adapted hardwoods in eastern Canada.. In response to a question, Cox stated that genetic variations in plant responses have been observed and that they hope to do some work in that area soon.

K Harrison presented a paper by E. Hurley and K. Harrison (Appendix J. Page 294) discussing the reddening of the foliage of red spruce which is widespread in southern and especially southeastern New Brunswick in 1993. Foliage reddening affected mainly the 1-year-old (1992) needle complement but, in the worst cases, caused damage to foliage as old as that produced in 1990. Those trees with more than 1 year's needle complement affected often had bud- and shoot-mortality as high as 70%. Entire crowns of red spruce had this striking damage, but the damage was more frequent and severe on the top third. Trees affected ranged in age from young to mature trees, growing within stands, at stand edges or in open areas. Red spruce in plantations and thinnings were affected as well. Often, there were many unaffected red spruce interspersed with damaged trees. Red spruce was found to be the only tree species affected. Similar damage was reported from Maine, Vermont and as far west as the Adirondack Mountains in the state of New York. Although there can be localized damage due to winter drying, ocean salt spray, roadside salt spray, etc., the authors suggest that, given the geographic scale of this event and the species specificity, damage was the result of a unique and perhaps complex weather anomaly. If these particular weather conditions, capable of creating this type of tree damage, are characteristic of climate variability/climate change, it may well be that they will occur more frequently and/or with greater intensity over time. They proposed red spruce as a biological indicator of climate variability and climate change.

M. Lavigne *et al* (Appendix J, Page 296) examined the role of carbon cyling in Atlantic Canada forests in relation to climate change. A significant body of evidence suggests that terrestrial ecosystems in northern latitudes are currently net sinks for carbon, and hence are slowing the rise of atmospheric CO_2 concentrations. About 7 Gt of carbon are emitted annually by fossil fuel burning and tropical deforestation, approximately half of this amount remains in the atmosphere, and at least 2 Gt y^{-1} of carbon are taken up by oceans. Uncertainty persists about where the remaining 1 - 2 Gt y^{-1} of carbon are sequestered, but a large body of circumstantial evidence suggests that some, or all, of it is absorbed by the biosphere and particularly forests of the northern hemisphere. Forests are sinks for carbon when photosynthesis is greater than the sum of autotrophic and heterotrophic respiration, and sources when photosynthesis is less than the sum of autotrophic and heterotrophic respiration.

Rates of carbon cycle processes change predictably as forest ecosystems age. Recently disturbed stands may have high rates of heterotrophic respiration because large quantities of recently dead biomass enters the soil pool, due to the disturbance, and soil temperatures are higher without the closed canopy above. Immature stands have relatively large annual increments of woody biomass, the production of new woody biomass is approximately balanced by mortality in mature stands, and usually there are greater losses from the living woody pool in overmature stands than there is production of new woody biomass. Therefore, very young stands are often sources of carbon, immature stands sequester carbon, and mature stands are weaker sinks than immature stands. Overmature stands become net sources of carbon when heterotrophic respiration rises, because of the increasing supply of detritus, to exceed net increases in the woody biomass pool. Approximately half of the New Brunswick forest is mature, and hence is at most a weak sink for carbon, and more likely is neither sink nor source. Much more of the forest of New Brunswick is immature than is overmature. Immature forests are sinks for carbon, and overmature forests are usually net sources of carbon. Therefore, the age class distribution of New Brunswick probably favours this province being a net sink for carbon. Lavigne *et al* assume that the age class distribution of the Nova Scotia forest is similar to that in New Brunswick, and hence that it also is currently a net sink for carbon.

Future carbon sequestration by the forests of Atlantic Canada will depend on the extent to which the regional climate changes, the levels of harvesting that are sustained, frequency and severity of insect outbreaks, the frequency and types of other disturbances, and the level of forest protection. With the possible exception of harvesting, the future of these factors affecting carbon sequestration are very uncertain. Moreover, carbon sequestration during the immediate future, say the next 100 years, could depend upon the rate of environmental changes, and this is clearly uncertain. If the climate warms to that expected for an atmosphere with doubled CO_2 concentration then the vegetation in the Maritimes will change from being cool temperate and moist boreal vegetation to being moderate temperate and cool temperate vegetation. It is possible that eventually the forests of Atlantic Canada will have the capacity to store more carbon than they can at present, but it is difficult to predict when this will be the case nor how the forest will perform during the transitional period. In a second paper Lavigne *et al* (Appendix J, Page 309) propose a project to evaluate forest performance in the face of climate change.

On the micro- and meso-scale, C. Bourque (Appendix J, Page 281) described a model to generate maps of land-surface irradiance and temperature for several regions in northern New Brunswick and for the Cape Breton Highlands. The regional distribution of solar energy amounts is highly variable and is controlled to a large measure by the underlying topography and vegetation cover which make up the regional landscape. The solar radiation model calculates hourly insolation values for every node of the digital elevation model according to the point-calculation of solar zenith angle, direct and diffuse solar radiation, aspect, slope, horizon angle, view factor (proportion of sky that is unobstructed from one's view), terrain configuration factor, and surface albedo (proportion of incoming solar radiation reflected by the underlying surface).

The temperature component of the model, based on a tested artificial neural network adaptation of the energy balance, calculates surface temperatures from estimates of incident and outgoing energies determined in part by the solar radiation module. The artificial neural network developed here does not address sensible and latent heat fluxes directly, but uses surrogate variables like wind, relative humidity, air density, partial water vapour pressures (based on calculated temperatures and relative humidity), estimates of vegetation cover stomatal resistance, etc., to account for the effects of surface ventilation (forced convection) and evapo-transpiration on the simulated energy balance and on the calculation of temperature. Obtaining values for these surrogate variables is not a trivial matter since they themselves respond to changes in the landscape. Work on this has yet to be fully developed, but conceivably the procedure will be based on estimating these variables from meteorological data obtained from local weather stations. Bourque reported that, in the future, it is planned that nighttime drainage of cold air resulting from radiative cooling of the land will be simulated by mathematically tracking the hour-by-hour movement of hundreds of thousands of individual simulated air parcels placed on top of the modelled land surface.

The model will be adapted to several regions in northern New Brunswick and the Cape Breton Highlands so that the micro climatology of these areas may be studied in greater detail. Maps depicting spatial distribution of surface temperatures will be generated for each of the study areas for selected times during selected days in the growing season. Also, maps depicting degree-day accumulations for typical growing seasons will be generated with the model.

9. EXTREME EVENTS

9.1: Synthesis paper

The Hyper-Active 1995 Atlantic Hurricane Season: A Spike or a Harbinger of Things to Come?

Stanley B. Goldenberg[1], Lloyd J. Shapiro[2], and Christopher W. Landsea[1]

INTRODUCTION

During most of the years 1970-87, the North Atlantic hurricane basin had experienced a relative lull in overall tropical cyclone activity. The below-normal activity was especially evident in drastically reduced numbers of hurricanes affecting the Caribbean Sea and Maritime Canadian regions and basin-wide numbers of major hurricanes[3] (MHs), and almost a total absence of MH landfalls affecting the east coast of the U.S. After the experience of renewed "normal" activity in 1988 and 1989 (with five MH during those two years), it was suggested that the Atlantic basin was returning to a long-term period of higher activity such as what was experienced back in the decades of the 1950s and 1960s and some earlier periods. The heightened activity in 1988 and 1989 was followed, however, by a marked downturn in activity from 1991-94. As a result of the resumption of the below-normal activity, primarily attributed to wind anomalies driven by the highly anomalous, long-lasting warm sea-surface temperature (SST) event (El Niño) in the tropical Pacific, the notion that the Atlantic basin had entered a high-activity regime was pretty much discarded.

The warm event in the Pacific finally ended in early 1995 and was followed by one of the most active hurricane seasons in the Atlantic on record with almost every measure of activity over twice the long-term mean. Of particular note was that the season produced five MHs for the first time since 1964. The chief issue being addressed in the current study is whether or not the activity of the 1995 season was simply an anomalous "spike" or a harbinger of multi-decadal-scale climate shifts signaling the probability of greater activity over the next ~10-20 years. Long-term climate changes are typically associated with slowly evolving fluctuations in the world's oceans. Some of these oceanic fluctuations will be examined and related to Atlantic tropical cyclone activity.

Most of the tropical cyclones in the Atlantic basin form from easterly (African) wave disturbances which move off of the African coast primarily between 10° and 15°N. Although the number of easterly waves in the tropical Atlantic tends to be fairly steady from year to year, the fraction of these that develop into tropical cyclones exhibits substantial variability. The easterly waves account for ~60% of the Atlantic basin tropical storms and minor hurricanes but ~85% of the MHs. The vast majority of the easterly-wave spawned MHs began development (i.e., reached tropical depression strength) in the southern band between ~10° and 20°N, stretching between the west coast of Africa and Central America, called the "main development region" (MDR) by Goldenberg and Shapiro 1996 (hereafter referred to as GS96). The implication of the vast majority of MHs developing in the MDR is that they are far more sensitive to conditions in the deep tropics than tropical storms or

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[3] MH corresponds to categories 3, 4 or 5 on the Saffir-Simpson scale (maximum sustained surface wind speed of ^{3} 50 m s^{-1}). Hurricanes of categories 1 and 2 will be referred to as minor hurricanes.

minor hurricanes and hence are much more sensitive to interannual and interdecadal fluctuations of environmental conditions in the tropics. The main key to understanding fluctuations in tropical cyclone activity in the Atlantic, especially on the interannual and interdecadal scales, is to focus on the MDR, across a portion of which *all* easterly waves *must* travel, at least initially. Conceptually, the tropical cyclone activity (and especially MH activity) can be thought of as operating similar to a sluice gate that "opens" and "shuts" in the MDR to allow easterly waves to "pass", i.e., to develop. (For a more complete discussion of this concept and of other issues addressed in this article, see Goldenberg, *et al.*, 1997; hereafter referred to as G97.)

The climatic factors that "operate" the sluice gate can be separated into those having "local" and "remote" effects. A factor having a local effect is one that is located in the actual region of tropical cyclone development, i.e., usually in the MDR, and has a direct thermodynamic or dynamic connection to development. A factor having a remote effect is one that is located away from the actual region of tropical cyclone development, but is either associated with (i.e., an indicator of), or causes, via teleconnections, fluctuations in conditions in the MDR.

The primary local factor is the magnitude of the vertical shear between the upper- and lower-troposphere, $|V_z|$. It is well accepted that strong V_z inhibits the formation and intensification of tropical cyclones, primarily by preventing the symmetric organization of deep convection. Conditions for development are usually deemed unfavorable when local $|V_z|$ exceeds ~7.5 m s^{-1}. During August-September-October (ASO), the peak three months of the Atlantic hurricane season during which virtually all of the MHs form, westerly V_z dominates most of the Atlantic basin, especially over the MDR, where the climatological $|V_z|$ is greater than 10 m s^{-1} for most of that region (GS96). These climatologically high values for $|V_z|$ are the main reason why the Atlantic basin is not usually favorable for development, even during ASO when the SSTs are sufficiently high and easterly waves are abundant. Increased (decreased) $|V_z|$ is generally caused by upper-level westerly (easterly) and lower-level easterly (westerly) anomalies which add to (subtract from) the climatological upper-level westerlies and lower-level easterlies over the MDR (GS96).

One of the main remote factors are SST fluctuations in the equatorial Pacific associated with El Niño/Southern Oscillation (ENSO). Positive (negative) SST anomalies associated with an El Niño (La Niña) event have been linked to unfavorable (favorable) conditions for development in the Atlantic basin due to an increase (decrease) in $|V_z|$ over the MDR (GS96). Another remote factor that has been linked to interannual variability in Atlantic basin tropical cyclone activity are rainfall fluctuations over the western Sahel (Landsea and Gray 1992) with positive (negative) rainfall anomalies associated with favorable (unfavorable) conditions. The Sahel rainfall factor has also been attributed primarily to its association with changes in $|V_z|$ over the MDR (GS96).

EVIDENCE FOR A MULTI-DECADAL SCALE SHIFT

Observations of Tropical Cyclone Activity

The first and most important indicator of a possible long-term shift is in the tropical cyclone activity itself. If one thinks of the interdecadal-scale fluctuations modulating the interannual-scale changes, then it is easy to see why not only the overall activity for the active decades was higher, but also the maximum values for activity were much higher. Although one might expect to see strong interannual fluctuations in activity in both active and inactive periods, the inhibiting environmental influences during the inactive decades seem to set a "cap" on the possible levels of activity. It is the assumption here that it would be highly unlikely to see certain levels of activity in the decades when decadal-scale fluctuations of certain environmental conditions are not in the phase favorable for Atlantic tropical cyclone development.

The parameter "Net Tropical Cyclone" (NTC) activity (see G97) gives a type of measure of the overall activity in a season, Figure 1 shows the Atlantic basin values of NTC for each of the seasons from 1950 through 1996. The mean for the years 1970-94 is only 75% compared to a mean of 116% for the more active period 1944-69. It is striking to note that only five years during the period 1970-94 had even marginally above average activity (i.e., >100%) compared to 15 of the earlier period being above normal. In addition, there was an apparent cap of 140% for NTC during the inactive decades. The more active 1944-69 period, however, equaled this cap two times and exceeded it six times. In 1995, for the first time since 1969, the NTC cap was exceeded with a value of 231%. In addition, the cap has been exceeded during 1996 with an operational value of 198%.

If years with values of NTC ³ 150% are designated as "hyper-active" years, then there were *five* hyper-active years during the more active 1944-69 period , while *no* years were hyper-active during the years 1970-94. The hyper-active year 1995 marked the first such year since 1969. The hyper-active years occurred, on the average, every five years or so during the previous active decades. However, 1996 has exceeded 150% NTC giving the Atlantic two hyper-active years in a row for the first time since the 1932 and 1933 seasons (154% and 225% respectively). These two successive hyper-active years give a strong reason to suspect that the Atlantic basin has made the transition to a more active regime, probably on a multi-decadal scale. Evidence for this transition is also strongly evident in MH activity (see G97).

Decadal-scale fluctuations in SST

Fluctuations in western Sahel rainfall have been shown to be associated with "local" SST fluctuations in the eastern tropical Atlantic, and "remote" SST fluctuations in the midlatitudes in the Atlantic (both North and South) and in the equatorial Pacific (associated with El Niño). The key region for interannual SST fluctuations, as shown by the empirical orthogonal function (EOF) analysis of global SSTs is the Pacific Ocean, primarily the region associated with El Niño (as shown in the second mode: SST EOF2). The key regions for decadal-scale fluctuations (SST EOF3) are the midlatitudes in the Atlantic Ocean, with opposite phases in the North and South Atlantic, i.e., the North-South Atlantic dipole. Ward (1997) has shown that the multi-decadal scale fluctuations in Sahel rainfall are related to the interhemispheric SST differences, i.e., the North-South dipole, while the interannual variability in the rainfall is more closely associated with central and western Pacific SST fluctuations. It is likely that the same teleconnection patterns that are producing the fluctuations in Sahel rainfall are also contributing to changes in environmental conditions in the MDR in the Atlantic, in particular, V_z, that are affecting Atlantic basin activity.

Ward (personal communication 1996) has noticed an increase in rainfall for the Sahel region of Africa and for an "all-India" index (both calculated for July-September) during the period 1988-95 compared to the 1970-87 period. This has been observed in conjunction with a warming of the Northern Hemisphere (mid-latitude) SSTs compared to those of the Southern Hemisphere. These upturns which began in 1988 in rainfall and Northern Hemisphere SSTs were accompanied by a decrease in the positive values of the "multi-decadal" SST EOF3 which has been positive since 1968.

Another SST indicator which points to a recent change on the decadal time scale in the Atlantic was presented in Hansen and Bezdek (1996). They examined the temporal and spatial fluctuations in the upper and lower deciles of low-pass filtered (at four years), locally normalized SST anomalies in the North Atlantic. The decadal-scale fluctuations (not shown here) basically point to warmer SSTs in the North Atlantic for the decades of the 1950s and 60s, predominately colder in the 1970s and 80s, with a reversal again (warmer anomalies dominating) manifesting itself in the late 1980s, more specifically 1987 or 1988. This shows a strong association with the observed decadal-scale fluctuations in MH activity in the Atlantic basin; greater activity in the earlier decades followed by the relatively inactive 1970s and 80s. The significance of the change at the end of the 1980s will be discussed in Sect. 3.

Vertical Shear Changes in the Main Development Region

Although a warmer tropical North Atlantic would seem to enhance tropical cyclone activity as a local effect (see Sect. 1), *it is unlikely that this is the main physical connection between the warmer (colder) North Atlantic and active (inactive) Atlantic hurricane seasons*. Shapiro and Goldenberg (1997) suggest that the local SST effect plays either a *negligible* role (in the case of MHs) or at best (in the case for all hurricanes) is a *second-order effect* for increased activity. The predominate effect, as discussed in Sect. 1, is more likely the fluctuations in $|V_z|$ in the MDR. It is certainly possible that the same favorable conditions for increased Sahel rainfall, i.e., warmer North Atlantic SSTs, also, by associative arguments, result in decreased $|V_z|$ over the MDR. In other words, the decadal-scale SST fluctuations affecting Atlantic hurricane (particularly MH) activity would likely produce the connection via changes in the upper- and lower-level zonal circulations over the MDR.

Figure 2 shows the fluctuations in ASO $|V_z|$ (see G97 for data description) for an area in the MDR that exhibits some of the strongest correlations between $|V_z|$ and MH fluctuations (GS96). The ASO $|V_z|$ in the MDR experienced a noticeable shift towards lower (more favorable) values starting in 1988. The years since the shift have had *much* lower than average $|V_z|$ values with the exception of the four years (1991-94) affected by the long-lasting anomalous tropical Pacific warm event. In addition, the lower than average values are the most favorable $|V_z|$ values in that region since 1975, the beginning of this wind data set. The shift starting with 1988 is noticeable in both the upper- and lower-level winds (not shown) for this region. The mechanism for reduced $|V_z|$ is the reduction of upper-level westerlies and lower-level easterlies.

DISCUSSION

The evidence presented in this study examined certain multi-decadal scale changes in Atlantic SSTs with a shift towards warmer conditions in the Northern Hemisphere beginning around 1988. This shift was accompanied by a shift towards lower vertical shear in the main development region of the Atlantic hurricane basin, a condition more favorable for increased tropical cyclone activity, especially major hurricanes. Although the lower, more favorable vertical shear conditions were modified somewhat from 1991 through 1994 during the long lasting El Niño event, the favorable values quickly resumed in 1995 as soon as the equatorial Pacific warming event had concluded. It seems indeed likely that a decadal-scale shift, associated with decadal-scale changes in Atlantic SSTs, towards a more favorable environment for Atlantic tropical cyclone development took place around 1988 but was subsequently temporarily masked by the highly anomalous, long lasting El Niño during the beginning of the 1990s.

If these changes are indeed taking place on decadal or multi-decadal scales rather than interannual scales, then the Atlantic basin may continue to see over the next decade or so, on the average, heightened activity on the order of what was seen in the 1950s and 60s rather than the suppressed activity of the 1970s and most of the 80s. What might be expected would be several years with very high activity, while most years would be close to average or slightly above average and only a few far below average. This would be dramatically different from the inactive decades when most years were below (often well below) average, some years were about average and very few years even just moderately above average. If the past holds the key to the future in this case, the overall increase would mean significant increases in the numbers of hurricanes affecting the Caribbean Sea and Maritime Canadian regions, basin-wide numbers of MHs, and MH landfalls affecting the east coast of the U.S.

The possible implications of these changes are staggering. The fact that major hurricanes have historically accounted for most of the damage and deaths due to tropical cyclones combined with the fact that there has been a dramatic population increase along the United States hurricane-vulnerable coasts during the two inactive decades, add up to the potential for massive monetary loss, especially when major cities are impacted. In addition there is a potential for large loss of life in the case of an incomplete evacuation during a rapidly intensifying system.

Concerning the question as to whether the increase in activity experienced in 1995 is due to anthropogenic global warming, Gray *et al.* (1995) states that; "The large increase in 1995 Atlantic activity ... was the result of natural variations in global circulation patterns and we are able to predict a portion of this increase without invoking global warming or greenhouse gas increases. Therefore, there is *no plausible way* that increases in man-induced greenhouse gases can be even *remotely* related to this year's extremely active Atlantic basin hurricane season." There have been various studies investigating a possible impact, if any, on the number and strengths of Atlantic basin hurricanes *if* the earth experiences a long-term global warming. The results are inconclusive (Houghton, *et al.* 1996), with some studies documenting an increase while others suggest a decrease in associated activity. In addition, the historical multi-decadal scale variability in Atlantic hurricane activity is much greater than what could be "expected" at the present time from a small, gradual global temperature increase.

Caution must be used in applying the conclusions suggested in this study. Firstly, extrapolation, especially for decadal (and longer) time scales, certainly has a high level of uncertainty. One of the main difficulties in observing long-term fluctuations in tropical cyclone activity is that the reliable data extends back only about 50 years. If the temporal scale being addressed here is on the order of 40 years, i.e., ~20 years of higher activity and ~20 years of lower activity, then only about one complete cycle has been adequately sampled. In addition, it is unlikely that the signal is so "clean" that it would always be manifested as the same time length of favorable and unfavorable conditions, i.e., the current favorable conditions might only last a total of 5-10 years or could extend for 20-30 years, etc.

Secondly, increased activity during a particular year does not automatically mean increased storm-related damage. Even relatively inactive years can produce hurricane-spawned disasters. It is not how many systems develop in a particular year that determine the amount of damage, but how many systems actually impact land and where. Far more damage can been done by one major hurricane impacting a heavily populated area than by several major hurricanes hitting sparsely populated areas, or of course, not making landfall at all. For example, there was ~$25 billion in damage to the United States caused by Hurricane Andrew in 1992, the only major hurricane during a relatively inactive year (NTC = 66%), compared to less than $6 billion in damage to the United States during 1995, one of the most active years on record (NTC = 231%) with five major hurricanes. In addition, disasters can occur even from weaker systems due to flooding. It is still obvious, however, that active years have a greater overall *potential* for more regions to be impacted than inactive years.

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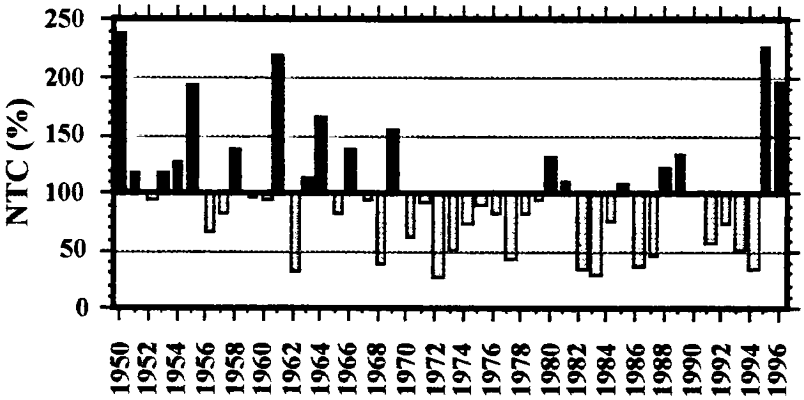

Figure 1. Net Tropical Cyclone activity (NTC) for the North Atlantic basin. Values for above (>100%) and below (<100%) average activity are shown as solid and shaded columns, respectively.

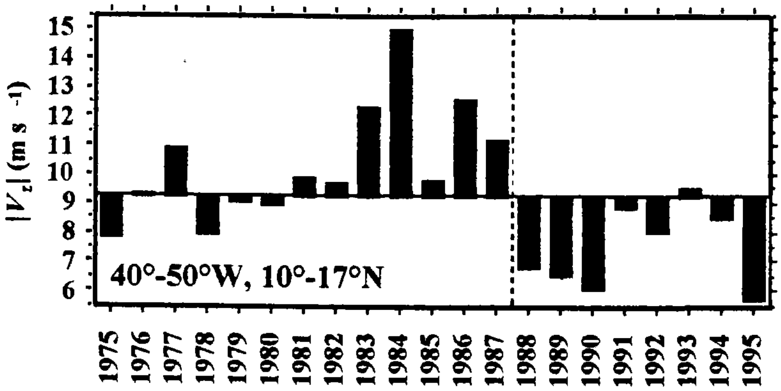

Figure 2. Average of ASO $|V_z|$ for the region from 40° to 50°W longitude and 10° to 17°N latitude. Solid horizontal reference line corresponds to sample (1975-95) mean.

9.2 Summary of other papers and discussion on extreme events

E. Higgins described an analysis carried out as a summer student of the frequencies of cyclogenesis and subsequent tracks of the cyclones over a 43-year period. The area of analysis was between 35 and 60 degrees North latitude, and 40 and 70 degrees West longitude in one-degree grid squares. Contour maps of cyclogenesis indicated that cyclones developed most frequently in the area near 35°N, 74°W. Higgins reported that there appeared to be a spike in cyclogenesis every 11 years, corresponding with the sunspot cycle. The 1950s and 1960s were times of increased cyclone activity.

G. Parkes and C. O'Reilly described their analysis of storm surges in the Atlantic Region. A "storm surge" is defined as a meteorologically-induced increase in sea level. They concentrated on storm surges which occur at high tide and have the strongest effect because the high tide "carries" the storm surge farther inland. To the surge and tide could be added the swell, which could be 1-2 meters. The Bay of Fundy is especially susceptible to storm surges at high tide. The authors stated that increased temperatures and less ice in the Gulf of St. Lawrence could make that area more susceptible to storm surges. Assessments of risk from storm surges should take into account areas of low relief, areas of frequent storm surges, coastal infrastructure, and the coincidence of spring tides. In the future, it is intended to monitor long-term water levels, review historic events, and develop an integrated model.

D. Piper discussed his work for using sedimentological proxies for storminess which took place in the Holocene period. The principle is that a basin in the ocean bottom will collect sand put into suspension by storms. Layers of sand in the bottom sediment will indicate storminess; microfossils can be dated by carbon-14 analysis. Piper has examined the past 10,000 years and especially the warm Holocene period about 6000 years BP. There are maxima in sand concentrations at 10,000, 6,000 and 500 years BP. The past century has been relatively stormy, as was the Holocene period, suggesting that warming might be associated with increased storminess.

V. Swail (Appendix K, Page 313), in his analysis of climatic variability in ocean waves in the northwest Atlantic Ocean, addressed two questions: (1) Is the climate changing?; and (2) Are storms becoming more frequent? more severe? The first major concern in looking at the long-term trend and variability in ocean waves is that there are no long term reliable wave data sets. Ships definitely do not provide the necessary observational quality, nor the stationary location. Drilling platform data are of better quality, but are spatially and temporally extremely restricted. Moored buoys provide the best source of quality data, and in some locations along the U.S. continental margin, include more than 10 years of data. However, this period is still far too short for analysis of trend and variability, and in Canadian waters the length of the buoy record was far less than that.

As a result of the lack of reliable observed data, Canada and other countries have turned to wave hindcast models to provide the data for engineering design as well as climate trend and variability analysis. The hindcast quality versus measurements is very good for storms, as has been shown in many hindcast evaluation studies. Recent hindcasts for the North Sea, using newly-developed state-of-the-art techniques, show virtually unbiased results with a scatter index for a 6-year continuous hindcast of 17%, over a wide range of sea states. Similar results have been consistently obtained for other ocean basins, including the northwest Atlantic off Canada.

Some results of the hindcasting study are as follows:

- There is no discernible trend in magnitude or frequency of extreme wave heights on the east coast of Canada, but there is significant inter-annual variability
- Any apparent trend is all caused by two or three recent events on Scotian Shelf (since 1991); this illustrates the real danger in using simple linear trend analysis over a long time period which contains cyclical behaviour.
- The extreme events of the early 1990's on the Scotian Shelf may represent a change in large-scale circulation patterns, but are not inconsistent with events experienced earlier in the century.
- Experimental results from strap-down accelerometers shows waves are underestimated by about 10%; "maximum" waves reported until at least 1997 are incorrect and should be avoided.

For the future, Swail stressed, among other things, that: 1) The U.S National Centers for Environmental Protection re-analysis project, and the Canadian reference wave climatology project deriving from it, are critical components of wave trend and variability research; 2) It is essential that we maintain (or enhance) the moored buoy network and validate offshore platforms for long term wind/wave monitoring.

The point was made by a member of the audience that the offshore oil and gas industry are not worried about climate change; they are essentially self-insured. Swail replied that one reason for their attitude might be that they have not seen any information to date that would change their minds.

D. Forgeron, representing the insurance industry, stated in his presentation that payments by insurance companies as a result of natural disasters has increased greatly in recent years. Prior to 1987, no insurance payout related to a single event had exceeded one billion dollars. Since then, there have been 18, one example being Hurricane Andrew which resulted in 16.5 billion dollars in claims. In Canada, the cost of insurance payouts have increased by 65% during the past five years. The two largest disasters were the 1991 hailstorm in Calgary (343 million dollars) and the 1996 floods in the Saguenay (350 million dollars). If in September 1996 Hurricane Hortense had made landfall a few kilometers west and affected Halifax, the damage would have been much greater than it actually was.

There may be several reasons for this increase. First, people are living increasingly in areas such as floodplains and coastlines that are vulnerable to natural disasters. Second, people may be buying more comprehensive insurance policies. Third, there may actually be an increase in natural disasters.

The insurance industry has been lobbying government on a number of fronts, such as more earthquake-resistant building codes in susceptible areas such as Vancouver. Another precaution woild be to build up through insurance premiums untaxed funds that would provide protection in the event of disaster. Another incentive would be to increase deductibles in policies to encourage policyholders to protect themselves more against natural disasters.

10. CLOSING PANEL DISCUSSION: GAPS, PRIORITIES AND NEXT STEPS

Summary of the Panelists' Statements and Open Discussion

by

Cindy Staicer
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PANEL CHAIR: Roger Street, Atmospheric Environment Service, Downsview, Ontario

MEMBERS OF THE PANEL: David Sawyer, EnviroEconomics, Halifax, Nova Scotia

David Stewart, Jacques Whitford, Dartmouth, Nova Scotia

Sandy Robertson, Memorial University, St. John's, Newfoundland

Howard Epstein, Halifax Regional Municipality

Alan Ruffman, GeoMarine Associates, Halifax, Nova Scotia

INTRODUCTION

Roger Street explained that the next phase of the Canada Country Study, after the initial literature review has documented the state of our knowledge, will be to address gaps and priorities and move towards regional studies. Towards this goal, the purpose of this final section of the symposium was to bring together panelists to identify gaps in our understanding and priorities for future work on climate change. After a short presentation by each panelist, which served to stimulate conservation, the discussion was opened up to the floor.

OVERVIEWS OF PANELIST STATEMENTS

David Sawyer of EnviroEconomics presented a model of uncertainty and decision guidance which may be useful in addressing the regional impacts of climate change. Three key components in the model--the regional climate change scenario, regional biophysical responses, and regional socio-economic responses--are viewed as mirroring IPPC work. Of these components, socio-economic changes and responses are the best understood and easiest to predict. Before these issues can be approached, however, a better understanding of biophysical responses to climate change is required.

As information accrues, policy would guide our responses to climate change and help to minimize its effects. The model is based on a sensitivity approach in which ranges for variables are derived from the literature. Such an approach is particularly useful when levels of uncertainty are high, such as those associated with climate change. We need to look at the range of options based on various scenarios.

This scheme acknowledges that we don't understand the systems we are dealing with or the changes and impacts that result from climate change. We therefore need a system that will recognize those uncertainties and provide us with a buffer. Theories of the past have seen resources as a commodity, but that cannot continue. Economics will have to adapt to changes in the environment.

David Stewart, of Jacques-Whitford, focused on the relationship between energy use and climate change. The influence of our actions on climate change is clearly energy-driven. The problem is simple--too much energy, in the form of fossil fuel, is being used. In only 150 years, millions of years of fossil fuel deposits have been released into the atmosphere. Although much information is available on energy efficiency, it is not being incorporated into the decision-making processes of government, industry, or the public.

Coping with the problem will require changing human behaviour. Energy could be used more efficiently, and the use of non-renewable energy sources could be reduced in favour of renewable or alternative energy sources. A carbon tax would help to alleviate the problem but would have especially detrimental economic effects on Nova Scotia. Although moving towards another energy economy will be difficult, it will have many positive effects. Increased energy efficiency will not only serve to combat climate change, but also improve air quality, combat ozone depletion, reduce acid precipitation, and increase employment.

Howard Epstein, Councilor of the Halifax Regional Municipality, also focused on energy and stressed the need for action. He pointed out that, whereas most of the presentations at this symposium have focused on the effects of climate change, it is more crucial to address the causes. The real question is: What policy tools will we use to change the behaviour of people and corporate entities? The main obstacle is not lack of scientific knowledge but its practical application, which is an economic and political issue.

The status quo presents the main obstacle to change in energy use. Elected officials have the responsibility to begin to change social behaviour by whatever means--education, regulations, taxes, incentives, etc. In 100 years the world will be a very different place; our current lifestyle cannot continue. Problems will intensify as more of the developing countries move towards our level of energy consumption. It is just not possible to support the present global population at this level.

So far there has been little regulation of the energy sector in Nova Scotia. The province failed to adopt an energy policy, by not proceeding beyond its 1991 draft. National shortcomings include the setting of a SO_2 emissions target that was too high, and the lack of regulations for NOx. The only progress in atmospheric change to date has been with the ozone layer, a problem that politicians couldn't ignore.

People are getting the wrong message--that they are consumers rather than citizens. Virtually all municipal decisions are environmental, i.e. ultimately affecting our atmosphere, water, forests, etc. We need to take an ecosystems approach in making these decisions, and consider the effects of alternative actions. Economics has no business dominating public decisions.

Sandy Robertson, Adjunct Professor at Memorial University, Newfoundland, suggested the need for a paradigm shift in dealing with climate data. Traditional statistics cannot incorporate the temporal-spatial chaos inherent in climate datasets, rapid short-term changes, or intermittent events. Use of other techniques, such as circular statistics, fractal geometry, and chaos theory should be considered. Chaotic change is governed by the initial conditions that trigger the movement towards one state or the next, and their following pattern of change and development, i.e. the initial state plays a key role in the future of a system.

A case in point is the dynamics of a forest ecosystem, in which most of the parameters are related to climate. Consider, for example, replanting a site after logging and the interactions with climate. The climate that is produced as a result of the cutting action will not be the same as the climate at the time of the original forest's development, and therefore the forest will not develop in the same manner.

Also stressed was the need for a solid foundation of monitoring data--a rich database representing many spatial and temporal scales. Climate data systems are essential for both good science and decision-making. Furthermore, the maintenance of a scientific services branch is fundamental to the accessibility, use and understanding of the data. With regards to maintaining a scientifically-appropriate climate monitoring network, the decimation of weather stations is viewed as a serious setback.

Alan Ruffman, President of GeoMarine Associates, emphasised that gaps in our climate monitoring database could be filled by incorporating existing historical information. Canada's worst disasters, the 1775 hurricane in which as many as 4000 died in Newfoundland, and the 1844 storm surge in the Great Lakes, pre-date our climate database. We must protect sources of historical climate and storm event information presently available in our libraries and archives. For instance, the records of the Hudson's Bay Company, newspapers, and diaries are rich sources of information. As pointed out by one of the participants, records for Sable Island that mention hunting walruses and "white bears" which would signify ice expansion to the island in historical times, which has implications for plans to develop a pipeline.

Another untapped source of historical data for the Maritimes is found in tree rings. Surprisingly, no researchers are working on the climatological record in tree rings of eastern Canada. For example, a charred beam from an old Halifax church contains 351 tree rings, dating back to 1448. Unfortunately, the Geological Survey of Canada no longer has the capability for dendrochronology.

Canada is presently suffering from a loss of intellect from our scientific departments due to retirements, emigration, and job loss associated with government cut-backs. We must fight for each other's monitoring networks. Scientists must support each other in the fight to protect and preserve the information which is now available (i.e. historical information as well as monitoring infrastructure). The problem in utilizing historical information is its relative inaccessibility--few people know of its existence or contents and locating records will be very time-consuming.

SUMMARY OF THE OPEN DISCUSSION

The following points were made during the open discussion. They are not listed in the order in which they were brought up; rather they have been grouped according to topic.

Gaps

Research

- More accurate models are needed. Global models are improving but there is much work to be done. The oceanographic community is starting to model the coastal shelf, but as yet this is not well-coupled to the deep oceans. More accurate regional models are also needed.

- A new statistical approach is warranted. The short length of time and the short cycles we are often dealing with means that traditional statistics are often of little use. It is recommended that paleoclimatology be used for looking back and discovering long-term cycles.

Data

- More complete regional climate information is needed, as well as a better understanding of sensitivities of the Atlantic Region systems.

Linkages and Communication

- The necessary connection between economics and the environment is missing. Rather than an ecologically-determined system, where economics is adapted to fit ecology, we have economic determinism that lacks significant feedback from the environment. Given this situation, how do we convince the proliferating MBA's to fund research and monitoring? Economics is a superficial structure, but propaganda and the status quo tells us that economics is the determinant that dominantly affects us. That perspective must change.

- Communication with the public must be improved. There is a lack of public acceptance of the problems which presently exist and a general failure to come to grips with policy questions pertaining to climate change. The scientific evidence is there, but it isn't affecting the public. Furthermore, the effects of greenhouse gas emissions go beyond changes in climate. What about the health costs of greenhouse gas emissions? The relationship between people and their automobiles is perhaps the deepest cultural problem. Education is the chief tool we have to change behaviour, but this will take time.

Priorities and next steps

Research

- The vulnerability of ecosystems to climate change should be a priority for the Canada Country Study. Of all the potential effects of climate change, we know least about how ecosystems may respond. The present ranges of different species can be expected to change in different ways. These changes in species distributions may result in a cascade of effects on ecosystem structure and function.

- Extreme events emerged as the most important aspect of climate change in the Atlantic Region. Is it climate change or climate variability that we need to understand? Variability in a system is just as important, perhaps more so, than any mean or normal value.

Data

- The importance of data cannot be over-emphasised. Data are our legacy to our children--loss of data and capability will severely restrict our children's ability to address their questions.

- A moratorium on closures of climate stations was called for unanimously. We must make it clear to policy-makers what they will loose if the government cut-backs do not stop. We need to emphasise that data can be used for many things. Even the people collecting data may not be aware of its full usefulness. For example, the Geological Survey of Canada is highly dependent on the databases collected and maintained by other departments.

- We need timely access to radar data of storm tracks, etc. It is necessary for Canada and the USA to rationalize an agreement to share that information in a timely manner.

Linkages and Communication

- Climate connects us with the global community. As our greenhouse gas emissions continue to increase, the resulting change in climate may have a significantly higher impact elsewhere in the world. We should consider the broader implications of our actions. As well, we need to pay attention to external events and conditions, such as world population size, that will be have an affect on our regional climate.

- More multidisciplinary science and interdisciplinary collaborations are needed. For example, the interaction between the Atmospheric Environment Service and the Department of Fisheries and Oceans needs to be strengthened if we are going to understand the role of oceans in climate change. Atlantic Canada needs a regional committee to foster collaboration and help to raise public awareness of the science of climate change. Such an initiative must come from outside of AES--the scientitifc community has to organize itself. More partners and a louder voice are needed.

- Meetings should have a goal of facilitating cooperation and communication. A meeting such as this symposium should provide the opportunity to meet new people and foster connections for collaborative projects. Perhaps at future meetings time could be set aside and a place arranged to enable people from different departments, organizations, and companies to become acquainted.

- The Climate Exchange website will serve as an electronic forum for communication. As a result of this discussion, Bill Appleby volunteered to establish and maintain the website, which will post information relevant to regional climate change and allow sector input. The first submission will be the proceedings of this symposium.

- We need to find ways to make science more understandable to the taxpayers who are paying for it. Open the doors of knowledge--don't wait to be asked, offer your knowledge. One idea for raising the profile of climatological science is to invite the media inside when the next hurricane approaches the Atlantic Region.

- It is essential that scientific services be maintained and strengthened. Environment Canada has a crucial role to play, handling the large volume of climate data and communicating trends to the public. That the Atmospheric Environment Service has moved towards a product-oriented strategy is troublesome and has alienated other branches of the government. Also, if government continues to charge the public for information they paid for, as taxpayers, they may stop buying it, at which point the government branch becomes obsolete. Another danger is privatization of data, as it gives power to those who have it. Already, It is difficult for non-government, non-academic persons to gain access to information which should be accessible to the Canadian public.

Economics and Funding

- Economics can play a significant role right now, before the change in public perspective is fully achieved. We need to appeal to the economic side of many people and groups, and use it as an incentive to change behaviours. We should be using the economic tools available, such as taxes, in combination with other incentives. Feebates would be a way to reward people for more environmentally appropriate behaviour. For example, Central Maine Power charges households more for electricity if a house does not meet energy conservation standards.

- To date, the private sector has shown little interest in atmospheric issues. Rather, science and engineering in universities has been heavily impacted by a government that embraced the profit-oriented approach of industry, such that science is now being directed from the outside, for political purposes. Yet, the private sector should be more aware of the potential effects of climate change. We don't know how whether, or to what extent, engineers are already factoring changing climate into their designs of structures.

- It is appropriate for insurance companies to fund climate change research. Alan Ruffman suggested approaching the insurance company that funded the earthquake assessment for BC, with a proposal for a collaborative project to assess the potential impact of major storms on the Maritime Region. He pointed out that pure research on climate change by David Scott and Eric Cullen is currently funded through the insurance industry.

11. CONCLUDING REMARKS

A very large amount of information on climate variability and climate change in the Atlantic Region was presented during the Symposium; the detail and wide scope of this information precludes a succinct summary here. The reader is urged to read the Executive Summary of these Proceedings which is a digest of the synthesis papers that were written to deal with various aspects of the topic. These concluding remarks will concentrate, rather, on what directions work on climate change in the Atlantic Region should focus in the future.

It was obvious from the Symposium that virtually all aspects of life (including the economy) in the Atlantic Region are highly dependent on the climate which, even at present, is highly variable both in space and in time. Apart from any trends in the mean values of climatic variables, any possible increase in climatic variability due to an increase in atmospheric concentrations of greenhouse gases (including the frequency and severity of extreme events such as unseasonable frosts and thaws, hurricanes and storm surges) will have a profound effect upon the Region.

Research will in all likelihood result in improved estimates of the impact of climate caused by increasing concentrations of greenhouse gases, but reliable predictions of climatic change on a regional scale are still some time away. In addition, even if large reductions in the emissions of greenhouse gases were to take place now, there might still be changes in climatic means and variability because of the inertia of the ocean-earth-atmosphere system. Therefore, it would be prudent to assume that the management and use within the next several decades of natural and man-made resources such as forests, agriculture and coastal structures may have to be carried out in the face of climatic uncertainty.

In the closing panel discussion at the Symposium, the participants (including the audience) made it clear that they felt that, while the development of climate models with better regional resolution needed to proceed, the vulnerability of ecosystems to climate change should be a priority for the Canada Country Study. Of all the potential effects of climate change, we know least about how ecosystems may respond. This same view was expressed in 1995 at the symposium *Science and Policy Implications of Atmospheric Issues in Atlantic Canada* [4] in connection with climatic change. In answer to the question: "What aspects of climatic change are of greatest importance in the Atlantic Region?" the 1995 workshop replied:

> **Despite the uncertainty in the projections of climatic change in the Atlantic Region, it is important to have an estimate of the sensitivity of Atlantic Canada resources to climatic changes in either direction. Such resources include agriculture, forests, wildlife, the fishery, coastal infrastructure, transportation, tourism and the human population.**

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[4] R.W. Shaw (Ed.), 1996: *Science and Policy Implications of Atmospheric Issues in Atlantic Canada: Workshop Proceedings.* Environment Canada - Atlantic Region Occasional Report No. 6, 143 pp. Available from Environmental Conservation Branch, Environment Canada - Atlantic Region, P.O. Box 1590, Sackville, New Brunswick E0A 3C0, Canada.

To the question: " What activities are needed to achieve these results[5]?", the 1995 workshop replied:

> **Formation of an interdisciplinary and multisectoral (public, private, academia) group to develop a matrix of sensitivity of various components of the environment of the Atlantic Region to climatic change. One dimension of the matrix would be the aspect of the resource (using indicators such as freshwater availability or forest biodiversity); the other would be climatic variables such as temperature, precipitation, frequency of sea level rise or storm surges. This activity would make use of existing information, ecosystem studies and modelling results.**

The above conclusions of the 1995 symposium could apply just as well to the 1996 Symposium on Climate Variability and Climate Change, judging from the discussion at the closing panel discussion that was reported in Chapter 10 of these Proceedings. It is obvious that an assessment of regional sensitivity to climate change will be an interdisciplinary effort. Furthermore, the importance of data cannot be over-emphasized. While it is important to make the observing networks as efficient as possible, it is important to leave future generations a sufficient legacy of data. so as to not restrict their ability to address questions of importance to them. *We cannot look at a replay if we have not made the tape!* In 1997, we may not be able to perceive the ways in which the data will be used. There was a certain amount of dismay expressed at the Symposium at the closure of climate stations, and the cost-recovery policy being applied to information that was initially collected at taxpayers' expense. There is a danger of the privatization of data which could reduce accessibility.

Finally, it is important that the public be kept involved in climate work in the Atlantic Region through lectures and devices such as Environment Canada's Climate Exchange website on the Internet. It is through better communication with the public, including an appeal to the economic aspects of climate change (such as higher insurance premiums for extreme events), that incentives will be created to change people's behaviour and reduce the chance (albeit still incompletely known) of climatic trends and increases in climatic variability in a region which is already so sensitive to climate.

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[5] Editor's note: "results" meaning an estimate of the Atlantic region's sensitivity to climate change and variability.

APPENDIX A: SYMPOSIUM PROGRAM

Tuesday 3 December

1030-1245	Registration
1245-1300	Introduction and Announcements (Jim Abraham and Tom Clair)
1300-1315	Welcome Address (Garth Bangay)
Session 1	**Overview** (Chair: Bill Appleby)
	Science Assessments and Policy Implications (Jim Bruce - presented at 1050 on Thursday 5 December)
1315-1330	*Canada Country Study* (Barry Maxwell)
1330-1350	*Climate Change: Science Overview* (Pamela Kertland)
1350-1410	*Two Ocean Models for Climate Change Research* (Dan Wright)
1410-1440	*Climate Network Rationalization* (Carr McLeod)
1440-1500	*Global Ocean Observing System* (George Needler)
1500-1530	Health Break
1530-1550	*Climate of Atlantic Canada* (Teresa Canavan)
1550-1620	*Socio-Economic Overview of Atlantic Canada* (David Sawyer)
1620-1640	*Industrial Impacts: Electric Energy* (Bob Boutilier)
1640-1700	*The Impact of Transportation Policies and Practice on Our Environment* (John Pierce)
1700-1720	*Adaptations in Northern Cities* (Sandy Robertson)

Wednesday 4 December

Session 2	**Climatology** (Chair: Bill Richards)
0830-0850	*Climate Trends in Atlantic Canada* (Peter Lewis)
0850-0910	*North Atlantic Cooling Explained by the Baffin-West Oscillation* (Amir Shabbar)
0910-0930	*The Chilling Aspects of Global Warming in Atlantic Canada* (M.R. Morgan and R. Pocklington)
0930-0950	*Within the Bonds of the NAO: Canada-UK Inter-relations of Temperature and Rainfall* (B. Topliss)
0950-1020	Health Break
1020-1040	*Interaction between Atmosphere and Ice Cover off Labrador and Newfoundland 1962-1994* (S.J. Prinsenberg
1040-1100	*Atmospheric and Oceanic Climate off Labrador and Newfoundland* ((Ken Drinkwater)
1100-1120	*Climate Variability in the Waters on the Scotian Shelf and the Gulf of Maine* (Brian Petrie)
1120-1140	*Wind-Driven Currents on the Canadian Atlantic Shelf* (Josco Bobanovic)
1140-1250	Lunch
1250-1310	*Supporting Climate Research* (Jean Gagnon)
1310-1330	*Contributions to the Atlantic Climatology* (Sandy Robertson)

Session 3 **Fisheries and Plankton** (Chair: Ken Drinkwater)

1330-1350 *Long-Term Climate Change and its Effect on Ocean Circulation, Temperature and Plankton* (P.J. Mudie)
1350-1410 *An Environmental Index for Detection of Climate Changes in the Gulf of St. Lawrence* (Jean-Claude Theriault
1410-1430 *Climate Variability and Aquaculture* (Fred Page)
1430-1500 *Synthesis of Climate and Climate Change Research Related to Fisheries* (Ken Drinkwater)
The Impact of the Groundfish Closure on Newfoundland Coastal Communities (Bernadette Dwyer, presented at 1245 on Thursday 5 December)

1500-1530 Health Break

Session 4 **Coastal Zone** (Chair: Dick Pickrill)

1530-1550 *Impact of Sea-Level Rise on the Coasts of Atlantic Canada* (John Shaw)
1550-1610 *The Potential for Satellite Altimetry for Monitoring Coastal Sea-Level* (Ross Hendry)
1610-1630 *Interdecadal Variability in Coastal Erosion Rates* (Don Forbes)
1630-1650 *Shoreline Response to Major Climatic Events* (R.B. Taylor)

Thursday 5 December

Session 5 **Ecosystem Science/Water Resources** (Chair: John Walker)

0830-0850 *Hydrological monitoring to Detect Climate Change* (William Brimley)
0850-0910 *Effects of Climate on River Ice Jams* (S. Beltaos)
0910-0930 *Potential Ecosystem Effects of Atmospheric Change: A Precautionary Tale* (Hague Vaughan)
0930-0950 *Linkages between Climate Change, Wetlands and Wetland-Influenced Waters* (Tom Clair)

0950-1020 Health Break

1020-1040 *Climate Change and Birds* (Tony Diamond)
1040-1050 *Synthesis of Water Resource and Ecosystem Science Research Related to Climate Change* (Tom Clair)
1050-1130 (presentation by Jim Bruce; see Session 1)

1130-1245 Lunch

1245-1320 (presentation by Bernadette Dwyer; see Session 3)

Session 6 **Agriculture** (Chair: Michael Guilcher)

1320-1340 *A Review of Impacts of Climate Variability and Change on Agriculture in Atlantic Canada* (Andy Bootsma)
1340-1400 *A Spreadsheet Model for Examining the Effects of Climate Change on Food Supply* (Rod Shaw)
1400-1420 *Impact of Current and elevated Levels of UV-B Radiation on Forage Grass* (Y.A. Papadopoulos)
1420-1435 *A Field Evaluation of a UV-B Exclusion System* (Rob Gordon)
1435-1450 *Efforts to Identify UV-B Tolerant Markers in Alfalfa Plants* (R.S. Bush)

1450-1520 Health Break

Session 7 **Forestry** (Chair: Sandy Robertson)

1520-1540 *Carbon Cycling in Atlantic Canadian Forests in Relation to Climate Change* (M.B. Lavigne)
1540-1600 *Accounting for Variable Terrain in Regional-Scale Forest Climate Models* (Charles Bourque)
1600-1620 *Winter Climatic Anomalies, Xylem Conductivity and Birch Die-Back* (Roger Cox)
1620-1640 *Red Spruce Bud and Shoot Mortality* (J. Edward Hurley)
1640-1700 *A Synthesis of Climate and Climate Change Research Related to Forestry* (Roger Cox)

1830-2000 **Poster and Icebreaker (Cash Bar)**

- *Climate of Atlantic Canada* (Teresa Canavan)
- *Climatic Implications of Benthic Foraminifera Assemblage Variations* (Charles Shafer)
- *Survey of NW Atlantic Cod Populations and their Distributions Relative to Temperatures* (K. Zwanenburg)
- *Cooling of the North Atlantic Region in Relation to Secular Climate Change* (Roger Pocklington)
- *Satellite Measurement of Sea-Surface Temperatures and the Study of Ocean Climate* (Clive Mason)
- *The Influence of Changing Climates in Modifying Discharge, DOC and Nitrogen Export* (Tom Clair)
- *Water Resources: Monitoring the Effect of Climate Change on Freshwater Ecosystems* (William Brimley)
- *Extreme Events: Christmas Mountain Blowdown* (Keith Keddy)

2000-2030 **Public Presentation: *Living Through a Category Four Hurricane*** (Stanley Goldenberg)

Friday 6 December

Session 8 **Extreme Events** (Chair: Jim Bruce)

0830-0900 *Weather Extremes: Impact on the Insurance Industry* (Don Forgeron)
0900-0930 *Storm Surge Climatology* (George Parkes)
0930-0950 *Sedimentological Proxies for Holocene Storminess in Coastal Bays and on the Continental Shelf* (David Piper)

0950-1020 Health Break

1020-1040 *Frequency Analysis of North Atlantic Cyclones: Tracks and Pressures Using 43 Years of Data* (Erle Higgins)
1040-1100 *Extreme Waves* (Val Swail)
1100-1145 *The Hyper-Active 1995 Hurricane Season: A Spike or a Harbinger of Things to Come?* (Stanley Goldenberg)

1145-1315 Lunch

1315-1515 **Panel Discussion: *Gaps, Priorities and Next Steps*** (Chair: Roger Street)

Panelists : Sandy Robertson, Memorial University of Newfoundland, St. John's, Newfoundland
: David Stewart, Jacques-Whitford, Dartmouth, Nova Scotia
: Alan Ruffman, GeoMarine Associates, Halifax, Nova Scotia
: David Sawyer, EnviroEconomics, Halifax, Nova Scotia
: Howard Epstein, Halifax Regional Municipality, Halifax, Nova Scotia

APPENDIX B: SYMPOSIUM REGISTRANTS

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APPENDIX C

EXTENDED ABSTRACTS

OVERVIEW PAPERS

The Canada Country Study (CCS)

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BACKGROUND

Since the early 1980s, Canada has been very active in the field of climate impact research. Much of the early impact work was single-sector oriented. That is to say, the impact of a given climate change scenario on Canada was looked at in terms of a single aspect of either the physical environment (such as permafrost or sea ice or sea-level), or the biological environment (such as the boreal forest extent or caribou migration), or the socio-economic sphere (such as offshore energy or transportation). As expertise developed, it was soon realized that there was a strong need for more integrated evaluation. There was a need for impacts on one aspect of the environment or economy to be weighed against impacts on others. Thus, integrated regional impact studies were designed and initiated in the early 1990s. One of these - the Mackenzie Basin Impact Study (MBIS) [Cohen, 1994] - has been recently completed; another - the Great Lakes-St. Lawrence Basin Study (GLSLB) [Mortsch and Mills, 1996] - will end in 1997.

Despite these efforts, many Canadians apparently still do not have a good understanding of what climate change could mean either for the country as a whole or for themselves individually. They are aware that they could perhaps experience warming and/or more precipitation in some areas and that there might be consequences in terms of altered agricultural practices, forest movement, or rising sea level, for example. What, however, does it really mean for the everyday social and economic environment in which they live, both in the near and more distant future? Does it really mean that they're going to have to start to do some things differently from the way they do now?

In order to answer such questions, a national evaluation of the impacts of climate variability and change upon Canada and potential adaptation options has been initiated. It is known as the Canada Country Study (CCS). The time is particularly appropriate to undertake the CCS now not only due to the country's expertise in this area and the large number of related, smaller-scale studies that have been done in Canada, but also due to the international interest that now exists. Current IPCC (Intergovernmental Panel on Climate Change) interest is now focused on the impacts of climate change and a number of technical reports on regional impacts are being prepared. Two of these reports (one on North America and another on the polar regions) are of particular interest to Canada and complement the CCS work.

CCS DEVELOPMENT AND ORGANIZATION

The development of the CCS was initiated with a three-day workshop held in Toronto in March 1996. The workshop, sponsored by Environment Canada (EC) and the Canada Climate Program Board and organized by EC's Environmental Adaptation Research Group (EARG), had some three dozen participants from federal, provincial and territorial governments; private industry, NGOs, and universities. The outcome of the workshop was agreement upon the need for "a comprehensive and integrated synthesis of existing knowledge concerning the impact of climate variability and change on Canada, and the potential adaptive responses" (Sanderson, 1996).

Subsequent to this workshop, EARG, which is a component of the Atmospheric Environment Service's Climate and Atmospheric Research Directorate, continued its leadership role in the Canada Country Study. After receiving EC senior management support, the CCS became part of the EC Minister's Clean Air Campaign in late spring 1996. Organization of the CCS initiative then began in earnest. A secretariat was formed in July 1996 and located at EARG's Downsview offices(see Annex 1). The CCS was envisaged as being a two-phase study. Phase I which would start immediately and conclude in late autumn 1997 would have as its objectives:

- Preparation of an integrated assessment of present knowledge concerning the impacts of climate variability and change on Canada and adaptive responses, and
- Identification of gaps in knowledge and the suggestion of priority areas where new knowledge is most urgently needed

Phase II would be the research phase which would address the gaps and priorities identified in Phase I. Planning on it would begin in late 1997/98 with actual research being initiated in 1998/99 and continuing for approximately five years.

Following the thinking developed at the March workshop, Phase I was structured around work intended to review climate impacts and adaptation from a regional perspective as well as from a national sectoral perspective. In addition, a number of cross-cutting issues which did not fit easily into either a regional or sectoral review were addressed. Lead authors were identified for all of these components and in order to provide broad leadership to the CCS, a Steering Committee was struck. Its membership consisted of the Director of EARG as chair and representatives from several of the regional and sectoral components, the policy area, and the secretariat.

There are six regional components in the CCS (Pacific & Yukon, Prairies, Ontario, Québec, Atlantic, and Arctic) and thirteen sectoral ones (agriculture; built environment; energy; forestry; freshwater fisheries; health; insurance; marine fisheries and mammals; tourism and recreation; transportation; unmanaged ecosystems, biodiversity and wildlife; water resources; and wetlands). The cross-cutting issues are: changing landscapes, domestic trade and commerce, extraterritorial influences, extreme events, integrated air issues, sustainability, and the two economies. Reports or papers will be prepared for each of these under the guidance of the lead authors with first drafts being targeted for early spring 1997 and final, reviewed versions due July 15, 1997. The lead authors are, collectively, representative of a broad spectrum of interests from various levels of government to academia to private industry.

These final reports will be used by the secretariat which in conjunction with the Steering Committee will prepare national policy-maker's and plain language summaries in final, reviewed form by December 15, 1997 (see Annex 2). Review will be the responsibility of the Canada Climate Program Board.

Activities in 1996 have included two meetings of the Steering Committee; two lead authors workshops; the initiation of several communications-related activities, including development of a WWW site; the preparation of a set of background GCM scenarios for Canada; and the writing of author guidelines. One regional workshop was held in Atlantic Canada and planning was begun for other regional workshops in 1997, the first of which will be the Pacific & Yukon one in Vancouver in late February. In many instances, work has begun on the draft reports due in early spring 1997.

The Canada Country Study is an important new initiative being undertaken under the lead of Environment Canada. As well as offering the promise of important information and guidance to Canadians for understanding and dealing with the implications of climate variability and change, the results of the study will be of great interest internationally as other countries also start to come to grips with such concerns.

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Canada Country Study: Climate Impacts and Adaptation Outline of Documents and Timelines

4

National Plain Language Summary (20-25 pp)
developed by the
Steering Committee/Secretariat

△ **Aug. 15, 1997** △ ***Dec. 15, 1997***
Draft ***Final***

2

Regional Plain Language
Summary (≤20 pp)
One for each region

Aug. 1, 1997 ***Dec. 15, 1997***
Draft ***Final***

▽

Policy Makers Summary (10-15 pp)
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Steering Committee/Secretariat

Aug. 15, 1997 △ ***Nov. 15, 1997***
Draft ***Final***

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1

Vol. I-VI
Regional Volumes:
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Vol. VII
Sectoral Volume:
Consisting of 12 Sectoral Papers

Vol. VIII
Integrative Volume
Consisting of 5-7 Papers

July 15, 1997
Final

Annex 1.

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The Impact of Transportation Policies and Practices on our Environment

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INTRODUCTION: CAUSE AND EFFECT

As a meteorologist, I could speculate on whether global warming would ease ice-breaking problems for ships in the Gulf of St. Lawrence. Alternatively it could increase winter snow in Prince Edward Island, the Cape Breton Highlands, and western Newfoundland as arctic air moves across warmer Gulf waters. We could talk about whether more icebergs or hurricanes would be a significant hazard to the offshore oil industry, or whether higher water levels would benefit major ports by allowing larger ships to enter. Would the cost of rebuilding wharves offset this?

However, as president of a consumer advocacy group promoting public transportation, my reaction to discussing the effect of global warming on transport is to reverse the roles of cause and effect. Rather than accept unrestricted global warming as inevitable, I will attempt here to outline some key environmental impacts of transport practices and suggest how policy changes could alleviate the pollution problem

TRANSPORT, ENERGY USE, AND GLOBAL WARMING

End-Use Energy in Nova Scotia

In 1989, Nova Scotians consumed "end-use" energy as follows(N.S. Energy Strategy Roundtable, 1990):

Sector	% of Demand
Transport	39
Residential	27
Industrial/Agricultural	17
Commercial/Institutional	17

Note that transport used more energy than industrial, agricultural, commercial, and institutional sectors combined. In addition, transport relies almost exclusively on energy from fossil fuels, while other sectors include water and nuclear generated electrical energy. Clearly then, to lower energy use and thus minimize "greenhouse gas" production we should concentrate on the transport sector.

Petroleum Consumption in Canada

If we look at petroleum consumption (only) across Canada (Figure 1), the significance of transportation in production of air pollutants producing global warming becomes even clearer. Since transport used 64% of petroleum burned in Canada in 1989, then shifts to more fuel efficient transport can produce very significant benefits. And since the road mode uses 79% of this transport fuel consumed (Figure 2), it is there we should look first for improvements.

Energy Efficiencies of Various Modes of Passenger and Freight Transport

If we look at comparative fuel efficiency of **passenger** modes (Figure 3), we see that coach (day) trains and interurban buses are far superior to air and automobile travel. This is true even for new, lighter, efficient models. These efficiencies are for **fully occupied** vehicles. Air and rail service typically have occupancies of 60%. However bus averages 30 to 40%, and the average of 1.5 people in a 4 or 5 seat car is similar. The overall result is that day train and bus are 3 to 4 times more energy efficient than an aircraft or the average car.

Much of the energy inefficiency of a jet aircraft is in landing and take-off, so that considering time saved, long-haul air flights make sense. However in the medium and short distances (100 to 800 km) it should be clear that a shift to improved train and bus services makes sense.

For **freight** traffic, a paper presented to the Transport Association of Canada (Blevins and Gibson, 1991) gives us some specific figures. In engineering (English) units based on 1990 equipment:

Mode	Ton-Miles/Imperial Gallon
Tandem Highway Truck	149
Truck Trailer on Rail Flat Car	412
Container on Rail Flat Car	514
Average Rail Carload	584

Steel wheel on steel rail and grades seldom above 1% gives rail about a 3 to 1 fuel-efficiency advantage over rubber tires on standard highway pavement with grades occasionally up to 10%.

The goal then should be to transfer heavy and long-haul freight shipments to rail, using trucks for local delivery where necessary. Of course our policy of abandoning rail lines and subsidizing highway expansion over the past 20 or 30 years has run counter to this idea.

Current Modal Choices for People and Goods

Unfortunately current choices and trends favour the least energy efficient and most polluting modes. For passenger trips over 100 km., 90% are made by auto, 6% by air, 3% by bus, and 1% by rail. Air becomes the dominant mode for the 3% of these trips over 1500 km. (Statistics Canada, 1988). The latter is probably acceptable as air efficiency grows for longer flights. However a shift of only 10% of auto trips to bus and train would double their traffic and lead to more frequent, efficient, and attractive schedules.
In terms of medium and long-haul freight traffic to/from/within Atlantic Canada, 79% travels by truck, 20% by rail, and 1% by ship. (Transport Canada correspondence, 1994). While there has been some growth in "intermodal" traffic (truck or container on railway flat car) in the last decade, rail branch line abandonments have offset the gains. .

Relationship between energy use and CO2 production.

In the above discussion we have talked about energy efficiency. Since virtually all transport uses fossil fuel and it is almost impossible to burn this without producing equivalent amounts of CO2, we treat them as synonymous.

THE PROBLEM OF PUBLIC PERCEPTION

From the above statistics and suggestions we move in a different direction to the public, government, and business perceptions and attitudes which support our current environmentally damaging situation.

1. In Figure 4, we see a photo from the Halifax Chronicle-Herald of December 14, 1990. The striking thing in the photo should be the large 2-bay garage attached to the R-2000 home. Energy savings in home heating are negated by accommodation for 2 large automobiles. The reality of the situation is that neither the builder of the home nor the reporter who photographed it and wrote the accompanying story noted any inconsistency. One presumes most of the readers didn't either. So there is a need to educate the public and policy makers about our priorities.

2. Most of us in government or big business have free parking provided at work. We are encouraged to dedicate an automobile to commuting to work each day. Thus we also likely own a second vehicle for a spouse to use at home or to commute to another free space at work.

Do any of us have an employer who offers a free transit pass (a roughly equivalent value) as an alternative to a parking space? Highly unlikely! If it did happen, Revenue Canada would tax the pass as an employee benefit (but not the parking slot).

3. A broader perception is that railroads are money-losers and a drain on the public purse, while our taxes fully support highways. Of course the opposite is true. For example, Richards (1994) found that the average external cost of inter-city trucking in Canada was 2.15 cents/tonne-km and

for rail was 0.51 cents. "External costs" are those not paid for by the operator/user. (read "subsidies" for rail lines, but "investments" for highways).

SOLUTIONS

Emissions of "greenhouse" gases have risen 12% from 1990 to 1994 (Findlay, Env.Canada, 1994). Thus we must move decisively if we are to stabilize emissions at 1990 levels by the year 2000, let along cut them by 20% by 2005.

Many logical solutions like those above have been proposed to reduce production of "greenhouse" gases from transportation. They include:

a) a "green tax" of 2c/litre for transport fuel
b) raising parking fees and limiting downtown spaces
c) paying rebates to purchasers of energy-efficient autos
d) building special lanes for buses and high occupancy vehicles
e) increase provincial funding for public transport
(the opposite has just happened for transit in N.S.)
f) design more compact communities (Canadian cities use 4 to 5 times the fuel for transport than comparable European ones)
g) practice "full-cost" accounting (i.e. include costs of accidents, land, pollution, noise, energy waste, social deprivation etc. in transport costs)
h) eliminate taxes on railway rights-of-way (highways aren't taxed)
i) practice integrated transport planning by all levels of government (e.g. no downloading of rail costs to provincial highways or provincial transit subsidies to municipalities)

The problem is that most of these suggestions are contained in environmental pollution studies, global warming consultations, reports of "round tables", Natural Resources energy studies, and papers by non-governmental organizations such as Pollution Probe, Sierra Club, or Transport 2000. Seldom is there any dialogue with federal or provincial transport departments, municipal planners, or their policy officials. Getting their commitment is a major political and policy task, but it must be our highest priority.

A refreshing change was reported from Charlottetown at the September 1996 Transport Association of Canada annual meeting. In the opening address to this prestigious government-industry association, the federal deputy minister of natural resources Jean McCloskey said: "there is a distinct relationship between the country's changing climate and the future of transportation." She challenged the many senior federal and provincial ministers and officials and association representatives present to "use energy more wisely in every aspect of your operation".

Let's hope this is the beginning of a real breakthrough.

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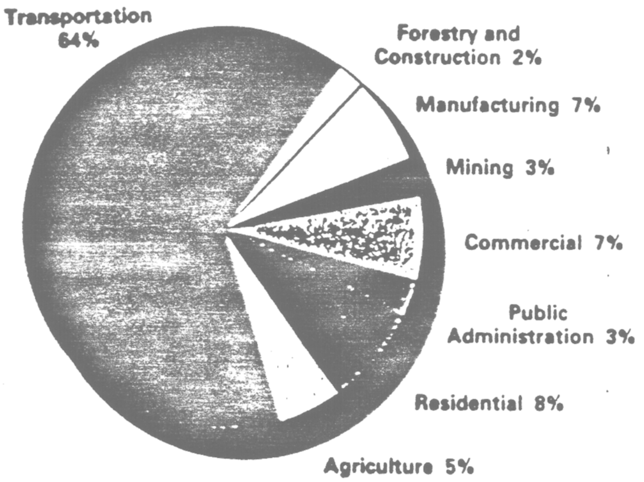
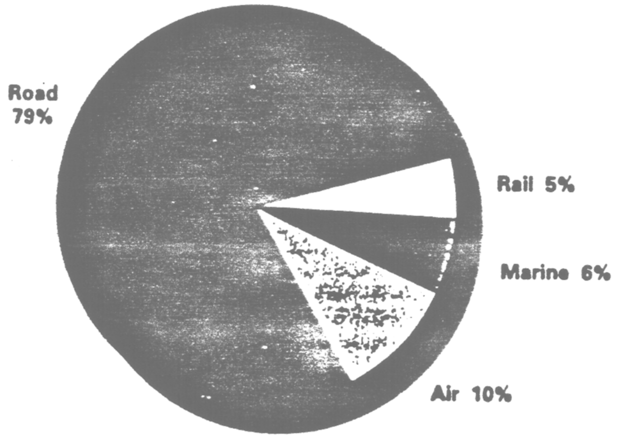
PETROLEUM CONSUMPTION BY SECTOR, 1989 Fig.1

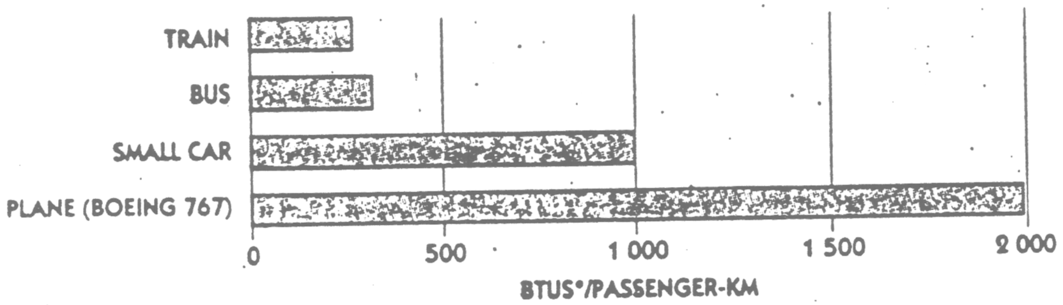


PETROLEUM CONSUMPTION IN TRANSPORTATION, 1989 Fig.2



Source: Statistics Canada, *Quarterly Report on Energy Supply-Demand in Canada 1989-IV*, Catalogue No. 57-003, July 1990.

COMPARATIVE FUEL EFFICIENCY



Source: Preliminary Program, 17th Annual Conference of the Solar Energy Society of Canada, June 21-16, 1991, Toronto, Ontario ◂

Figure 3

Transport is a guzzler

Dear Editor:

The photo and write-up about an "environmentally friendly" R-2000 home in Port Mouton (The Chronicle-Herald, Dec. 14) is somewhat incongruous.

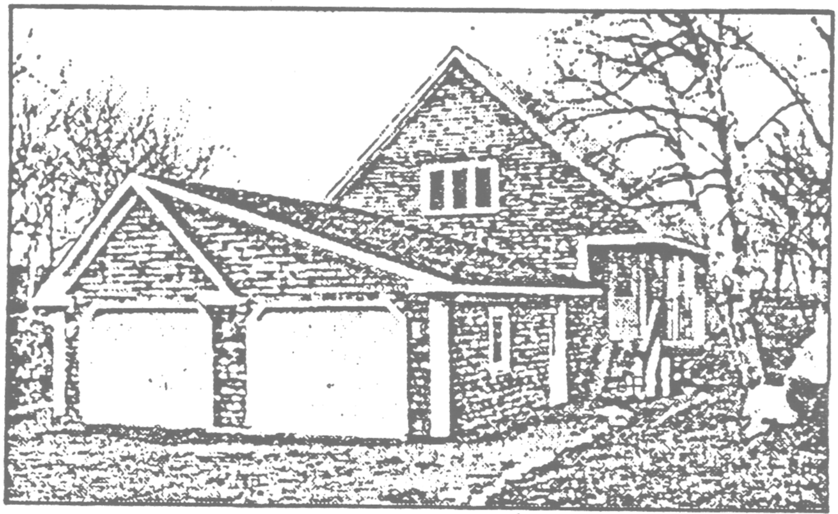
In the foreground we see a large, two-bay garage with extra wide doors for a pair of gas-guzzling cars which spoil the home's image as energy efficient.

While residential uses comprise 27 per cent of our energy consumption in Nova Scotia, transportation leads the list at 39 per cent. Residential energy consumption is a mix of oil, electricity from coal, wood and even solar. Transportation, on the other hand, depends totally on insecure and expensive foreign petroleum.

Thus, the largest potential to save energy lies in the transportation sector, but is largely ignored. Individuals and governments in the Maritimes would be well advised to support improved passenger transport by bus, train, and urban transit. Bulk and long-haul freight should travel by rail or ship, if at all possible, instead of by truck.

John Pearce

Design saves energy, environment



Nadine Fownes/South Shore Bureau

An R-2000 home in Southwest Port Mouton constructed by Ian Startup. The house, designed to be environmentally friendly, is the first of its kind to be built in Queens County.

Figure 4

Convention and Chaos: Perspectives on Climatology

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INTRODUCTION:

Climatic shifts are a common occurrence. Over geological time scales (10 million years) the uplift of plateau and mountains changed global circulation patterns, which invoked changes on major biomes. For example, the mean winter position of the jet stream, i.e., the boundary between polar and temperate air masses, affects the movement of low latitudinal treelines. Shifts in the mean summer position of the jet stream changes the boundary between forest and grassland in the plains of central Asia and North America.
There is an old adage that "civilizations lead to aridity" In fact, a popular notion has it that regional climatic change, caused by deforestation, is at the root of periodic cultural recessions during the Greco-Roman-Byzantium period. This prompted von Humbolt to comment that: *"By felling trees, which are adapted to the slopes and summits of mountains, men of every climate prepare for the future ages at once two calamities: want of wood and scarcity of water."* However, since the last sub-Pluvial (4000-5000 Bp), the climate is essentially unchanged apart from short-term variations. And, although climate shifts cause episodic human suffering, the demise of the ancient civilizations had more to do with economic and social instability and much less environmental influences.

Nevertheless, there is often a tenuous relationship between climatic shifts, deforestation and human population. In the late 1960's and early 1970's the southward shift of rainbelts, coupled with prior to deforestation in the Congo, followed by non-sustainable land-usage, triggered the expansion of the Sahara Desert and desertification over much of equatorial Africa. In the Sahel region alone, more than 100,000 people starved and 1/3 of the cattle died. Though not as devastating, the state of the forests in many parts of Atlantic Canada has been rendered unto a non-sustainable scrub forest (krummholz) by a combination of over-exploitation and suppression by a harsh winter weather.

THE PROBLEM WITH CONVENTION

The standard climatological approach is to treat the influence of human and environmental interactions as composites of linear systems. In parametric statistics, it is considered that variances are normally distributed and potentially predictable. The problem with this approach is that it cannot deal with the myriad of interscale relationships nor can it deal with the fact that new phenomenon are encountered as one scales up or down between from say plot- forest type- landscape mosaic- biome.

A popular solution is to use a Monte Carlo procedure called Latin hypercube sampling to link say physiological, succession and environmental management models. Part of the procedure involves a technique called extended-range modelling. That is, in simulation models, when spatiotemporal domains of soil-vegetation-atmosphere are extended new phenomenon are added. The product of these simulation models are frequency distributions which can be used to determine confidence intervals for statistical comparison. With this technique, scaling up spatially from the plot level to the landscape level and temporally from hourly to annually, makes it possible to generalize linear changes in the landscape ecology in response to various climatic regimes.

However, natural and cultivated environments landscapes are non-linear dynamical systems that are inherently historical, evolutionary and irreversible. Consequently, it is not possible to address the question of sustainability from the standard approach.

In the cultivated environments, sustainable management implies that forests can be genetically and technologically engineered for a specific regional "climate" but rarely, if ever, for the vagaries of weather, or rather, weather extremes. However, the ability to describe the coupling between forests and climate depends on how well we model wind in the context of small-scale turbulence within and around structures, the passage of frontal systems or shifts in the mean seasonal position of the "jet stream".

Forests respond differently to abiotic factors at climate and weather scales. For example, while the extent of wind throw in a forest is primarily a function of strong winds associated with the passage of a frontal systems; dieback, on the other hand, which makes the forest prone to wind throw from less severe storm winds, is a function of seasonal climate. At longer time scales, changes in the trajectory of frontal systems associated with shifts in the mean position of the jet stream, as result of climatic change, has a considerable influence on landscape dynamics in the Atlantic region. These would include changes in wind regimes, regional rainfall patterns and rate of evapotranspiration which affect, forest stability, tree growth, biodiversity and wood quality, regeneration and fire hazard, and human activities.

DYNAMICAL PERCEPTIONS

Forest climate is usually thought of as average weather; unchanging over the long term, but comprised of many short-term physical processes that are largely beyond human control. In cultivating forests, silviculturists tend, intuitively at least, to treat climate and weather as separate entities.

Different emphasis on climate depends also on the different philosophical viewpoint of the dynamical nature of forests. Basically, there are two basic schools of thought: the "climax" or "Equilibrium" theorists and "Mosaic-Cycle" or "Dynamical" theorists, respectively.

CLIMAX THEORY

According to this rather prevalent school of thought, forests are generally long-lived and have a slow response to climatic change. That is, forests develop within a unique set of predictable climatic limits such that climate and forest are in equilibrium. In other words, forest succession trends towards a final climax state determined by the local climatic and biophysical environment. This concept of a natural ecosystem is, in dynamical systems parlance, a fixed-point systems whereby its long-term trajectory trends towards a fixed point (climax). useful to forest policies with an immediate or relatively short term interest in the resource - in plantations and managed forests for example.

Climax theorists tend to stress the biological aspects So that when shifts in climate occur, then forest succession is comprised of a series of definable units of ecosystem which trend towards a new climax However, the variability of climatic and weather constantly changes forest dynamics. Hence, forests are rarely if ever in equilibrium with the climate. Which means that it is virtually impossible to define and predict the impact of an "average" climate on a particular forest type beyond the crudest circumstances. For example, when climax theorists discuss the role of disturbance in gap formation, they focus primarily on biotic factors and rarely ask how gaps are formed and expanded by abiotic factors.

One reason for this, of course, is the paucity of reliable abiotic data due to the difficulty in measuring environmental variables over any but the shortest spatiotemporal scales. Besides, from an applied climatological perspective, there is the paucity of standard meteorological stations located within natural environments principally because of the overwhelming bias towards monitoring urban corridors. Another has to do with the different criteria for standard meteorological stations and a specialized bioclimatological station, respectively. Standard weather stations are designed to monitor basic weather and climate usually as part of a national or global network.

MOSAIC CYCLE THEORY

The corner-stone of mosaic-cycle theory is that ecosystems consist of patches of "mosaic stones" which cycle continuously through a set of states, with adjacent patches cycling asynchronously (out-of-step). The dynamical systems approach, is embodied in the "shifting mosaic steady state" or simply the "mosaic-cycle" theory. The concept of shifting mosaic cycle is an apt description of patterning in cultivated landscapes or, stated another way, patterning in cultivated landscapes is a function of shifting priorities that reflect market and social demands plus climate and weather effects.

From a climatologists standpoint, the dynamical systems approach is a more enlightened concept: firstly, because it tends to stress the role of climate and weather more so than classical bioclimatologists do; secondly, it has a more direct link with other scientific disciplines, notably atmospherics, geophysics, and mathematical modelling, which are firmly rooted in dynamical systems theory.

In the context of my own research on forest dynamics, I emphasize the abiotic factors, namely wind, which cause gaps and many forms of forest dieback - notably the peculiar mosaic cycle of wave forests or "Shimagare" phenomenon characterized by dead tree strips moving across the landscape. From a different perspective, others of like mind have resorted to cellular automaton modelling of the dynamics of patterning which tends to emphasizes the importance of strong solar radiation as the primary forest dieback, of beech in Europe for example, at crucial times in the mosaic cycle. Incidentally, most of the forested land in Atlantic Canada which have been harvested or manipulated are an example "economic" mosaic cycling.

Most studies of climate-landscape interactions, including those by mosaic cycle theorists, are based on conventional climatological, statistical and physical models that are necessary to provide a basic understanding of "average" relationships between climate and weather and landscape ecology. Conventional approaches necessarily involves reliance on and improvement of a formidable array of classical measurement and modelling of climatological techniques.

However, before we can define, describe and utilize the relationship between climate and forests we must improve our understanding of their interactive spatiotemporal characteristics. More precisely, we should focus on initial (deterministic chaotic) events which trigger particular pattern formations and how these evolve through disruptive processes throughout the course of the interrelationship between climate and weather and landscape dynamics.

THE PROBLEM WITH CHAOS

Chaos, or more precisely, spatiotemporal chaos, is the initial condition that results in a patterned but only partially predictable instability such as a phase change from rain to freezing rain. The process is variously referred to as "self-organizing complexity", "non-linear determinism", "patterned but unpredictable", "patterned instabilities" and other seemingly contradictory terms. From a bioclimatological viewpoint, our interest in this phenomenon is aimed at describing the deterministic processes such as the pattern-forming instabilities which governs the dynamics of vegetation mosaics.

Various dynamical states evolve from both natural and human non-equilibrium pattern forming processes with a large number of deterministic chaotic elements and localized random shocks. In some respects, the relationship between silvicultural operations and extreme climatic events is a prime example of a non-equilibrium pattern-forming process. On one hand. silviculture, such as thinning, is representative of deterministic chaos that equates with stabilizing (exploitive) processes. Whereas, localized random shocks embedded within the deterministic chaotic system, say wind throw or frost damage, is responsible for the noisy (disruptive) transient states. In natural forests much the same thing happens through spatiotemporal adaptations (deterministic chaos) in response to disruptive changes in climate and weather (random shocks).

The interaction between vegetation and climate is a system of interlocking stable and unstable states with a large number of chaotic (non-linear) elements that characterizes atmosphere-vegetation-soil interactions. These interlocking states include: homogeneity (stable), periodicity, quasi-periodicity, and spatiotemporal chaos. Spatiotemporal chaos arise from a phenomenon known as intermittency; that is, an abrupt change from one dynamical state to another such as damage to parts of a forest caused by an episode of freezing rain or wind throw caused by moderate winds from an unusual direction. More often than not the impact of these small, brief weather events are the catalyst for major transformations in terms of the forest architecture. Furthermore, spatiotemporal chaos is both the bane and a product of environmental management policy makers because the coupling between climatic change and changes in the landscape, trade and land use priorities is viewed as a complex interactive processes have a huge number of chaotic elements that are impossible to describe and predict.

Fortunately, comparatively few degrees-of-freedom is involved in extreme variability over a wide range of time scales. In fact, many bioclimatic models attempt to take advantage of this property by focusing on "effective" parameters. Landscape mosaics are fractal (self-similar) in nature such that only a small number of dynamical systems exist at a phase transition between stable and unstable landscape regimes and that these systems generate multifractal structures.

Incidentally, fractal geometry has been called the "calculus of heterogeneity". fractals are not defined in a formal, legalistic statement, but by mathematical and graphical representations. A fractal is quantified by its fractal dimension: which essentially measures how efficiently an object fills space. A patch created by cutting is likely to have smoother edges and lower fractal dimension than a patch created by climate and weather events. Apparently, fractals are products of dynamical (spatiotemporal chaotic) systems and, as such, may provide a link between the abiotic (i.e., mechanistic) processes of climate and weather and the resultant biotic (architecture) forest. For example, on a poor, exposed site, tree have heterogeneous (asymmetric) profiles with a high fractal dimension; whereas, on a rich, sheltered site, trees tend to have homogeneous (symmetrical) profiles with a low fractal dimension.

In the case of forest mosaics, the magnitude of a fractal dimension of patches that make up a forest mosaic reflects the geometrical and dynamical complexity of the forest. The geometric complexity can be described by a simple fractal diversity index which relates the roughness of a particular forest patch to that of its neighbours. Fractal diversity, indicates the number of degrees-of-freedom (dynamical systems) needed to model forest dynamics such as predicting the susceptibility, intensity and rate of spread (percolation) of disturbances, particularly weather-related disturbances, across a heterogeneous landscape.

From a climatology standpoint, the principles and applications of the topologically related paradigms of fractal geometry and chaotic dynamics suggest that overly complex models or analytical systems are not necessary to arrive at a description of spatiotemporal chaos.

Overview of the Atlantic Canadian Economy

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INTRODUCTION

In this paper we present an overview of the Atlantic Canadian economy. General economic indicators are presented including employment and Gross Domestic Product (GDP) by industry and province. Comparisons are also regularly made to the Canadian economy.

THE ECONOMY

Some Basic Indicators

In Table 1, a number of indicators of the Atlantic Canadian economy are presented. As is indicated, unemployment in Newfoundland and PEI are well above the national average. Employment in Nova Scotia and New Brunswick, while above the national average, are only slightly greater. GDP per capita in 1995 was well below the national average for all provinces in Atlantic Canada.

Table 1

Socio-Economic Indicators, 1995

	Newfoundland	PEI	Nova Scotia	New Brunswick	Canada
Population	575,000	136,000	938,000	760,000	29,606,000
Labour Force	242,000	69,000	437,000	354,000	14,928,000
Unemployment Rate	18.3%	14.9%	12.1%	11.5%	9.5%
GDP/Capita	$17,318	$19,051	$20,000	$20,833	$26,347
% of Canada	65.73%	72.31%	75.91%	79.07%	

Source: Statistics Canada. Provincial Economic Accounts.

Regional Income

The Atlantic Canadian economy can be characterized as diverse, with a heavy reliance on primary and related industries, such as fishing and fish processing. An overview of GDP by province and industry is presented in Table 3 and the proportion of total GDP from primary industries is presented in Table 2. As can be seen, the primary industries as a proportion of the total economy are greater in Atlantic Canada (Table 2) than the Canadian average.

Table 2

GDP in Primary Industries as a Proportion of Total Economy, 1995

	Agriculture	Fishing	Forestry	Total Primary Industries
Newfoundland	0.35%	1.19%	0.81%	2.34%
PEI	9.20%	2.04%	0.39%	11.62%
Nova Scotia	1.18%	1.59%	0.77%	3.53%
New Brunswick	1.21%	1.00%	1.78%	3.99%
Canada	**2.11%**	**0.15%**	**0.54%**	**2.8%**

Source: Statistics Canada - Cat. No. 15-203-XPB

The manufacturing sector is 5-12% below the national average as a proportion of the total economy (Table 3) with the manufacturing industries related to the primary sector contributing greatly. For example in Nova Scotia, the two largest manufacturing industries in 1992 were fish processing, which accounted for 17% of the value of all manufacturing sector shipments, and other food products, which accounted for 15%.[1] In Newfoundland, even with the moratorium on groundfish, GDP for the fish processing sector accounted for approximately 35% of manufacturing GDP.

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[1] Nova Scotia Department of Finance. *Nova Scotia Statistical Review 1996*. Halifax, NS.

Table 3

GDP by Industries and Province, 1995. Constant 1986 Dollars

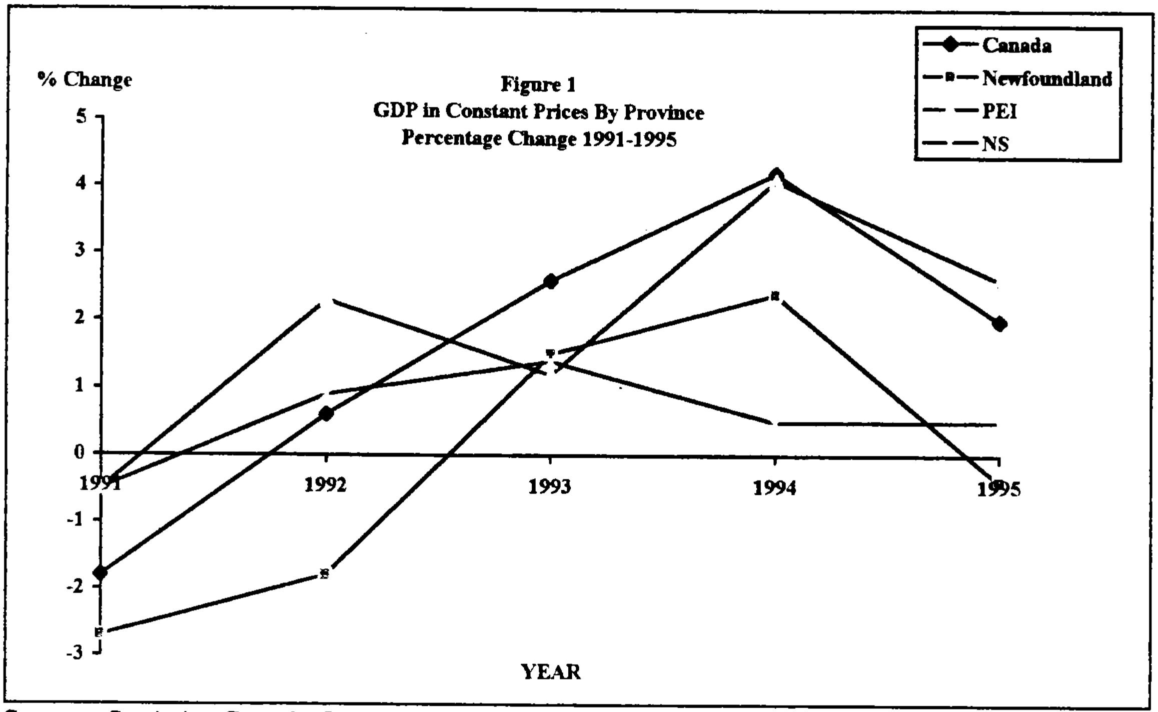
Sector	Newfoundland	PEI	Nova Scotia	New Brunswick	Canada
Goods Producing Industries	**26.17%**	**30.62%**	**25.18%**	**31.04%**	**34.26%**
Agriculture	0.35%	9.20%	1.18%	1.21%	2.11%
Fishing and Trapping	1.19%	2.04%	1.59%	1.00%	0.15%
Logging	0.81%	0.39%	0.77%	1.78%	0.54%
Mining	4.35%	0.00%	1.62%	1.78%	4.36%
Manufacturing	6.95%	8.70%	11.92%	14.02%	18.87%
Construction	7.49%	7.21%	5.62%	6.65%	5.13%
Transport and Utilities	5.65%	3.08%	2.48%	4.62%	7.48%
Service Industries	**73.83%**	**69.38%**	**74.82%**	**68.96%**	**65.74%**
Total Economy (millions $)	$6,579	$1,816	$13,184	$10,638	$542,534
% Total Canadian Economy	1.21%	0.33%	2.43%	1.96%	

Source: Statistics Canada Cat. No. 15-203-XPB

GDP Change Over Time

In Figure 1, the yearly percentage change in GDP is presented for the Atlantic economy. Much of the variation in the yearly GDP can be explained due to changes in individual industries. In Newfoundland, for example, GDP losses in the fishery due to the groundfish moratorium were offset by increases in construction in 1993 and 1994 owing to Hibernia. The result was positive economic growth despite the losses in fishing and related activities. Construction sector increases continued though 1994, but fell in 1995 as Hibernia construction slowed. Coupled with decreases in government spending in 1995 and low fish catches relative to the past, the GDP growth decreased in 1995 relative to 1994.

In PEI, a good potato harvest in 1992 resulted in substantial positive GDP growth (Agricultural GDP grew 26% relative to 1991). A sharp increase in construction activity in 1994, due to the fixed link project, likely offset an average agricultural performance in 1994 to result in a sharp percentage change in GDP versus 1993. Decreasing construction GDP was offset in 1995 by a very good potato year. The net result was strong economic growth in that year. As we can see, the performance of individual industries, such as fishing and agriculture, in Atlantic Canada can have an impact on economic performance.



Source: Statistics Canada Cat. No. 15-203-XPB

Employment

As with GDP, primary and related industries account for a large proportion of employment in Atlantic Canada (Table 4). Relative to Canada, the proportion of employment in resource-dependent industries relative to all industries ranges between 3% (Nova Scotia) and 14% (PEI) above the national average.

Table 4

Employment in Resource-Dependent Industries as a Proportion of All Industries, 1991

	Agriculture and Food Products	Fishing and Fish Products	Forest and Forest Products	Total Resource Dependent Industries
Newfoundland	1.5%	12.3%	2.7%	16.5%
PEI	10.4%	9.8%	0.9%	21.1%
Nova Scotia	3.2%	4.8%	2.2%	10.2%
New Brunswick	3.9%	3.8%	5.2%	12.9%
Canada	**4.5%**	**0.7%**	**2.0%**	**7.2%**

Source: Statistics Canada - Cat. No. 11-509E

Fish processing accounts for a large proportion of employment. In Nova Scotia, fish processing was the largest employer in manufacturing industries in 1995. In Newfoundland, fishing and fish processing account for a significant level of total employment.

In Table 5, employment by province and industry is presented. Employment in Atlantic Canada in 1995 was 7% of the total employment in Canada. High employment in transportation industries in Atlantic Canada can be explained by the need to haul primary industry outputs to markets and to processing facilities. Employment in manufacturing industries is below the national average for all provinces.

Table 5

Employment by Industry and Province, 1995.

	Newfoundland	PEI	Nova Scotia	New Brunswick	Canada
Goods Producing Industries	**22.3%**	**29.0%**	**22.9%**	**25.8%**	**27.0%**
Agriculture	1.1%	6.6%	2.2%	2.2%	3.2%
Fishing and Trapping	4.7%	4.1%	1.7%	1.2%	0.2%
Logging	1.2%	0.0%	0.8%	1.3%	0.7%
Mining	3.0%	0.0%	1.0%	1.3%	1.3%
Manufacturing	6.6%	8.5%	11.2%	12.8%	15.3%
Construction	5.6%	6.8%	4.9%	5.4%	5.4%
Transportation and Utilities	9.1%	6.8%	7.8%	8.6%	7.6%
Service Industries	39.0%	35.8%	37.7%	37.3%	37.3%
Total Employment (thousands)	197.3	58.37	384.3	313.6	13,506
% Total Canadian Employment	1.46%	0.43%	2.85%	2.32%	

Source: Statistics Canada Cat. No. 15-203-XPB

Income Distribution

During 1990 in Canada, 60% of the population received less than $35,000 of income while in Atlantic Canada, 60% of the population received incomes of less than $20,000. This difference implies that the disparity between rich and poor in Atlantic Canada is greater than the difference in Canada.[2]

GDP per capita (GDP divided by the provincial population) for the Atlantic provinces remains consistently below the national average. In 1991, as a proportion of national GDP per capita,

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[2] ACOA. 1994. *Atlantic Canada: Facing the Challenge.* DRI/McGraw-Hill

Newfoundland was 67%, PEI was 66%, Nova Scotia was 80%, and New Brunswick was 76%. A variety of alternative income per capita measures, reported over the years 1971-1989, highlight a similar disparity between incomes in Atlantic Canada and Canada.[3] It can be concluded that incomes in Atlantic Canada remain below the Canadian average.

Distribution of Economic Activity by Sub-Provincial Region

In Table 6, labour force by industry is used to highlight comparisons of the regional structure of industry compared with the Canadian average. An index is used where the labour force for each industry in each sub-region, as reported in the 1991 census, is compared with the Canadian average. If the index for the industry is below one, then, on average, there is less activity for that industry in that region compared with the Canadian average. Conversely, a number greater than one would indicate a higher proportional level of activity relative to Canada.

Based on the information in the table, a number of conclusions can be made. First, it is clear that the Atlantic Canadian economy is heavily reliant on primary industries. Sub-regions, with the exception of those containing major cities, are dominated by primary industries. Other related industries such as transportation are also high relative to the national average.

Secondly, sub regions within provincial economies vary considerably in structure. In Nova Scotia for example, the index of industry structure for primary industries ranges between 0.25 for Halifax, and 2.01 for the South Shore. This disparity between urban and rural regions within Atlantic Canada is consistent.

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[3] Bradfield, M., 1988. *Regional Economics: Analysis and Policies in Canada*. McGraw-Hill Ryerson, Toronto, and ACOA 1994.

Table 6

Industry Structure by Sub-Provincial Region, 1991
(National Average = 1)

	Primary	Manufacturing	Construction	Transportation	Government Service	% Population
Newfoundland						
Avalon Peninsula	0.59	0.70	1.10	0.93	1.77	10.8
South Coast	1.70	1.59	0.86	1.35	1.46	2.4
North Peninsula - Labrador	1.23	0.08	0.24	0.23	0.73	5.5
Notre Dame	1.86	1.11	1.19	1.13	0.99	6.0
PEI	**2.42**	**0.71**	**1.00**	**1.15**	**1.54**	**5.6**
Nova Scotia						
Annapolis Valley	1.56	0.81	1.26	1.87	1.66	5.0
North Shore	1.59	1.12	1.08	1.60	0.94	7.0
Cape Breton	1.66	0.70	0.98	2.17	1.07	7.1
South Shore	2.01	1.48	0.76	1.23	0.92	5.6
Halifax	0.25	0.46	0.88	2.07	2.09	13.8
New Brunswick						
Moncton	0.59	0.65	0.98	1.90	1.20	7.4
Edmunston	1.93	1.31	0.97	1.33	0.82	3.7
Chaleur - Miramichi	1.86	1.09	1.23	0.81	1.11	7.8
Saint John	0.61	1.06	1.00	1.06	0.95	7.3
Fredericton	0.81	0.41	0.97	0.80	2.70	5.0

Source: Statistics Canada 1991 Census and EnviroEconomics.

CONCLUSION

Based on the information presented in the above sections, four conclusions can be made about the Atlantic Canadian economy:

- the industrial structure of the economy is greatly varied between provinces and sub-regions with primary industries dominating the rural areas;
- the performance of individual industries can impact provincial economies, especially the primary sectors;
- income and employment disparities exist amongst regions in Atlantic Canada and relative to the Canadian average; and,
- the economy of Atlantic Canada is diversified, however the primary sectors and related industries account for a high proportion of economic activity, relative to the Canadian average.

Given these socio-economic characteristics, the implications of climate change and variability for Atlantic Canada are clear - the structure of the Atlantic Canadian economy makes it more susceptible than other parts of Canada to changes in the level of economic activity in response to changes in climate variables such as temperature and precipitation.

APPENDIX D

EXTENDED ABSTRACTS

CLIMATOLOGY

Supporting Climate Research

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ABSTRACT

Several ongoing long-term physical oceanographic and biological programmes are conducted by Canadian and foreign researchers on global and regional scales. Some of the in-situ data collected under these programmes date back to the previous century. Physical oceanographic data in particular continue to be integrated, quality controlled to documented standards, and made available from the Marine Environmental Data Service (MEDS). The Internet has recently provided a communications system whereby improved access to these data is now available. Regionally, the Atlantic Coastal Zone Monitoring Programme will take advantage of this technology to make active documents, information, data and data products pertaining to the programme available to participants via World Wide Web pages on the Internet. Access to these and other continuously updated MEDS database holdings which are of use to climate researchers is described.

INTRODUCTION

More and more ocean data are being exchanged in real or near real time whereas historically these were exchanged in delayed mode. This has caused a need for improved communications and management of duplicate information. Fortunately, the requirement for a significant leap forward in the capacity to handle ocean data is occurring at a time when computer and communications technology have taken significant steps forward in terms of capability and, more importantly, connectivity. In fact, connectivity may be the most fundamental "new technology" affecting the ways in which we handle data and information in the ocean sciences. One of these is the Internet.

Climate researchers require access to long temporal datasets, updated continuously and collected on a broad regional or global scale. These data must have well documented quality standards and, in some cases, be limited by programme objectives to specific datasets and derived products.

The following describes a data management model proposed for the Atlantic Coastal Zone Monitoring Programme, which makes use of the Internet to provide direct access to active collections and associated historical datasets, with the ability to share this information globally. We also present an overview of three active databases managed by MEDS, which may be of interest to climate researchers in general.

ATLANTIC COASTAL ZONE MONITORING PROGRAMME

The programme objectives are to provide the reference and long time series datasets that are necessary:
- to track and predict changes in ocean and ecosystem state and productivity;
- to respond to immediate questions posed by clients;
- to alert clients to short and long term changes; and
- to provide an adequate data base to meet future needs.

The data management objectives are as follows:
- to facilitate data and information exchange among participants (Newfoundland, Maritimes and Laurentienne regions of DFO);
- to ensure that data are documented to an agreed standard and that there is sufficient information to assess the quality and limitations of the data;
- to integrate all aspects of the ongoing monitoring programme (i.e. physical and biological data, documentation and quality standards, and products, such as climate indices derived from these observations);
- to ensure that datasets collected are made available in a timely fashion; and
- to ensure the longevity and long-term multiple re-use of the data as a coherent data set.

Data submission policies and access restrictions to the data and information relevant to this programme have yet to be finalized; however, a demonstration Internet site has been set up at MEDS to provide access to existing data, information and products of interest to participants. Capabilities to download data, information and products directly from the OMWG server to the client's desktop are already available. This latter functionality will also help meet national and international commitments to several global climate programmes.

Continuously updated and quality-controlled time series of physical and biological observations at fixed stations, standard oceanographic sections and repeated surveys relevant to the monitoring programme are under development and posted on the Internet as they are assembled.

ACTIVE EAST COAST TIDAL STATIONS

Other information relevant to this programme's activities will be posted by MEDS on the WWW site as it is available. This includes management reports, such as minutes of meetings, cruise summary reports, data inventories and summaries, documentation standards and protocols, descriptions of quality control and other processing procedures and a host of other information deemed valuable to participants and global climate researchers in general.

MEDS DATABASES OF INTEREST TO CLIMATE RESEARCH

Physical and Chemical Profile Data

MEDS manages a continuously updated database of physical and chemical profiles of oceanographic data reported on a daily to monthly basis globally, but primarily for the north western hemisphere. These subsurface profile measurements include parameters such as temperature, salinity, oxygen, and a variety of nutrients and chemicals from CTD, XBT, BT and Bottle instruments. Over 80,000 new profiles are updated annually, half of which are received and updated on a daily basis as operational oceanographic data (Figure 1).

Sources of these data include various international exchange programmes, other federal government departments, such as National Defence and Environment Canada, and Fisheries and Oceans regional organizations, such as the Bedford Institute of Oceanography in Dartmouth NS; Institut Maurice Lamontagne in Mont Jolie QC; the Northwest Atlantic Fisheries Centre in St. John's NF; St. Andrews Biological Station in St. Andrews NB; and the Institute of Ocean Sciences in Patricia Bay BC. Universities, the private sector, and provincial government agencies also contribute data.

Some historical oceanographic datasets date back to the 1900s and the database contains over one million such profiles. Since 1990, MEDS has been active in the development and implementation of standardized quality control and duplicate detection software. These quality control tests are described in IOC Manuals and Guides #22. Duplicate detection software identifies profiles that occur at nearly the same place and time. Both the quality control and duplicate detection procedures rely upon human operators to make the final decisions; however, the software may also be run in an automated mode.

Tides and water level time series data

MEDS manages operational tides and water level data (observed 15-minute and hourly heights and monthly instantaneous extremes) collected from the Atlantic, Pacific, and Arctic coasts, the Great Lakes and the St. Lawrence River (Figure 2). These datasets are reported on a daily to monthly basis by the Canadian Hydrographic Service (CHS) active permanent water level network. Approximately 70,000 new readings are updated every month via the network.

Some historical tide and water level datasets date back to before the turn of the century and the database contains over 30 million records. Quality control is effected on all in-situ water level data prior to inclusion in the databases. A variety of first and second difference calculations are used on a station by station basis to identify possible time and level errors. For tidal stations, computed differences (residuals) between observed and predicted water levels help identify time errors and gross errors in levels, particularly reference datum changes over time. Comparisons of daily means between adjacent nearby stations also assist in identifying gross height or time errors. The data are corrected where necessary; however, the databases store processing history records of all changes effected to the original data.

Drifting buoy data

In 1986, the Intergovernmental Oceanographic Commission (IOC) and the World Meteorological Organization (WMO) selected MEDS as the Responsible National Oceanographic Data Centre for drifting buoy data. MEDS manages a continuously updated database of drifting buoy data reported globally by Service ARGOS and other sources on a daily basis. Over 100,000 new messages are updated monthly as operational drifting buoy data from this network (Figure 3).

The drifting buoy database holds over eight million drifting buoy reports on the world's oceans. A drifting buoy report consists of the buoy position and numerous variables which may include surface and subsurface water temperature, air pressure, air temperature, wind speed and wind direction. The data start in 1978 and have been increasing at a rate of more than one million messages per year in more recent years.

To effect quality control on these large global datasets, MEDS displays buoy tracks on interactive graphics terminals, and the time series of sea level pressure, sea surface temperature and inferred drift velocity are examined. The examination of sea surface temperature includes a check against climatology. Spikes and data which appear erroneous are flagged and the flags are preserved with the data in the database.

SUMMARY

Data management is the activity of organizing, integrating, documenting, distributing and archiving data so that they are available where needed and when needed, and have all the supporting information necessary to enable the user to understand and use them to their full potential. Data management is vital to the success of small and large experiments, and must be addressed as a separate and important issue, particularly in programmes that involve the sharing and exchange of data, and that provide data of multiple use.

Data centres have the fundamental responsibility of preserving the integrity of the original data while striving to improve the quality, and more recently, delivering the information to clients as quickly as possible. To ensure high quality of data in the database, metadata, such as the source of the data and the methodologies used in their processing, must be kept with the data. As well, data which appear erroneous or suspicious must be flagged and these flags preserved along with the data values.

Several continuously updated long-term physical oceanographic datasets managed by the Marine Environmental Data Service and quality controlled to documented standards are available to climate researchers. Global access to these and other specialized datasets are now provided through improved connectivity via the Internet.

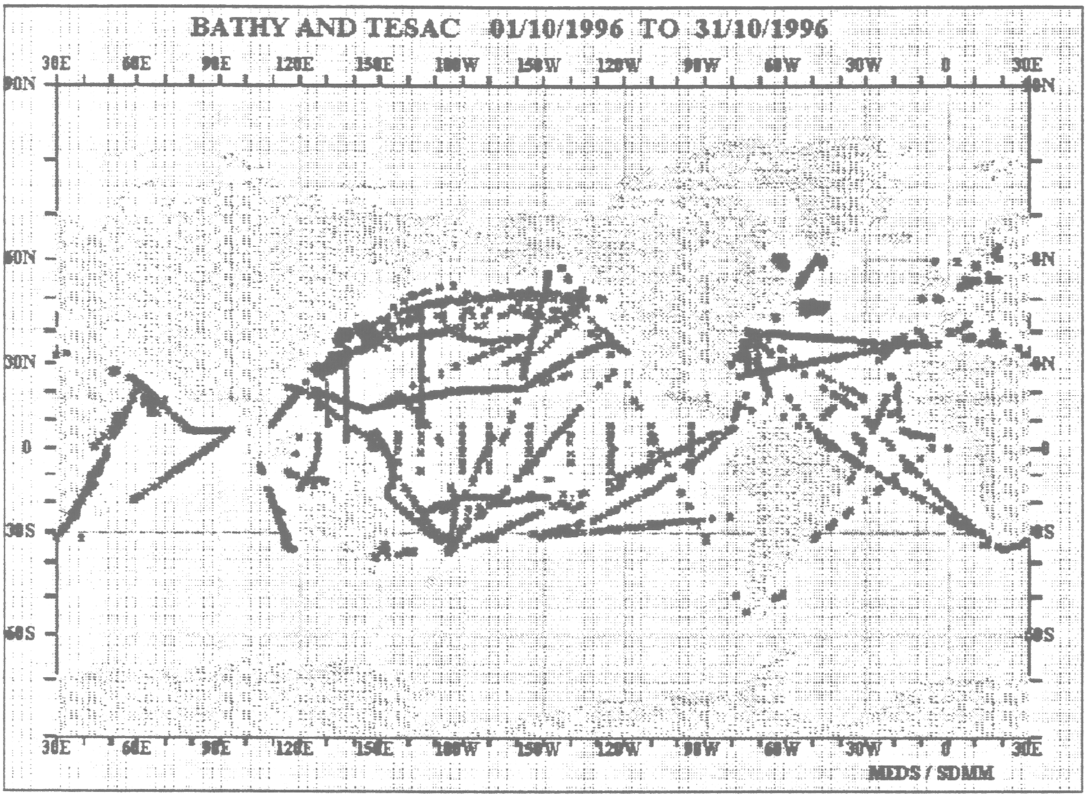

Figure 1: Locations of physical and chemical profile data in October 1996

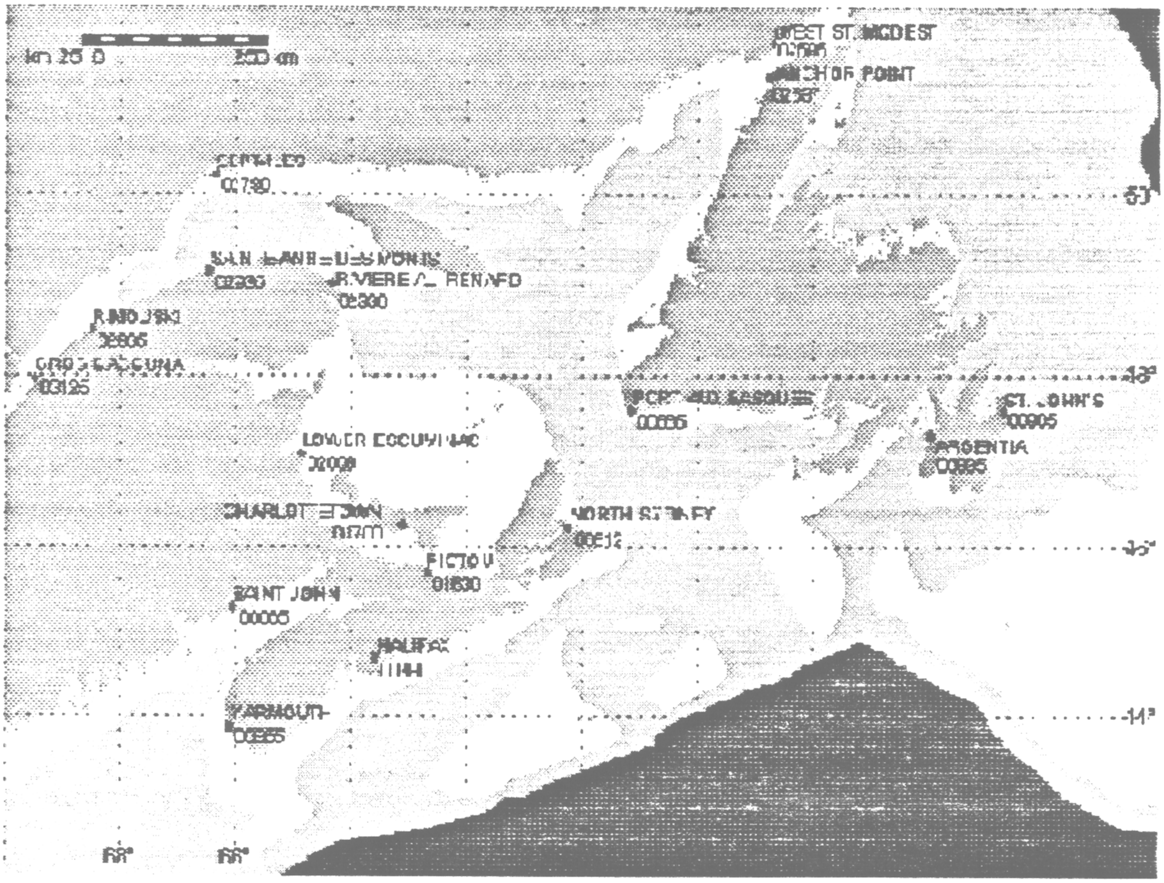

Figure 2: Locations of tide and water level data in the Atlantic Region.

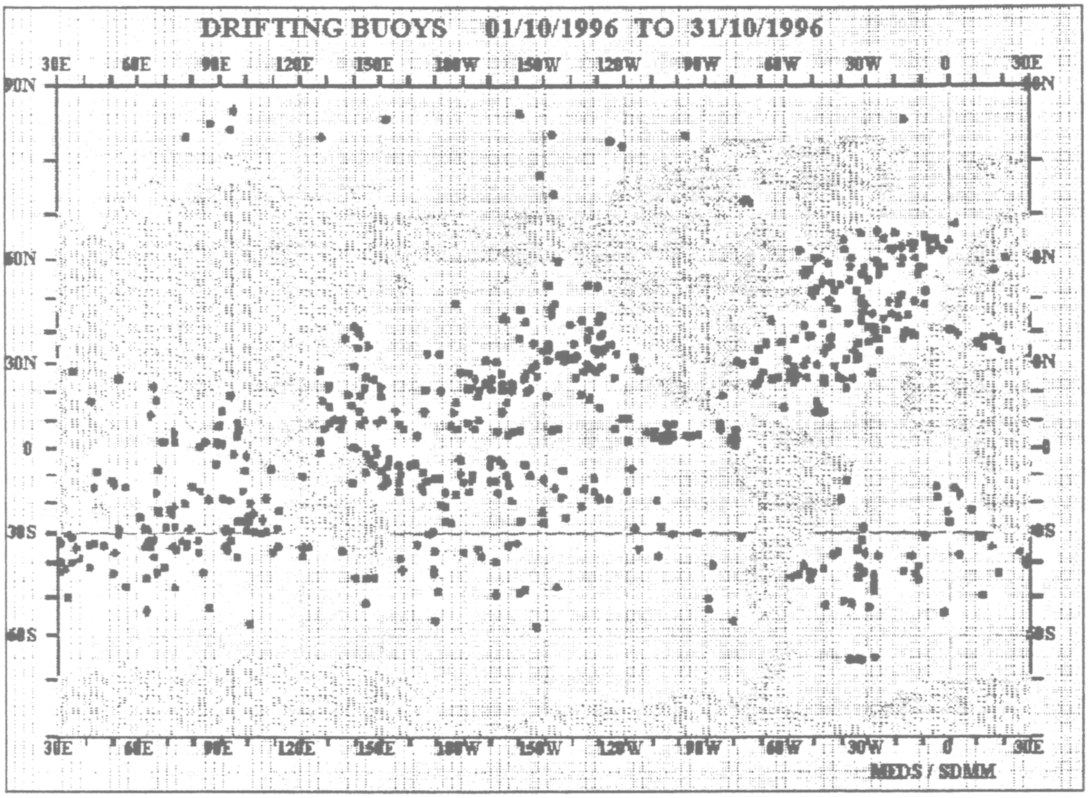

Figure 3: Locations of drifting buoys in October 1996.

Climate Trends in Atlantic Canada

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INTRODUCTION

Temperature trends in the Atlantic Region are considered in comparison with global and Canadian trends. Trends in precipitation and cloud cover are also briefly considered. Most of the analyses were performed by the Climate Monitoring and Data Interpretation Division of the Climate Research Branch, Atmospheric Environment Service, Downsview Ontario (see Environment Canada 1995). Some preliminary work by the author on trends in temperature and precipitation extremes in the Maritime Provinces is briefly reviewed.

The data sets used in most of the analyses were the Historical Canadian Climate Database (HCCD) (Gullett et al 1992). There are 131 HCCD sites across Canada, which is split into 11 Climate Regions. With the exception of Labrador, all of the region lies in the Atlantic Canada climate zone where there are 15 HCCD stations. The stations selected are long term sites, missing data gaps have been filled. The station data sets have been tested for homogeneity and the data has been adjusted for inconsistencies.

TEMPERATURE TRENDS

Global temperature trends since 1895 show a warming trend of 0.3 to 0.6°C (IPPC 1995). The trend is characterized by a warming from 1895 to the 1940s, followed by a cooling trend until the mid seventies, then a marked warming into the mid 90s (Fig. 1(a)). Globally, the 10 warmest years on record have occurred since 1980. On a national basis, Canada shows a similar warming and cooling pattern with a higher overall warming trend of ~1.1°C since 1895 (Fig 1 (b)). The Atlantic region shows a warming trend from 1895 which peaked in the mid 50s followed by a cooling trend into the 90s (Fig 1 (c)). However, the overall linear warming trend of 0.4°C (1895-1991) is not statistically significant. For the period (1895-95) the warming trend in the Atlantic Region has decreased to 0.2°C. On a seasonal basis the only statistically significant trend for the period (1895-92) is a warming of 0.8°C (1895-1992) for the summer season.

Complete data sets for all 11 Climate Regions across Canada are only available for the period 1948-95. For this period, the trend in Atlantic Canada shows a marked difference from Canada as a whole with a cooling of 0.7°C. Seasonally, the trends are: winter (-2.2°C); spring (0.0°C); summer (+0.5°C); and autumn (-0.8°C). The national trend for Canada for this period is a warming of 0.5°C.

For the approximately 40% of the land area currently analyzed over the globe, nighttime minimum temperatures have typically increased by twice as much daytime maximums over the last 40 years (IPCC, 95). Over Canada, 1895-91 minimums have increased by 1.4°C while maximums have increased by 0.6°C. For Atlantic Canada during the same period, minimums have increased by only 0.2°C while maximums have increased by 0.4°C. However, investigations by the author on a, 13 station data set in the Maritime provinces for the period 1945-93 showed an increase in minimums of 0.3°C but a **decrease** in maximums of 0.8° C.

PRECIPITATION

Trends in precipitation are much more difficult to determine than those in temperature. This is due mainly to the difficulty in obtaining accurate and consistent measurements of rain and snow amounts and the wide temporal and spatial variation in annual amounts. Due to lack of data, national trends are restricted to 1948 onwards. The national trend shows an increase since 1948 but a decline since the mid 80's. The Atlantic Region shows an increasing trend since 1948. Globally precipitation has increased overland in high latitudes in the Northern Hemisphere especially in the cold season (IPCC, 1995).

CLOUD COVER

A complex relationship exists between cloud cover and global warming and cooling. IPCC currently estimates that the total cooling effect of clouds exceeds warming by ~25%. Changes in cloud characteristics could be as important as changes in cloud cover. Globally cloudiness appears to have increased since the 1950's over the oceans. In many land areas where the daily temperature range has decreased, cloudiness increased from the 1950's at least to 1970's. Records of cloud cover in Canada are only available in digital format since 1953. Atlantic Canada has shown an increase in cloud cover of 1% (1953-91); this increase is not statistically significant, however. On a seasonal basis the Atlantic Regional trends are: winter -2%; spring +2%; summer +2%; and fall +2%.

TEMPERATURE AND PRECIPITATION EXTREMES

Some preliminary analyses of trends in extreme temperature and precipitation events for an 8 station data set in the Maritime provinces for the period 1944-90 indicate the following:
1) a decreasing trend in the number of days per year with a maximum temperature above 25°C;
2) an increasing trend in the number of days per year with a minimum temperature below -15°C;
3) an increasing trend in the number of daily precipitation events above 20mm and; 4) a very slightly increasing trend in the number of daily snowfall events above 15cm.

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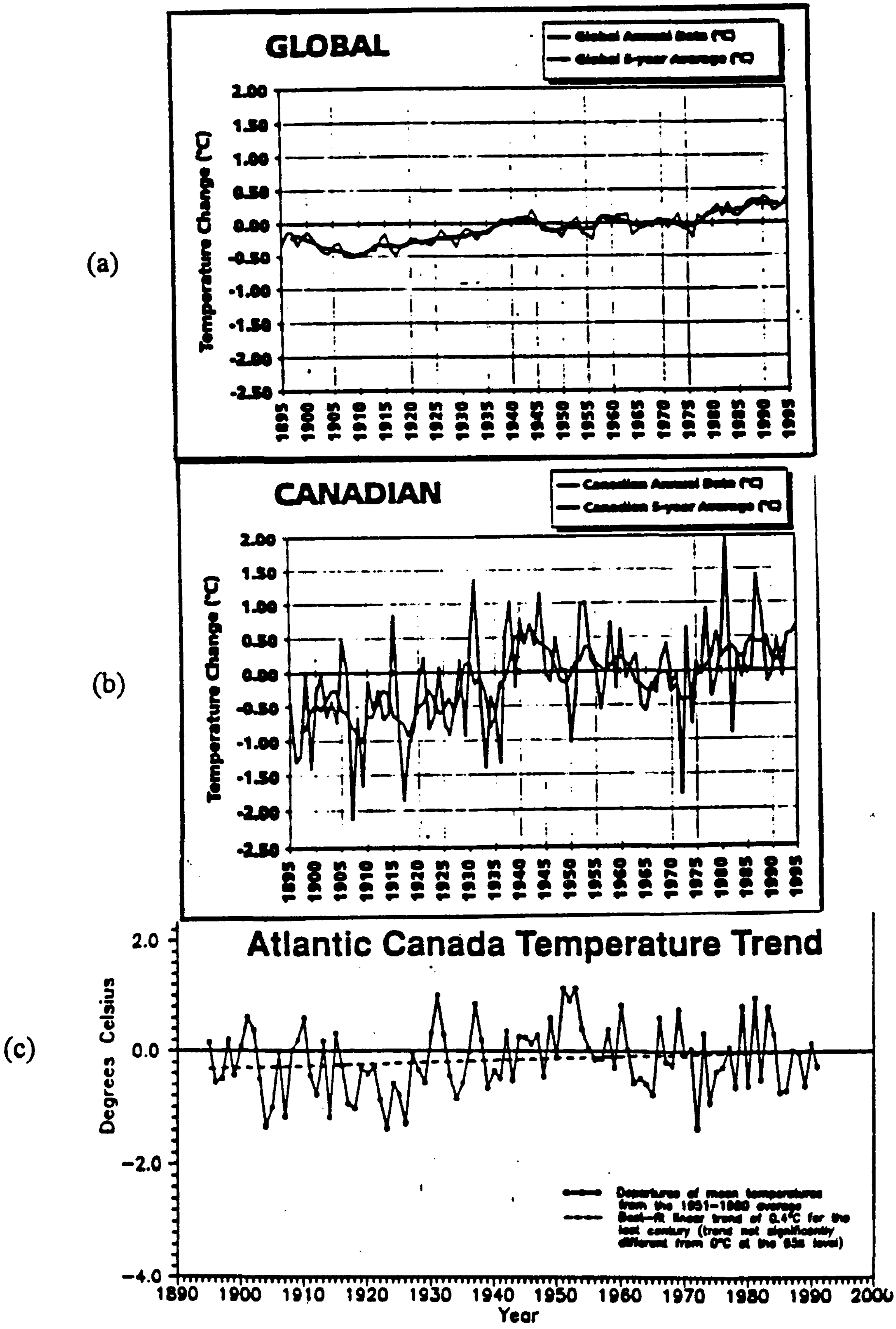

Figure 1 Global (a), Canadian (b), and Atlantic Canada (c) Temperature Trends from 1895

The Chilling Aspects Of Global Warming In Atlantic Canada

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EXTENDED ABSTRACT

Although the global warming hypothesis was initially well supported by the scientific community, it has come under increasing debate as to the authenticity of the data base and the limitations of early models used in estimating climate change. Satellite data from an equi-spatial global network over the last 16 years has failed to confirm the warming trend derived from the terrestrial data base over the same period. Until this enigma is resolved, the reliability of our climatic records is suspect. Moreover, more advanced computer models of climate change which take into account the effect of aerosols, water vapour, etc. are indicating that the original estimates of warming were excessive and in need of considerable revision. However, what is more important to policy makers and planners is the fact that climate change is regional (or even local), and may differ widely from the global average trend.

The annual mean temperature for Atlantic Canada over the 1900-1995 period, when subject to simple linear analysis over-all, shows a positive trend supporting the global warming hypothesis. However, if the data are divided into two periods, up to 1950 and from 1950 to date, the trend over the latter period is strongly negative. This shows that regional climate change, over the past 40 years has not been compatible with the quasi-exponential increase in "greenhouse gas "emissions, or the purported rise in global average temperature over this period.

From analyses using pentadal, decadal and "Normal" (30 year) filters, we deduce that the temperature for Atlantic Canada may be resolved into quasi-decadal trends, superimposed upon a secular trend which peaked in the mid-century period. This is not unique to Atlantic Canada but is shown to be present throughout the east coast of North America from Labrador to the Gulf of Mexico. Evidence from sea surface temperatures and surface air temperatures at coastal stations in the northern North Atlantic also support this premise.

The important impact that this regional climate trend has had upon domestic, industrial and commercial activity is shown by the trend since 1940 with regard to heating degree days (mean temperature <18C), freezing degree days (mean temperature <0C) and growing degree days (mean temperature >5C). The over-all decline in temperature has resulted in an increasing demand for heating energy to off-set this cooling. However, it is interesting to note that growing degree days have been fairly steady in recent years indicating that, although winters may have been colder, changes during the summer season have been more balanced.

The term "global warming" is a misnomer and should be discouraged. It is leading to a public and political misconception of climate change where some regions will be warming and others cooling periodically. Long term records of temperature from stations with over 200 years of record show that the latter part of the 18th century was just as warm as that being experienced today. Proxy data (derived from ice cores, tree rings, isotope analyses, etc.) indicate that there have been three secular trends of about 200 years periodicity which have occurred during the past millennium prior to the rise in "greenhouse gases" since the industrial revolution and the world population explosion. The temperature rise from the Maunder minimum (1640-1710) appears to have been just as dramatic as that which has occurred since the Dalton minimum of the last century.

Regional cyclical trends of short duration have been contrary to the steady rise in CO2 emissions and it must be assumed that other contributors to temperature change have been capable of negating warming from this source, over the past 40 years. This is not to imply that greenhouse gases are not contributing to climate change , particularly in areas of high population density and industrial activity, or that improved monitoring and control measures are unnecessary. On the contrary, it must be realised that the rise in CO_2 emissions is accompanied by similar rises in hygroscopic pollutants, particulate matter and acid rain. These are detrimental to our health, affect the regional biosphere and inhibit in-coming solar radiation. We need more of the latter in Atlantic Canada - not less!

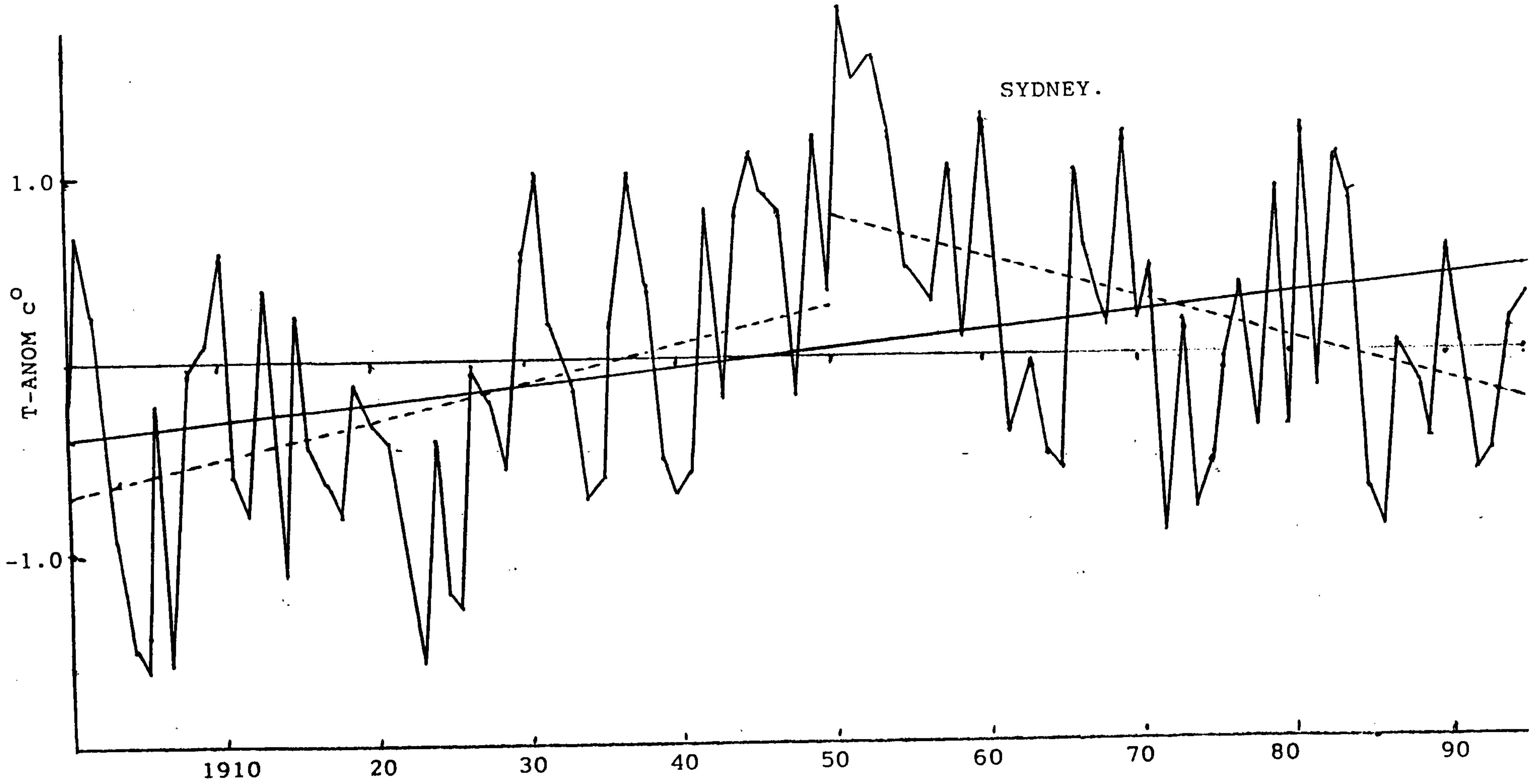


FIGURE: 1. ANNUAL MEAN SURFACE TEMPERATURES AS DEPARTURES FROM 1900-1995 MEAN

LINEAR TRENDS FOR PERIODS 1900-1995 and 1900-1950 also 1951-1995

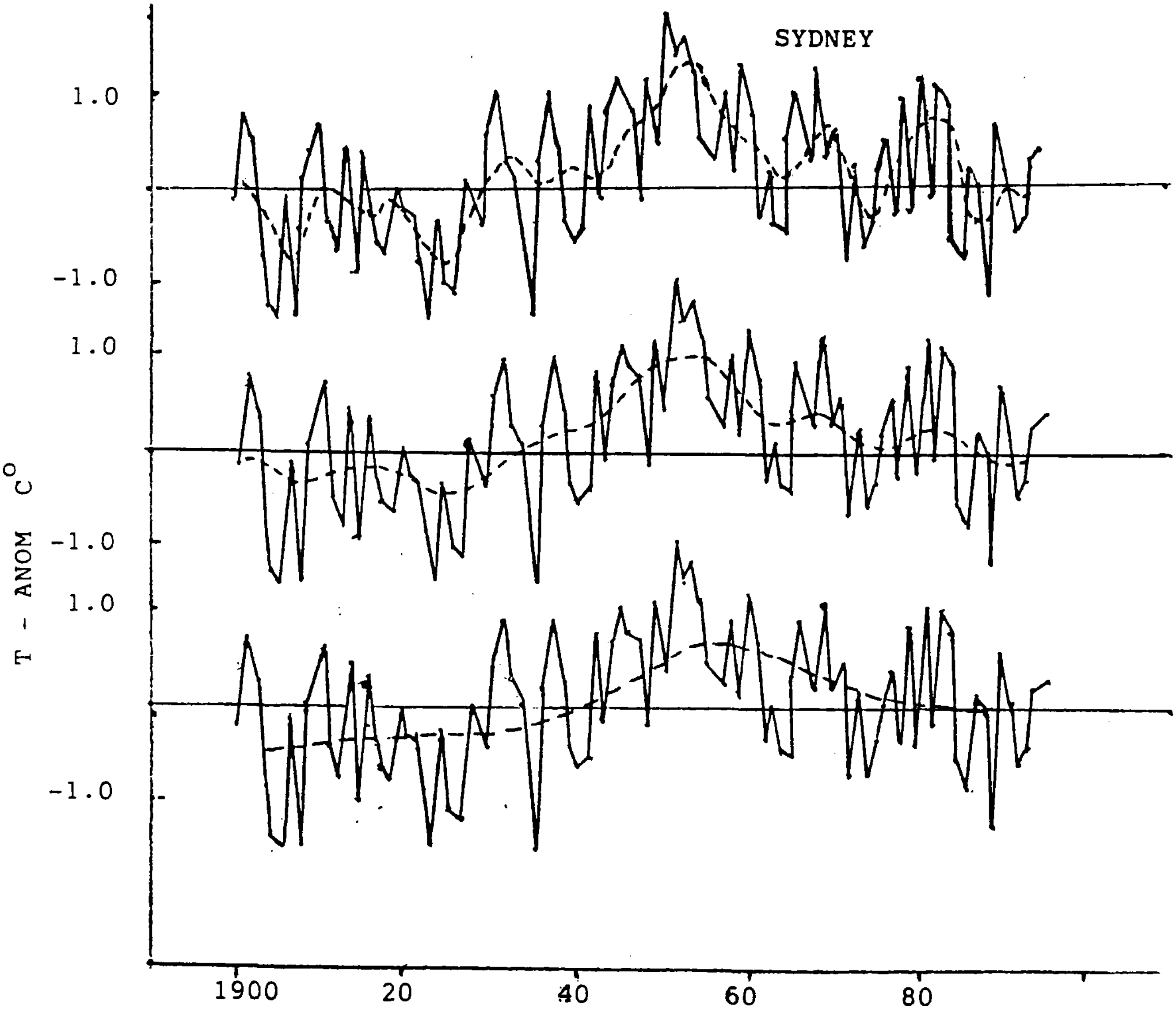


FIGURE: 2 A. RUNNING PENTADAL MEAN TEMPERATURE
B. RUNNING DECADAL MEAN.
C. RUNNING NORMAL

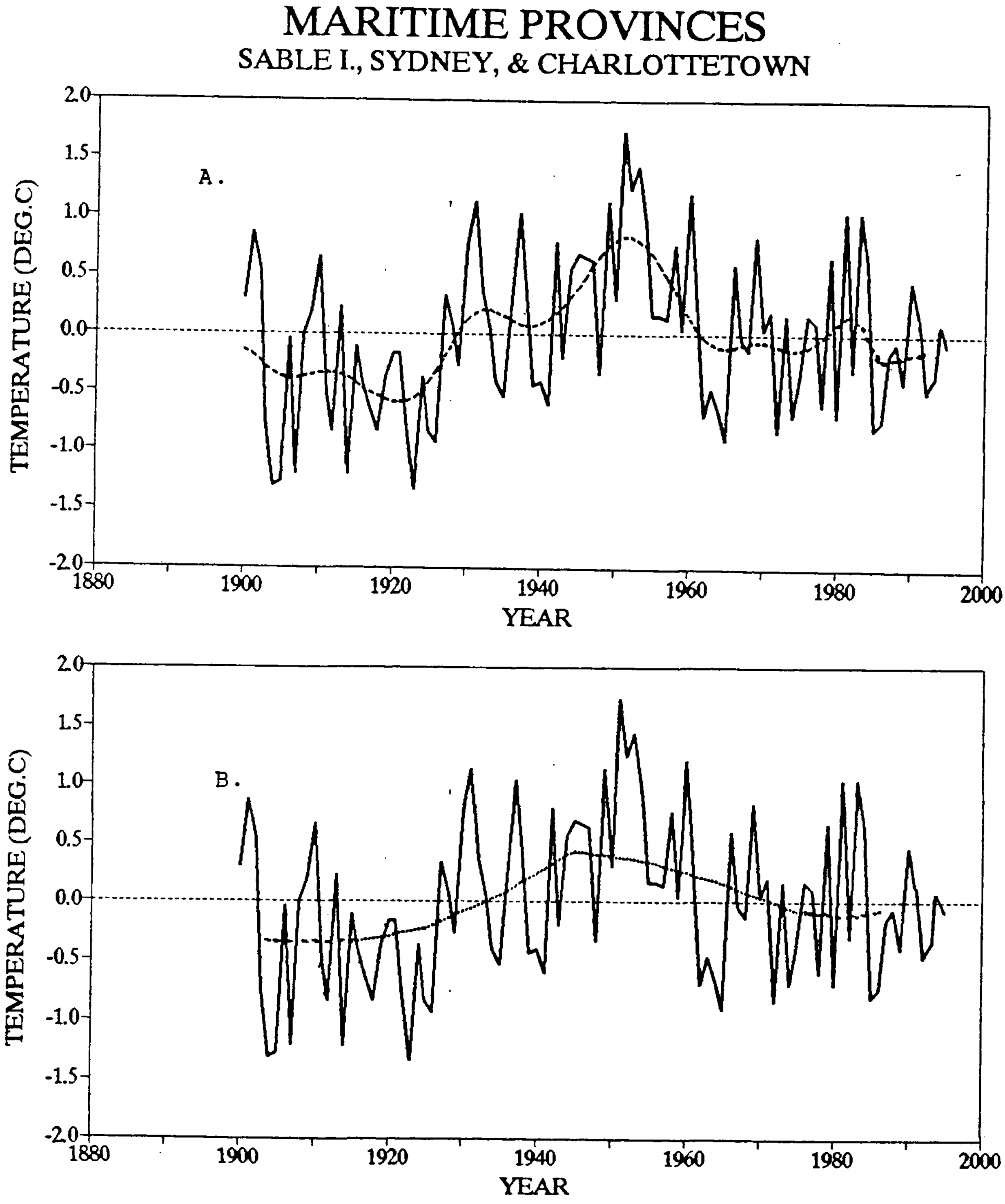
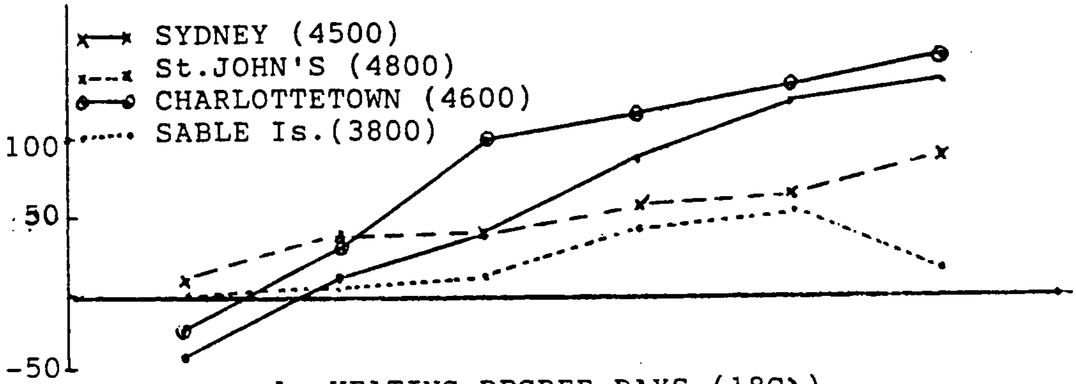
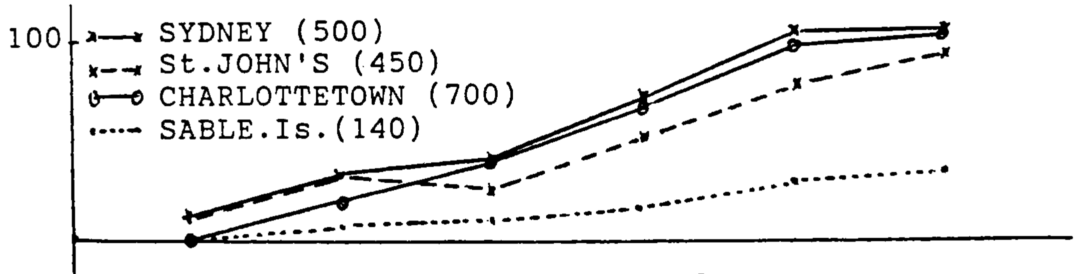


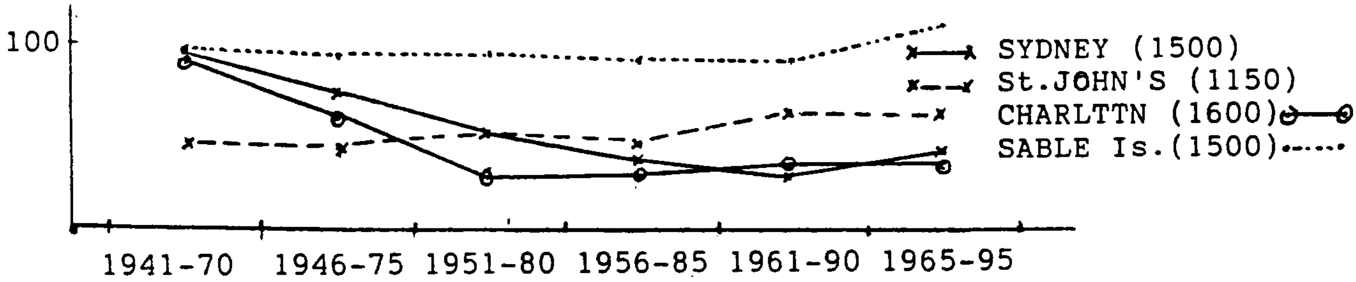
FIGURE 3 MARITIMES COMPOSITE ANNUAL MEAN TEMPERATURE
A. DECADAL TREND B. NORMAL TREND



A HEATING DEGREE DAYS (18C>)



B FREEZING DEGREE DAYS



C GROWING DEGREE DAYS.(5C<)

FIGURE: 4 HEATING,FREEZING AND GROWING DEGREE DAYS AS DEPARTURES FROM STATED BASES.

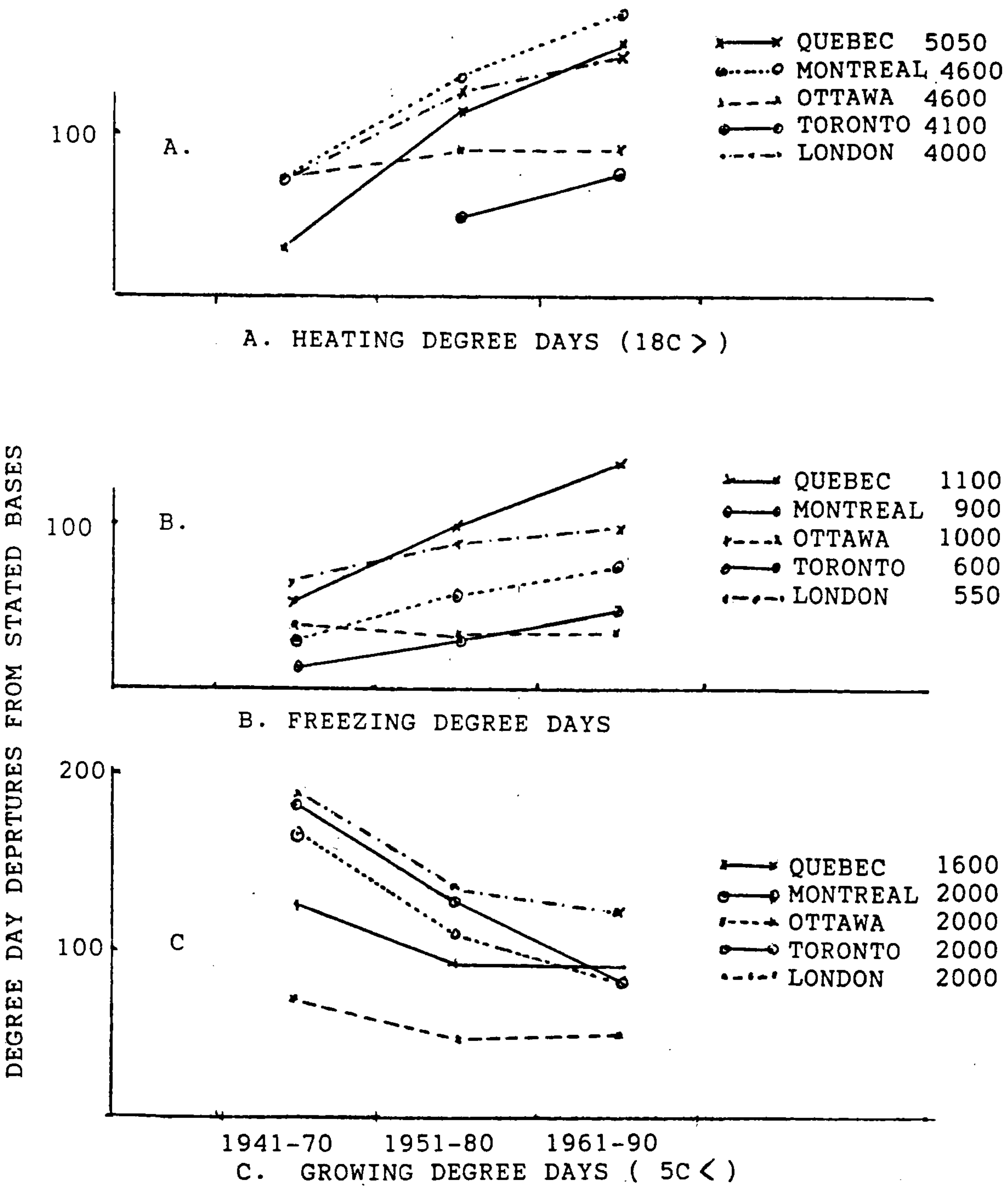


FIGURE 5. HEATING, FREEZING AND GROWING DEGREE DAY NORMALS AS DEPARTURES FROM STATED BASES.

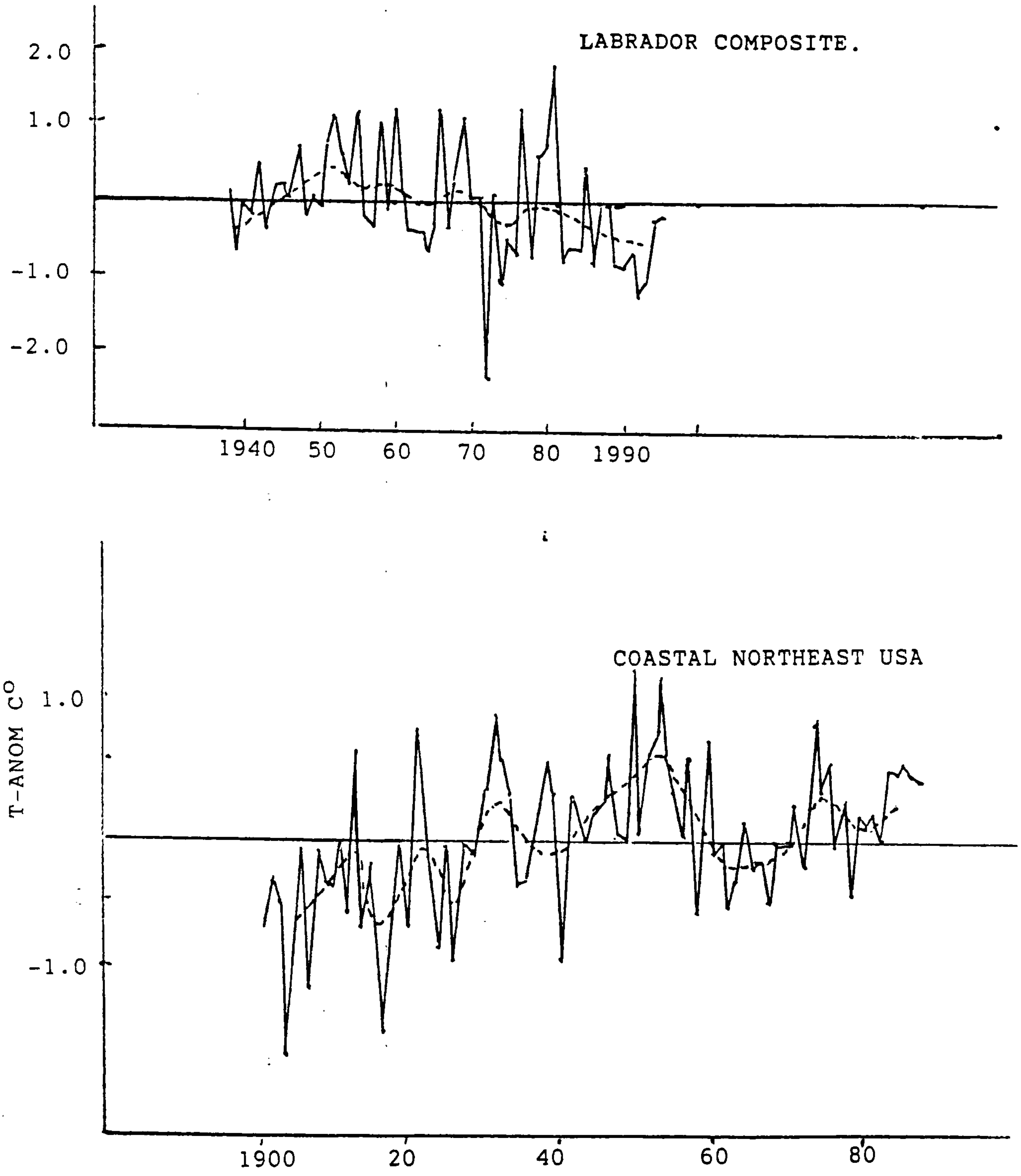


FIGURE 6 COMPOSITE REGIONAL ANNUAL MEAN AND PENTADAL RUNNING MEAN TEMPERATURES FOR

A. LABRADOR
B. COASTAL NORTHEAST USA

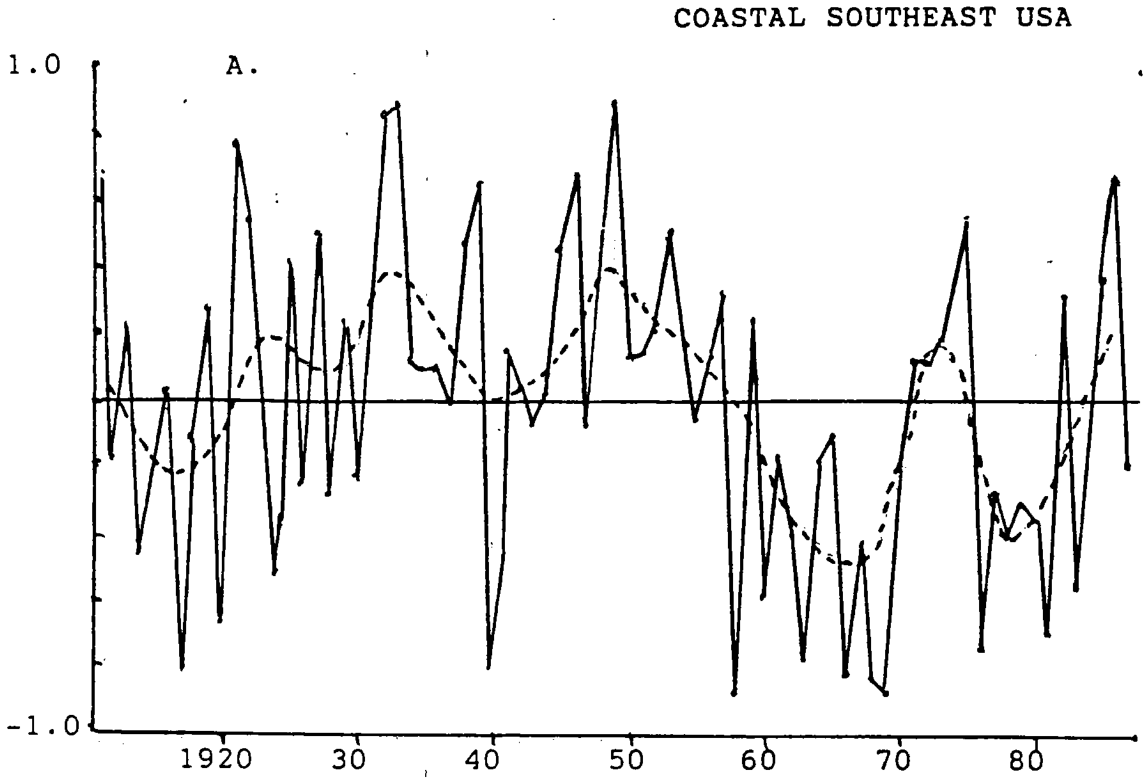
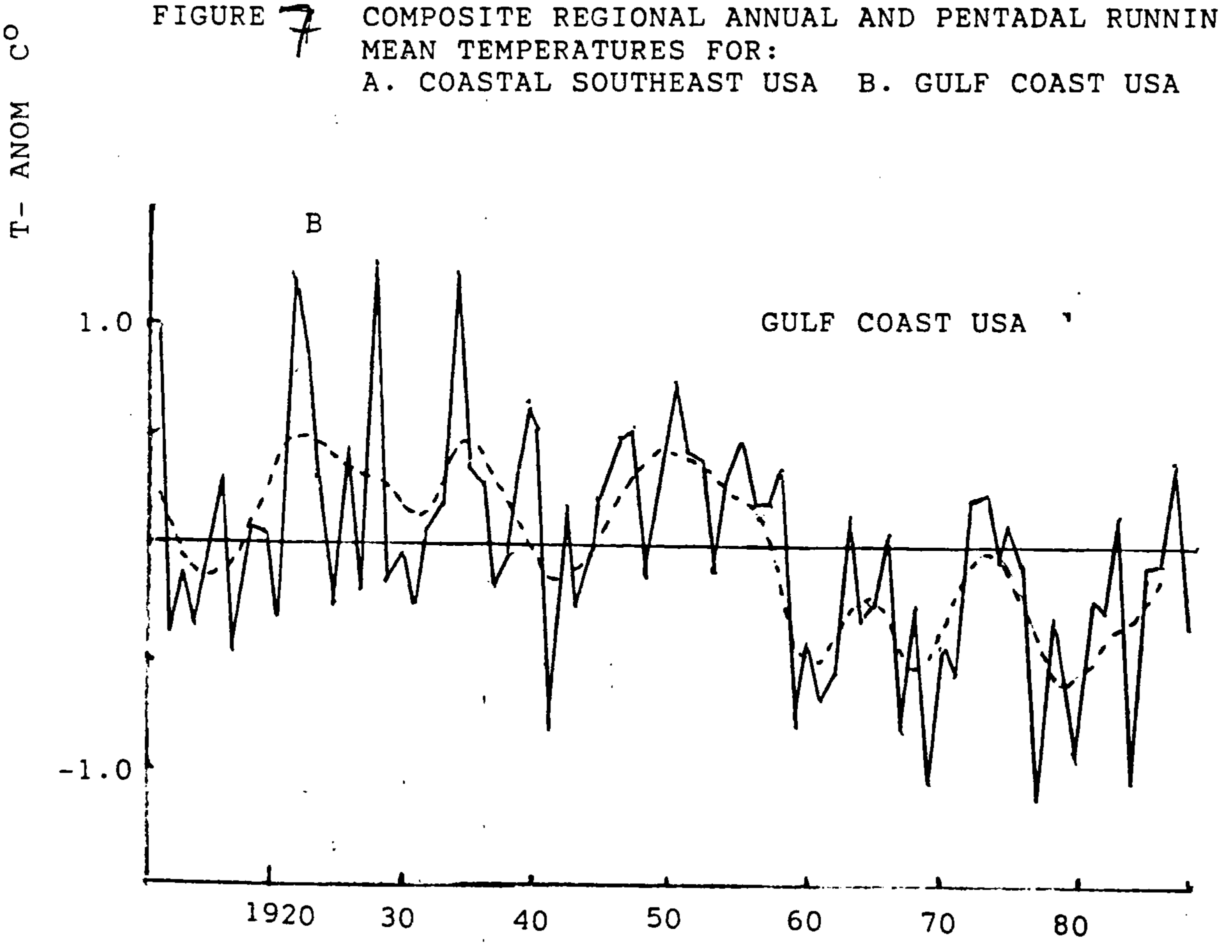


FIGURE 7 COMPOSITE REGIONAL ANNUAL AND PENTADAL RUNNING MEAN TEMPERATURES FOR:
A. COASTAL SOUTHEAST USA B. GULF COAST USA



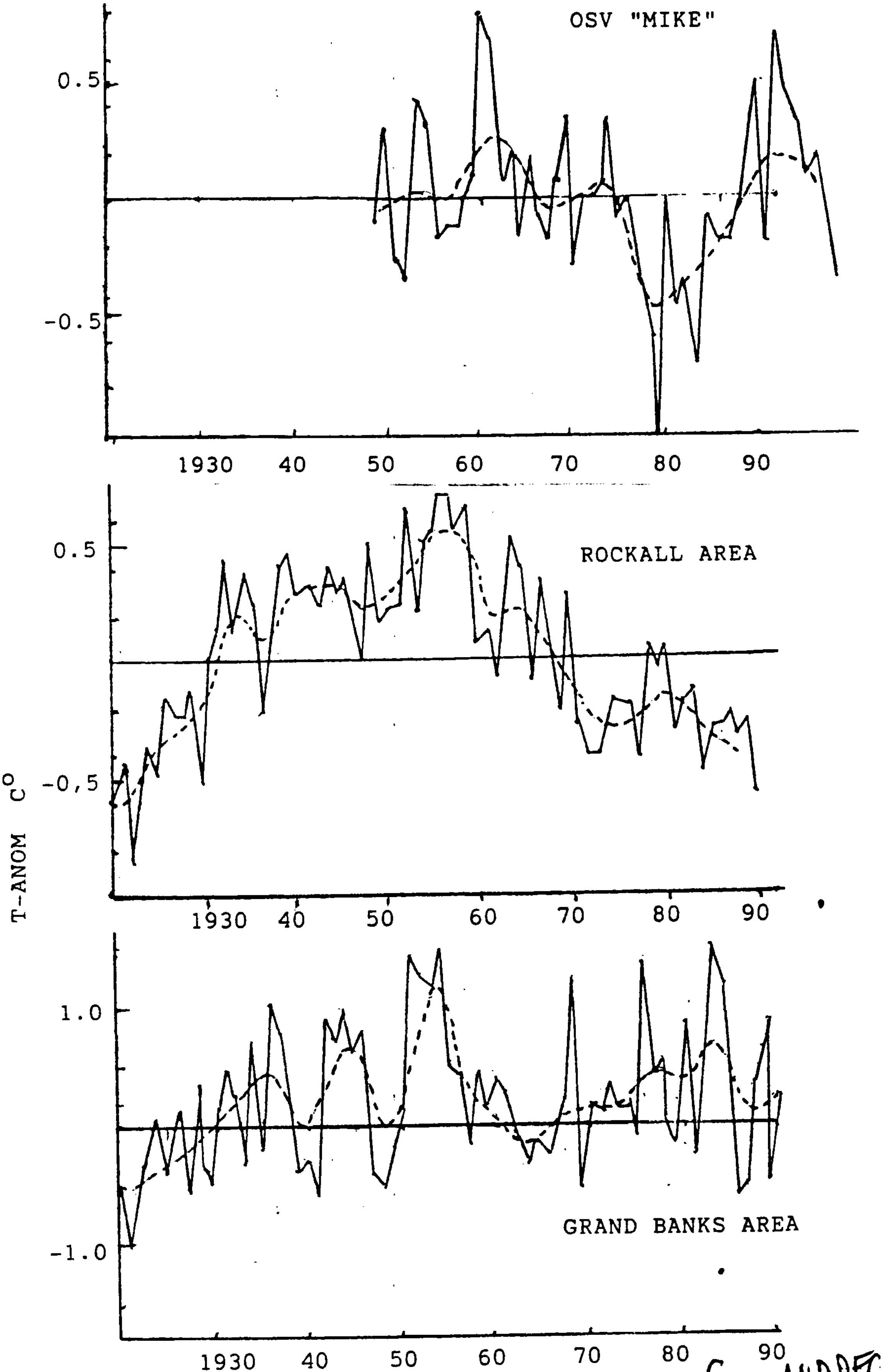


FIGURE 8. REPRESENTATIVE TRENDS of ANNUAL AND DECADAL MEAN SST

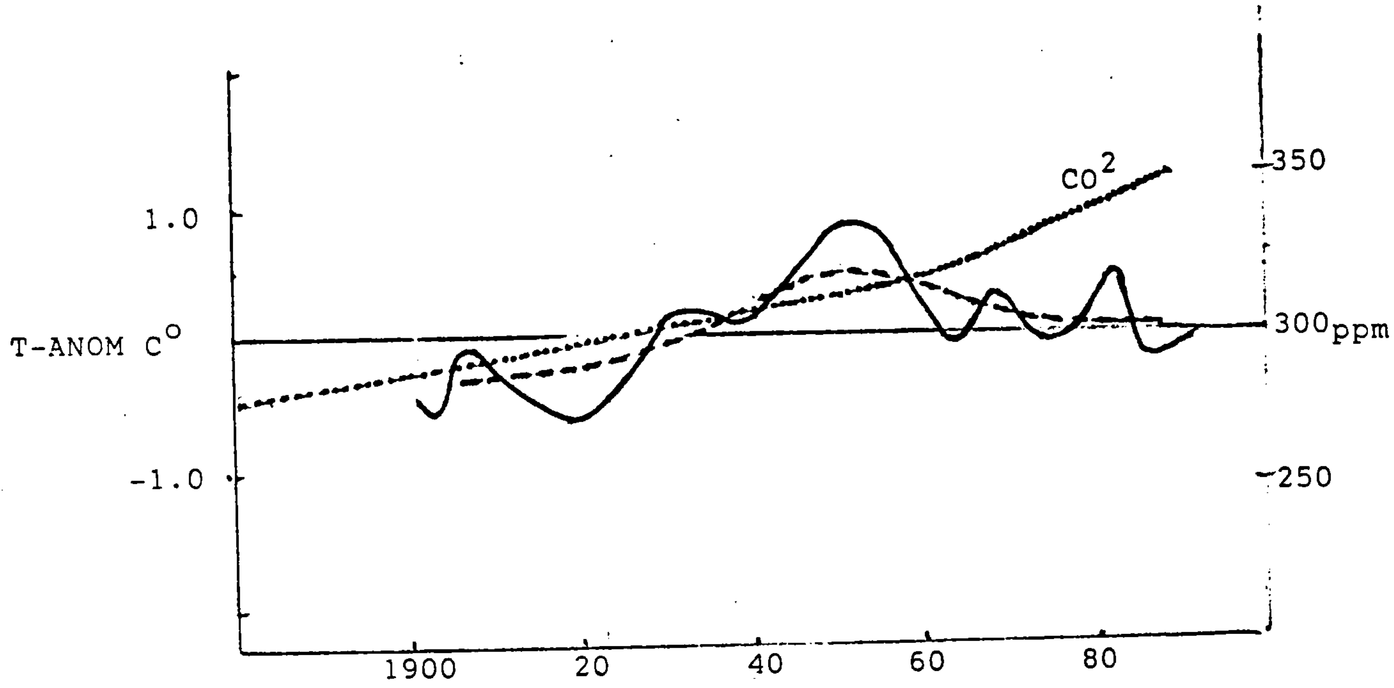


FIGURE 7 PENTADAL AND NORMAL TEMPERATURE TRENDS FOR MARITIME PROVINCES RELATIVE TO THE GLOBAL TREND IN CO2 EMISSIONS.

Interaction Between Atmosphere and Ice Cover Off Labrador and Newfoundland From 1962 To 1994

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ABSTRACT

The interannual variability of sea ice extent along the Labrador and Newfoundland coasts is shown to be caused by atmospheric circulation anomalies over the North Atlantic, typified by deviation in the strength of the Icelandic Low and the sea level air pressure gradient across the Labrador Sea. During deepening of the Icelandic Low, stronger and more persistent northwesterly winds over the Labrador shelf not only increase the southward ice flux but also cause abnormally low local air temperatures which increase local ice growth and decrease ice melt at the ice edge. The winter ice extent south of 55°N varies by as much as 65% about its 30-year mean. Variations about the normal ice extent depend throughout the ice season on air temperature in addition on offshore wind anomalies in spring, but on alongshore wind anomalies in winter. Regional numerical ice-ocean coupled models are capable of simulating the seasonal advance and retreat of the pack ice while simple regression models show some forecast capability (2 months) of the ice extent and icebergs numbers over the Newfoundland shelf.

INTRODUCTION

In contrast to world-wide global warming, Canada's coastal areas of Newfoundland and Labrador have experienced several anomalously cold periods since the early 1960s. The latest cold period started in the early 1980s and is continuing into the 1990s after a slight warming in the late 1980s. This extended abstract explores the relationships between the ice cover, atmosphere and ocean for the Canadian East coast. Results of ice-ocean coupled model, simple regression model and cause-effect relationships will be presented.

ICE PROPERTIES

Weekly composite ice maps from the Canadian Ice Service were digitized to form a thirty-two year time series of the pack ice properties for the Canadian east coast. The maps provide not only the ice extent but also information on the ice volume through the ice concentrations for each of five ice categories (new, grey, grey white, first-year and old). All this information was digitized into 0.5° latitude by 1.0° longitude grid cells. From this, the total surface area within the ice edge (ice extent), the total area of the ice itself (ice area) or the total ice volume for the total or portions of the shelf area can be calculated. Ice, thicker than 30cm (first-year), is lumped into one category whose mean thickness is assumed to be 100cm. Ice volumes are thus subject to large errors but do help to distinguish the two ice production processes: local ice growth versus ice advection.

Water column conditions over shelf areas enhances ice conditions relative to those found offshore. Over the continental shelf, vertical water stratification associated with the low salinity water from the Arctic Ocean inhibits deepening of the surface layer. Cold air will cool the surface water layer to the freezing point initiating local ice growth by mid-December. Offshore in the Labrador sea, the less stratified waters continue to mix to deeper layers due to surface cooling so that the surface temperatures do not drop below 2 to 3°C and ice does not form. Winter temperature and salinity observations collected through holes drilled in the ice show that the water inshore is near freezing throughout the water column, while over the offshore banks, slightly warmer saltier water was found below the cold surface mixed layer.

In January and February, the predominant strong northwesterly winds advect ice southwards faster than ice melts at the ice edge resulting in a southwards advancing ice edge. The pack ice reaches its most southernmost extent by mid-March and usually has a narrow tongue of ice extending eastward along the northern flank of the Grand Bank. By April, northwesterly winds decrease while the atmospheric heat flux increases. Ice starts to melt faster than it is advected southwards, resulting in a northwards retreating ice edge. By the end of June, the Newfoundland shelf is normally ice free.

The gridded time series data from the weekly ice maps can provide means, anomalies and the maximum and minimum ice extent for any particular or total area of the Labrador/Newfoundland shelf region. The area normally used in analysis is the area south 55°N (Fig. 1), its winter mean ice extent (February-March) varies greatly from year to year with periodic variations of 6 and 12 years with low values in late 1960s and high values of the early 1970s, the mid 1980s and early 1990s. The ice area varies as much as 65% (1.5×10^5 km^2) about the 30-year mean of 2.25×10^5 km^2. The heat required to melt the pack ice with an average 1m thickness is equivalent to the heat needed to warm a 30m oceanic surface layer of the same area by 2.5°C. A 65% variation in ice area thus cause a variability in the 30m ocean surface layer temperature of 1.5°C.

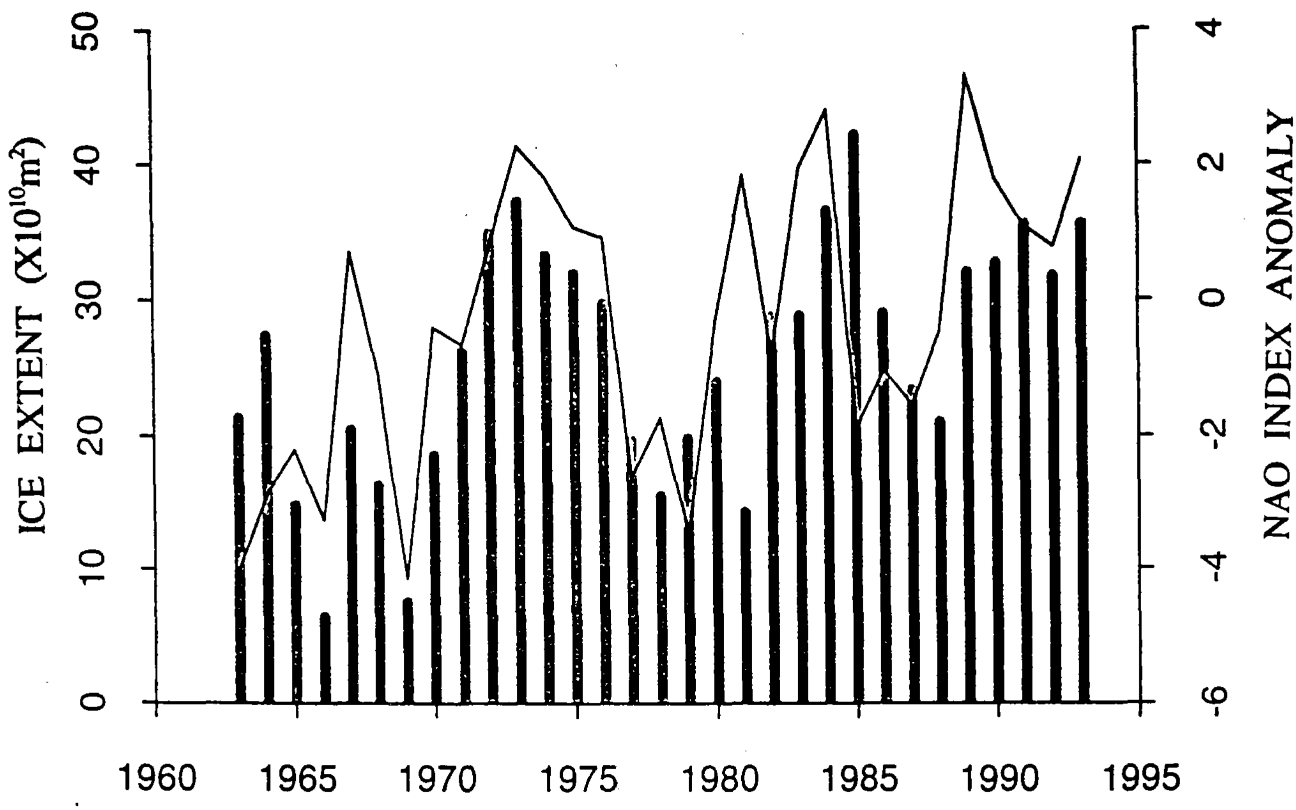

Figure 1: Time series data of winter mean ice extent south of 55°N and winter mean NAO index anomaly.

ATMOSPHERIC PARAMETERS

The atmospheric circulation in the Northwest Atlantic is predominantly from the north-west transporting cold Arctic air masses to the area. Variability in the winter atmospheric circulation can either be quantified by the strength of the Icelandic Low (North Atlantic Oscillation index (NAO)) or by the surface air pressure gradient across the Labrador Sea. During deep Icelandic Lows, the pressure gradient across the Labrador Sea increases which causes stronger and more persistent northwesterly winds to occur over the Labrador Sea and Baffin Bay. During these periods of northwesterly winds, air temperatures are below normal enhancing ice growth. High correlations exist (Table 1) between ice parameters (ice extent and icebergs) and atmospheric parameters (air pressure gradients and air temperatures). This suggests a direct cause and effect relationship between the atmospheric circulation and the sea ice extent of the area. During winters with high positive NAO indices, NW winds along the Labrador and Baffin Bay coasts increases causing severe ice conditions as in the early 1970s and 1990s and the mid-1980s. However during some years, the strong winds do not reach as far south as the Newfoundland shelf even though abnormal low temperatures do occur causing severe ice conditions (i.e. mid-1980s). The correlation (0.56) between ice extent and pressure gradient across the Labrador sea does not increase relative to the correlation with NAO (0.59). The highest correlation for the ice extent (-

0.82) is in fact with the local air temperature of Cartwright. This should not be interpreted that winds are not important but instead that both winds and temperature effects are important as the temperature regression includes both effects since the NW winds and cold air temperatures are in phase. One other ice parameter shown in Table 1, is the number of icebergs crossing 48°N. It varies similarly to ice extent as the ice cover protects icebergs from wave erosion and melting in warm water. Forecasting two months ahead the ice extent and the number of icebergs crossing 48°N in the spring (Feb. - June) is possible from the mid winter air temperatures and sea surface pressure gradients (Dec. - Feb.) explaining 80% of variance in ice extent and 50% of the variance in the number of icebergs.

	ice extent	NAO	pressure gradient	Iqaluit	Cartwright	icebergs
ice extent	1.00	0.59	0.56	-0.57	-0.82	0.67
NAO	0.59	1.00	0.61	-0.74	-0.70	0.54
pressure gradient	0.56	0.61	1.00	-0.72	-0.61	0.61
Iqaluit	-0.57	-0.74	-0.72	1.00	0.81	-0.68
Cartwright	-0.82	-0.70	-0.61	0.81	1.00	-0.63
icebergs	0.67	0.54	0.61	-0.68	-0.63	1.00

Table 1. Correlation matrix for 1962-1994 data using: ice extent south of 55°N (Feb.-April), NAO (winter), pressure gradient across Labrador Sea (Dec.-Feb.), Iqaluit air temperature (Dec.- Feb.), Cartwright air temperature (Dec.-Feb.) and # of Icebergs crossing 48°N(Feb.-July).

CAUSE-EFFECT RELATIONSHIP

Regression analysis indicates if two parameters vary similarly in time; it does not indicate if they are directly related or just dependent on a third party. Variability in wind strength can be related to variability in ice flux and variability in air temperature can be related to ice growth and ice melt. These variabilities can then be compared to the observed variability in the ice cover extent to see if the high correlation between the atmospheric variables and ice extent represents a direct cause and effect relationship. Net monthly ice advection in alongshore and offshore directions were derived from wind data by assuming that ice drifts directly downwind at 1.8% of the geostrophic wind speed. The alongshore ice drifts due to NW winds were largest in winter with maxima in the early 1970s and early 1990s but not in the mid 1990s, the three periods that large positive NAO indices and severe ice conditions occurred. The NAO index has a peak in the mid-1980s as winds were indeed stronger to the north over Baffin Bay and Labrador Sea. The winter mean (Jan-Mar) alongshore ice drifts due to wind varies 200km/month about a mean of 250km/month. Over three months, this causes a variability in ice flux of 1.2×10^5 km^2 for the 200km wide Labrador shelf. Thus the variability in ice drift due to wind accounts for 80% of the variability of 1.5×10^5 km^2 in ice extent seen below 55°N.

The variability of ice growth in winter and ice decay in spring due to temperature variability can be shown as Freezing Degree Days (FDD) or expected thickness of land-fast ice inferred from FDD. Increased ice growth did occur in land-fast ice at Cartwright for the cold periods of the early 1970s, mid-1980s and early 1990s. In contrast to the wind data, the temperature data clearly shows a cold period in the mid-1980s for the Labrador shelf as suggested by both the NAO index and ice data but not by the wind data. Expected ice growth varies 20cm about a mean of 86cm for Cartwright. Thus during cold winters, not only is the ice extent increased, but possibly the ice is also 25% thicker. However, offshore ice thicknesses from the ice maps are based on grey-tone of the ice and not accurate enough to verify this. Correlations of winter ice extent were higher with air temperature than with winds (Table 1) as temperature regression analysis include both effects. Also correlations of winter ice extent were higher with winds and air temperature at Cartwright than those farther south along Newfoundland coast.

Unlike in winter, spring ice extent and air temperatures are not significantly correlated with NW winds or with the NAO index. But there is a significant correlation between spring air temperature at Cartwright and ice extent (r=-.67). The ice extent also appears to be sensitive to the frequency of offshore winds rather than alongshore winds reflecting the effect of increased atmospheric heat flux into the ocean with more low albedo open water areas. Since the average spring air temperature increases at 1.1°C per week, an anomaly of 1.8°C represents a time delay or advance of about 10 days for the possible advent of spring ice melt. During May, the atmospheric heat input to the ocean at this latitude is 150W/m^2 or 300 Cal/cm^2 per day. A 10-day delay in ice extent represents a heat loss to the ocean equivalent to a 1°C decrease in water temperature over a 30m oceanic surface layer.

CONCLUSION

Although the existence of sea ice along the Canadian coast results from favourable oceanographic conditions, the interannual variability in sea ice conditions are caused by the variability in the large scale atmospheric circulation which locally manifest itself as air temperature and wind anomalies. Severe mid-winter ice conditions occur during years with deep Icelandic Lows when stronger and more persistent NW winds increase the southwards ice transport and when colder air temperatures increase local ice growth and decrease local ice melt. On the other hand, spring ice extents in addition to depend on air temperatures are correlated with ice dispersion processes (offshore winds) rather than with ice advection (alongshore winds). Ice extent variability can be forecast to 80% of the variance two months in advance by winds and air temperatures.

Contributions to Newfoundland Climatology

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INTRODUCTION

This paper highlights climatological research in Newfoundland and Iceland by the author and his colleagues. Briefly, the research focused mainly on energy flux and radiation balance measurements, the role of wind on forests, and the application of circular statistics, fractal geometry and chaos theory to studies of on the dynamics of the natural environment. Incidentally, research was also conducted on many other aspects of the natural and urban environment, but these are indirectly related to climatology, per se.

ENERGY AND RADIATION BALANCE MEASUREMENTS.

The field work for energy flux measurements (based on the Bowen ratio method) was initially conducted with automatic stations located on a field stripped of vegetation at Salmon Pond, near Glenwood, central Newfoundland during the summer of 1986-88. A second system was operated on a forest cutover, during the summer at St. George's, southwestern Newfoundland between 1988-1990. Year-round measurements of the radiation balance over a willow coppice in a nursery at Pasadena, western Newfoundland. The main purpose of the radiation interception experiment at Pasadena was to measure the amount of solar energy converted into chemical energy in a plot of fast-growing Salix. Despite, the finicky nature of the reversing psychrometric system for Bowen ratio measurements, measurements from the wide array of instruments is still the only detailed database of energy and radiation balance of a boreal forest ecosystem in region.

Because of a long association with Icelandic foresters and the uniqueness of the site from an experimental and maintenance standpoint, a biometeorological and bioclimatological experiment was established on a 16 ha site at Gunnarsholt in south Iceland in 1990. This station, which is operated year-round, is essentially a long-term measurement of changes in energy balance (Bowen ratio and eddy correlation methods) and carbon dioxide fluxes, radiation balance and interception, stomatal conductance, nutrient cycling, biomass productivity and partitioning, development of mycorrhizae and other factors in a developing black cottonwood plantation on homogenous volcanic soils in south Iceland.

EFFECTS OF WIND ON LANDSCAPES

The field work on this aspect of climatology was conducted throughout Newfoundland with the most detailed measurements made in a unique coastal wave forest complex at Spirity Cove in the Great Northern Peninsula. Generally, applied research was aimed at developing new principles and applications for use in environmental assessments and landscape management as well as the possibility of regional and global climate change. This involved parameterization of a broad range of environmental (climatic) influences such as the relative importance of wind effects on changes in population structure, stand density, self-thinning processes, bole form factor, partitioning of biomass yield and cone-mass distribution. Incidentally, Voronoi tessellations, well-known to climatologists. was adapted for describing sequential point pattern processes within the cyclical development of wave forests from regeneration through to senescence and wave dieback. This work led to the theory that special aerodynamic features, known as helical role vortices combined with Honami winds, is responsible for creating wave forests and how those features cause instability of forest edges in cutovers and plantations. Which, in turn, spawned further research leading to fractals geometry and spatiotemporal chaos to explain the dynamical systems in climate-landscape interactions.

A map of surface wind flow patterns across the island was based on a tree deformation indice. Similarly, a map of wind flow in the Cities of St. John's and Mount Pearl, respectively, also based on a tree deformation indice, demonstrated the effect of certain wind regimes on urban forests and, more importantly, how living windbreaks should be designed and oriented for year-round effectiveness.

CIRCULAR STATISTICS, FRACTAL GEOMETRY AND CHAOS THEORY

Because of the chaotic nature of climate and weather, landscape ecology has very complex (non-linear) dynamics that are inherently historical, evolutionary and irreversible. When assessing forest changes it becomes obvious that new phenomenon are observed that are not present at smaller and larger scales. The traditional paradigms of normality in statistics and Euclidean geometry cannot deal with the myriad of interscale relationships that characterize the ever-changing forest vegetation and growth. The new paradigms of circular (directional) statistics, fractal geometry and chaos theory have emerged that can describe and explain the architecture and changes of forested landscapes.

Circular statistics (that is the analysis of directional data) is particularly useful for isolating the impact of relatively short term events; namely, the role of particular weather (frontal) systems in directional aspects of landscape patterns. This work formally demonstrated the close directionality in both abiotic and growth response to them. In colonizing birch stands in Iceland, for example, crown asymmetry poplar saplings and the strong curvature of isolated birch stands is a response to humid southwesterly winds, but that regeneration of birch seedlings is dependent on strong, dry easterly and north easterly winds. Similarly, the fungal spore distribution of the potato wart disease (*Synchytrium endobioticum*) is strongly influenced by the direction and relative humidity of the wind - particularly in winter. The directionality of many aspects of wave forests (direction and rate of dieback and regeneration, wood properties, crown asymmetry, etc., is also a function of the directionality of wind.

Fractal geometry quantifies the nature of heterogeneity. Fractals are not defined by a formal, legalistic statement, but by mathematical and graphical representations. A fractal is usually quantified by its fractal dimension which measures how efficiently a fractal structure, such as a cloud, turbulence, forests, etc., occupies space. By combining measures of roughness (fractal dimension) and diversity (spatiotemporal variability) we can derive an index known as the fractal diversity. This is particularly useful for comparing patterns of vegetation mosaics or simply the distribution of seeds and spores in quadrats which are largely a function of weather events and climatic variability. Scale invariance in complex phenomenon, namely fractal diffusion, i.e., a cascade of multifractal fields, belies the dynamics of atmosphere-vegetation-soil interactions. For example, the percolation wind-related disturbance regimes in landscape dynamics - whether it be relatively benign as in the general turbulent flow above and within a forest, or extreme as in gale-force winds - it can be described in terms of multifractal cascades.

Colloquially, *chaos* means formless matter or social confusion. By contrast, its meaning in statistics, meteorology and physics is similar: that is, in statistics it means non-random (order) but unpredictable; and in meteorology and physics it means a patterned instability. Furthermore, it implies that if a system is inherently chaotic, then its description may not require complex models. Indeed, many studies of chaotic systems, particular in dynamical and ecosystem dynamics show how a few dominant frequencies (degrees-of-freedom) can entrain other, lesser processes. Biospheric models work in this way by focusing on effective parameters, such as extreme weather events, while ignoring the effect of small-scale landscape heterogeneity on large-scale energy fluxes. Similarly, there is an advantage in concentrating on the macro-mechanisms in atmosphere-forest interactions which characterize the fractal diversity of a landscape, even though the micro-mechanisms (principle pattern-forming instabilities) may never be entirely predictable. For example, the relationship between climatology and forest development in a region is predictable. However, the relationship between the inherently chaotic dynamics of weather systems and the fractal diversity of the resultant vectors in social, economic and environment entities. Collectively, the process of interlocking stable and unstable states is known as spatiotemporal chaos with a large number of non-linear elements, many of which defy description. Apparently, in studies of biotic (forests) and abiotic (weather) interactions in wind-shape wave forests, suggests that chaos equates with stabilizing (exploitive) processes - characterized by natural scaling power laws; while localized random shocks embedded within the deterministic chaotic system is responsible for the noisy (disruptive) transient states. Some climatologists have translated the concept of deterministic chaos into practical tools that can distinguish between the predictable vs. unpredictable analogues of climate variability. To do this, climatologists need to understand the root causes that trigger pattern forming phenomenon - i.e., self-organizing complexity - which lead to spatiotemporal chaotic systems. For example, given that the fractal diversity of an agroforestry landscape is influenced by the dynamic states of regional climate, human and physical environment, then it follows that the agroforestry system should also exhibit broad range of dynamical states. Within the last couple of years, theoretical meteorologists and physicists have discovered a process called weak spatiotemporal chaos. They used coupled lattice maps (CLM=s) to model rich spatiotemporal patterns with solutions for homogeneity (fixed point), periodicity, quasi-periodicity, deterministic chaos and deterministic chaos collapsing to soft and hard turbulence. Noteworthy studies on spatiotemporal chaos related to impact of climate on terrestrial environments are forest dieback aeolian sand dune formation

Ongoing research on wave forests is addressing a number of bioclimatological questions.

1. Is the frequency of regional distribution of wave forests a function of long-term changes in the trajectories of weather systems, or short-term changes in local wind regimes.

2. Where does a wave forest fit within in the evolution of climate-forest interactions.

3. What are the principle biometeorological factors that create and perpetuate the wave forest phenomenon.

4. Are wave forests stochastic, chaotic or quasi-periodic dynamical systems.

To date, the answers have only been partially addressed,. However, based on several analogues of spatiotemporal chaos, it is clear that wave forests are a system of interlocking dynamical states created and perpetuated by weather systems of many dynamical states which may also be a consequence of shifts in the mean trajectories of the jet stream.

THE ROLE OF FORESTS IN REGIONAL AND GLOBAL CHANGE

Includes research on the role of forests in regional and global climatic change, particularly in harsh environments in Newfoundland and Iceland. Applications emanating from this research is applied to many facets of forestry, particularly in protecting, increasing or improving and rehabilitating forested landscapes in general: also, improving the microclimate of small gardens to improve the livability of northern communities and the cultivation of fast-growing plantations and understanding and manipulating the vegetation dynamics of forested landscapes; and the role of forests in regional and global change.

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Within the Bounds of the NAO: Canada-UK Inter-Relations of Temperature and Rainfall : Implications for Agriculture and Oceanography?

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INTRODUCTION.

The work presented at this workshop is a brief look at parts of a multi-pronged climate study still in progress. This text attempts to make a coherent story out of those several, larger, different studies. Since the work is still in progress initial interpretations of results from these studies may change after further work. Readers may wish to verify the current status of any findings with the author, at the above e-mail address, before referencing any of this text.

This work ties in with studies which have been conducted on the UK side of the Atlantic over the last ten years. There studies have been able to show that climatic signals such as the North Atlantic Oscillation (NAO) and the Gulf Stream Position (taken as a climate index; Taylor, 1995) can be clearly detected in different parts of the environment - in marine, aquatic and land parameters. In particular spatial differences in marine species of zooplankton have been shown to relate to changes in the NAO (SAHFOS, 1995).

This text examines basin-scale climatic signals with respect to how such large scale signals might have effects on the climate in Atlantic Canada and to determine if such climate signals might also show up in local environmental parameters. This study does not look at climatic trends but at shorter, almost cyclic variations and primarily concentrates on winter processes.

VISUALIZATION APPROACH

The classic climatic index for the North Atlantic is the NAO. Defined as the pressure difference between Iceland and the Azores for the winter months of December, January and February (Rogers, 1984). Recently studies, for specific reasons, have used similarly named indices taken from different pressure stations and covering different months to the classical index (Hurrell, 1995). This study has no *a priori* reason for adapting the index and so continues to use the classical version of the NAO.

How the NAO effects temperature and precipitation patterns has been well documented (Walker and Bliss 1932, Wallace and Gutzler 1981). There is however more than one way of looking at any data set and this author has found it helpful to work in terms of spatial probability maps. The global gridded air temperature anomaly data set is correlated with the NAO series. Passing each resulting gridded correlation value through a probability look-up table and coding the output permits an easy visual representation of the spatial extent of the probability of detecting a NAO like signal in winter temperature records for any location. Transferring the sign of the correlation to the probability code also allows these plots to show where significant relationships will be positive and where they will be negative. A suitable choice of colour (shades of yellow increasing to red for the positive relationships and shades of green increasing to blue for the negative relationships) allows the user to quickly assess the "seesaw" nature of the physical process. Similar processing of the global gridded rainfall anomaly data set provides a similarly easy means of viewing maps of regions of increased and decreased precipitation, all agreeing with the patterns as described in the above references.

No new science is involved but rather an alternative visualisation technique which may help some users link spatial and temporal climate changes to changes in other environmental parameters. In recent years distinct decadal signals have been observed in climate records (Kushnir, 1994, Hurrell, 1995) so as a starting point the probability maps were produced for 10 year intervals. Around 1963 a distinct change or transition occurred in the climate regime of the northern hemisphere as defined by variations in the troposphere (Shabbar et al., 1990). Apparently successful attempts to "model" climate-environmental relationships with more recent data often breaks down once applied to the early 1960's and the years before [personal interaction with UK studies]. Hence the occurrence of some form of discontinuity in the climatic regime altering climate-environment relationships appears likely. So the division of the decades was made to divide around 1963; that is 1954-1963, 1964-1973 etc.

VIEWING THE PATTERNS

By creating a 50 year probability map we can define a long term "classical" or "typical" pattern for the NAO. Regions of positive response to the NAO occurring over Europe and the eastern USA and regions of negative response over Western-Greenland, Labrador and over northern Africa and parts of the Mediterranean. Looking at that "classical" seesaw pattern of warmer and colder winter regions associated with the NAO, it is also clear that certain regions are sandwiched between these positive and negative regions. On the Canadian side the sandwiched region included Nova Scotia, on the European side the sandwiched region runs throughout the Mediterranean as far as the Black Sea.

Decadal probability plots of NAO - air temperature patterns were examined. For the periods 1974-83 the extent of the eastern US positive region was large and included Nova Scotia. The very high NAO index occurring during this period was associated with a warming of winter temperatures which extended into the Maritimes. Similarly colder winter temperatures were occurring over the Labrador sea and most of the Mediterranean for this period.

The period 1964-1973 included the period of the lowest recorded NAO values. The probability map clearly showed that correspondingly warmer winter conditions occurred over the entire Hudson Bay region over the Gulf of St. Lawrence and covered the Cape Breton region of Nova Scotia. Combined, these two decadal maps help illustrate how winter climate records in Atlantic Canada may be related to the coverage of either the northern or the southern climate sub-systems of the NAO.

THE 1920's.

If we looked at the decadal probability maps for this century we would find that the "typical" NAO structure for temperature fails to appear for the first two decades of this century and is distorted for the third decade. The "typical" NAO pattern can still be seen in the temperature - probability maps for 1865 - 1901 as well as in the rainfall patterns of the same period. Hence lack of an NAO pattern at the start of this century is due neither to poorer data nor to reduced coverage.

At the start of the century, anomalous atmospheric circulation patterns persisted and it is likely that several different processes were occurring. One particular feature can be clearly seen in temperature records around the 1920s. An approximately 2°C "jump" occurred around 1918-1925 in the region of Iceland. It is possible to use this "jump" feature, with the temperature records either side of the jump heavily smoothed, as a search index to look at the spatial probability of where such a feature may occur in the temperature anomalies throughout the northern hemisphere. The actual processes occurring are much more complicated than a single jump in temperature. Jumps occurred at different times and to different scales throughout the region. At the most northern extent of Baffin Bay, a jump in winter temperature anomalies of approximately 7°C occurred 4-5 years later than the Iceland feature. A probability map for the Iceland jump does show that most of the coastal stations from 60°N and above have such a feature, all of the same positive sign. Hence such a positive feature occurring in the winter records, the timing staggered throughout the region, will contribute to masking the positive-negative patterns of the NAO. That secondary climate feature can also be shown to be present in varying degrees through the other seasons.

The fact that a warming influence occurred in the 1920s is well documented. From the start of the century the frequency of westerly winds across the Atlantic increased, peaking around 1920. That westerly flow was considered a contributing factor to bringing warmer water into the UK region and an associated increase in herring catches peaking in 1927. At the same time western Greenland experienced large rises in Cod catches in the second half of the 1920s (Buch et al., 1994).

How those early events might be summarised are; that a basin scale disruption of the typical NAO pattern was the result of additional climate systems whose spatial and temporal extent had major effects on parts of the environment. Most of the evidence readily available to the author related to changes in the fisheries and oceans side of the environment; information from other disciplines may also exist.

THE LAST DECADE: 1984-1993.

The NAO temperature probability map for the period 1984 to 1993 does not appear to be typical. The northern half of the typical (negative-positive) NAO pattern is clearly evident. The spatial extent of the probable relationship between warmer winters and the NAO was exceptionally large covering both western and eastern Europe and extending into northern Asia. However, the southern part of the NAO pattern over the eastern USA and Africa is missing. Would such a change in pattern represent a major basin scale disruption in the climate system and would we find any associated major changes in environmental parameters?

The answer to the second question appears to be, yes. The marine, colour indices for the north of Scotland and North Sea exhibit the greatest values, since records started in 1948. Both regions exhibited a double peak, the highest at the end of the 1980s with a smaller, secondary peak in the early parts of the 1990s. A principal component analysis of hay yields from the South of England exhibited a decrease within the same time frame as the larger peak in the marine records. Nova Scotia and the Black Sea normally lie between the positive and negative phases of the NAO. In the early 1990s both these regions exhibited exceptionally large changes in some of their environmental parameters. The turbidity of the central core of the Black Sea rose to the highest ever recorded. Similarly a principal component of hay yields from Nova Scotia exhibited a decrease in the early 1990s.

Long term marine data indicating biological activity in Canadian fisheries areas are scarce. Satellite observations of ocean colour are available for cloud free areas, from 1979 to approximately 1983 (1986 is come cases) so do not adequately cover the decade under consideration. Canada financed the restarting of the UK-CPR monitoring program for the Canadian sections of the North Atlantic in 1991. Those four years of data (1991-1995, continuing) indicate that Canadian east coast waters may have also experienced increases in biological activity in the early 1990s. No direct data exists to determine whether or not Canadian waters experienced the earlier, higher peak as measured in UK waters.

Some climatic process needs to be identified which would link these environmental signals in Europe, the Black Sea and Atlantic Canada. By using a wider range of data and analysis techniques than is touched on in this text, it is possible to identify a potential climate system linking these regions. The proposed system has the same annual variation as the NAO but persists over the winter and spring seasons and may even have isolated residual effects in summer, namely an association with the period of hot, dry summers in the UK. Having the same sign as the primary NAO signal the secondary climate system may have contributed to the increased spatial extent of warmer conditions over Europe. Over North America the secondary system occurred from western Canada down to the eastern US with an inverse phase to the primary NAO signal. These two systems, of opposite phase, would appear to cancel each other out and so result in no statistically significant signal being mapped out for US eastern regions. In this decade two climatic systems may have existed; supplementing their winter-time climatic effects over Europe but negating their effects over the eastern USA with associated large scale changes in environmental parameters in some regions. Hence the traditional double pattern of the NAO lost its lower half and appeared as a single system.

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APPENDIX E

EXTENDED ABSTRACTS

FISHERIES AND PLANKTON

Climate Variability and Aquaculture

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INTRODUCTION

In 1985-86 a workshop on regional climate change was held in Nova Scotia and the consequences for aquaculture were not considered (Scarratt et al. 1987). The marine aquaculture industry has continued to grow since then, and has become established as a significant socio-economic activities, particularly for the culture of Atlantic salmon and the blue mussel. The salmon industry in southwestern New Brunswick is now worth approximately $120 million annually and has generated about 1500 jobs. The potential for additional growth and diversification of the industry is such that it could rival and exceed the dollar value of traditional harvest fisheries in Atlantic Canada. As a consequence, the influence of climate on aquaculture is beginning to be considered Scarratt et al. (1987) and Boghen (1995).

The purpose of the present communication is not to repeat these efforts. It is to remind us of how climate variability influences aquaculture within the marine environment and why it is important to consider these influences. A brief overview of the climatic factors that influence aquaculture will be followed by a more detailed look at salmon and scallop culture. More complete summaries and introductions into specific issues pertaining to these and other species are found in the above references.

GENERAL CONSIDERATIONS

Many aspects of the marine aquaculture industry take place in the coastal marine environment. The success of the culture operation therefore depends upon the characteristics and suitability of this environment. There are three main factors to consider for each culture species; hydrology (the physical and chemical characteristics of the water), the existing flora and fauna, and culture technology (Rosenthal, Scarratt and McInemey-Northcote 1995). These affect the physiology of the organisms being cultured, the operational (husbandry) and facility needs of the culture operation, and the quality of the product produced. All of these influence the economics of the industry.

Many of the major environmental or climatic factors influencing aquaculture are in Table 1, along with the category of influence. Estimates of the critical ranges of some of these factors, temperature and salinity are in Table 2. These have been determined from limited information and may not robust estimates.

Table 1: Environmental factors of importance to aquaculture.

CLIMATE FACTORS	PHYSIOLOGICAL LIMITATIONS	OPERATIONAL LIMITATIONS	PRODUCT QUALITY LIMITATIONS
Temperature	yes		
Salinity & rainfall	yes		
Dissolved oxygen	yes		yes
Sunshine, cloud cover	yes		
Water current and exchange	yes	yes	yes
Waves	yes	yes	
Ice	yes	yes	
Water depth	yes	yes	
Turbidity/suspended sediments	yes		yes
PSP & Ecosystem state (functions of above as well)			yes

Table 2: Approximate range and optimum temperatures and salinities for some selected marine species that are being cultivated or have culture potential in Atlantic Canada.

SPECIES	TEMPERATURE (°C)			SALINITY (ppt)		
	Min.	**Max.**	**Optimum**	**Min.**	**Max.**	**Optimum**
Salmon	-0.7	18	8-16	0	35	
Cod	-1.0	15	7-9			
Haddock	-1.0	14	7-9	20	35	
Halibut	-0.7	14	9-11			
Striped Bass	-1.0	30	20-22	0	30	15-30
American oyster	-2.0	40	8-25	18	35+	23
European oyster	0.0	25	8-20	20	35+	
Mussel	-2.0	25	10-20	15	35+	25-30
Giant scallop	-2.0	25	10-20	20	35+	25-35
Bay scallop	0.0	30	12-25	20	35+	25-35
Soft-shell clam	-2.0	25	8-20	20	35+	25-35

Note: The information in this table has been extracted from Rosenthal, Scarratt and McInerney-Northcott 1995.

Knowledge of the historical and expected climate change in these factors is useful for several reasons. It helps to avoid poor projections of economic and social potential, improves policy and investment decisions by improving the evaluations of site suitability, site abundance, and advice on carrying/holding capacity.

The central tendency, trend (spatial and temporal) and variability (including extremes, frequency of return, duration of events) of these factors is important. Identification of the microscale (site specific) conditions are of importance because these are what the operation experiences. The temporal variability is particularly important, since a single rare event can have severe consequences for a culture operation and industry. Temporal changes in the spatial pattern of the characteristics can change the geographic range suitable for culturing a specific species. Changes in the time trend at a site may make the difference between a site being suitable or not for culture. Once started, the industry can grow quickly - on the order of 10y. This is the same time scale as the climate temporal variability. Therefore, it is important to industry development to determine whether a culture operation is beginning in a suitable area that may become unsuitable sometime in the future, before the industry has turned a profit.

SALMON AQUACULTURE

Salmon aquaculture is the biggest aquaculture industry in Atlantic Canada (Boghen 1995). It is reportedly larger than the potato business in New Brunswick. The development of this industry and its linkages to the environment serve as an example for how climate variability influences aquaculture finfish production.

Salmon culture is spread over land based hatcheries, grow-out in sea cages, processing in land based plants and marketing. Climatic conditions primary influence the grow-out phase of the industry. Salmon is a relatively sensitive fish and therefore water quality is of utmost importance to salmon culture (Monahan 1993, Wallace 1993). Temperatures below -0.7°C and above 22°C are lethal (Monahan 1993, Saunders 1995). The optimum range for survival and growth is generally considered to be 4-15°C (Monahan 1993). Relative to many other species of fish, salmon require high levels of oxygen. Although they can tolerate levels of $3.5 \text{mg} \bullet \text{l}^{-1}$ for short periods (hours) but they require a minimum of about $5 \text{mg} \bullet \text{l}^{-1}$ for prolonged time periods (Wallace 1993). Higher levels are required for optimum production. The oxygen content of the water is influenced by temperature and salinity, as well as the demand and rate of supply, the water flow rate into the culture facility.

These environmental criteria influence where salmon farming may be possible and whether it is economically feasible and profitable. For example, temperature influences survival and growth (food conversion efficiency) and the geographic range suitable for coastal salmon culture. Salmon culture, for the most part, is limited to between latitudes of 40° and 70° (Monahan 1993). In western Europe salmon aquaculture is conducted along the coast of Norway. The conditions are influenced by the Gulf Stream and its extension, the North Atlantic Drift. In eastern Canada, salmon aquaculture is limited to the south coast of Newfoundland and in the Bay of Fundy. The coasts of northern Newfoundland and the Labrador are to cold due to the Labrador Current. Many areas of the Gulf of St. Lawrence are to warm in the summer and too cold in the winter. Similarly, the major ocean currents in other parts of the world control the local environment and its suitability for salmon culture. Currents and waves influence growth, product quality and mooring technology. Salmon also require fish feed whose supply and price is strongly influenced by the availability of lesser valued fish species such as anchovy. Global climate change that influences the supply of these lower valued fish therefore influences the price of the fish feed and the marketability of the cultured salmon..

On a regional scale salmon culture is limited to eastern Maine, southwestern New Brunswick (SWNB), parts of Nova Scotia and microclimates in Newfoundland. In SWNB temperature variability influences the salmon farming industry (Page and Robinson 1992, Saunders 1995). In this area winter temperatures can drop below 0.0°C in some micro-environments. This has resulted in significant salmon kills, dollar loss and media attention in the past. The industry was established in 1979 and has grown continuously, expanding into "marginal" habitat. As a consequence, "winter kill"/"superchill" has been a periodic problem for some farms. Disease and parasitism have also occurred and these have been suggested to be influenced by the thermal environment.

The water temperatures have been recorded in the area since the early 1900's, particularly at Prince 5, an offshore station in the mouth of the Bay of Fundy and at the wharf of the St. Andrews Biological Station. The temperatures have fluctuated by several degrees with temperatures sometimes dropping below 0.0°C during the winter. At the offshore station measured winter near-surface temperatures have dropped to critical levels less than 1% of the time. At the inshore station critical levels have observed between 1 and 5% of the time. This inshore amplification is due to the shallower water and proximity to extensive intertidal areas that promote considerable spatial microscale (100-1000m) variation. For example, temperatures recorded at 5m depth at 20 salmon farms within the SWNB area during 1995-96 show that spatial variation in the temperatures varies seasonally, being about 7°C in summer and 5°C in winter.

GIANT SCALLOP

Scallop aquaculture is an example of shellfish culture that has potential in Atlantic Canada. Young scallops (spat) are collected in the field or produced in a hatchery. In either case they are placed in situ to grow to market size. Therefore, culture of this species is closely linked with the environment and may be susceptible to climate variability, particularly with respect to spat concentration and plankton production, the latter for its importance as the food supply and its consequences for marketing when toxic algae blooms occur.

SUMMARY

In summary, marine aquaculture is an established and g rowing industry within Atlantic Canada and like agriculture, it is dependent upon the environment - its mean conditions and particularly its variability both temporally and spatially. As the industry grows and diversifies the role of climate will become more important. It will be more and more useful to define and predict local climate variability and the critical values of environment conditions, since these are still poorly defined.

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Climate Implications of Benthic Foraminifera Assemblage Variations Near the Mouth of Chezzetcook Inlet Since About 1550 AD (+/- 50yr)

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EXTENDED ABSTRACT

Chezzetcook Inlet, a small estuary 25 km east of Halifax, is characterized by several distinctive foraminiferal assemblage zones that reflect the ambient salinity gradient of this aqueous system. Two vibrocores (93305-9 and 93305-10) collected near the mouth of the inlet in the summer of 1993 (Fig. 1) show a transition from "open bay" to "lower estuarine" conditions at the coring site (Fig.2). This transition is comparatively abrupt and is presently estimated to have occurred in the middle of the 15th century (+/- 50 yr). The variability of fossil benthic foraminifera populations observed in C^{14} date-extrapolated late 16th to early 19th century lower estuarine facies of the two vibrocores has been evaluated to test for climate impacts associated with Little Ice Age cooling and subsequent warming. The evaluation focuses on differences between mean numbers of species and specimens in sections A and B of core 9 and equivalent sections C and D in core 10 (Table1). Differences in mean values were evaluated using a standard error criterion which reflects the size of the standard deviation of the distribution of mean values (see: Moroney, 1964).

In core 9, there appears to be a very significant statistical difference (> 3.0 standard errors) between the mean number of species (X_S) in the 1820 AD (+/- 50 yr) to 1700 AD (+/- 50 yr) interval (X_S = 7.9) compared to the 1695 (+/- 50 yr) - 1575 AD (+/- 50 yr) section of this core (X_S = 9.6). The difference in Foraminiferal Number (FN) mean values for these two intervals is not statistically significant (< 2.0 standard errors). In core 10, the difference in X_S for the 1827 (+/- 50 yr) -1702 AD (+/- 50 yr) and 1697 (+/- 50 yr) - 1577 AD (+/- 50 yr) intervals is not statistically significant but the difference in FN means ($FN_{1827-1702}$ = 598; $FN_{1697-1577}$ = 749) is "probably" significant (standard error is >2.0<3.0). These observations can be interpreted as the consequence of a transition to progressively more intensive lower estuarine conditions. The change from "open bay" to "lower estuarine" conditions may be related to either an increase in freshwater flux to the estuary, or to a decrease in tidal flushing caused by changes in the geometry of bay mouth barriers. Details on the history of barrier dynamics along this part of the coast can be found in the "Coastal Zone" chapter of this volume (see: Forbes, 1997; Taylor, 1997).

There are relatively large numbers of species in the lower estuarine environment of this part of the inlet for comparatively long periods of time between 1620 (+/- 50 yr) and 1682 (+/- 50 yr) i.e., during the initial cooling phase of the Little Ice Age (LIA) in western Europe. Whether these data are linked to changing precipitation patterns at that time or to outer shoreline dynamics remains an open question at this point in the investigation. The general characteristics of lower estuarine

foraminiferal assemblages observed in the two cores do not include any unambiguous indicators of a persistent response of these organisms to climate forcing; this effect may be masked by more profound changes related to tidal flushing patterns and outer shoreline geometry. Standard deviations of FN and X_S are higher in the 1575 - 1695 (core 9) and 1577 - 1697 (core 10) intervals suggesting that climatic forcing may have been more variable during the cooling phase of the LIA interval along this part of the coast.

Regional evidence for the LIA cooling event and its impact is manifested in a number of ways from one location to another. These include geothermal gradient effects in central and eastern Canada (Beltrami *et al.*, 1992), tree growth variations and changes in species dominance in northeastern United States forests (Russell *et al.*, 1993) and in those of the southern Sierra Nevada (Graumlich, 1993), by above average flooding events in the upper Mississippi region, especially during the transition from the Medieval Warm Interval to the cooler LIA (Knox, 1993), by the maximum Neoglacial extent of glaciers in Norway (Nesje and Dahl, 1993), by major periods of glacial moraine development in the Canadian Rockies (Luckman, 1993), by higher frequencies of westerly winds and storms in the Skagerrak area of the North Sea (Haas, 1993), and by distinctively stronger offshore winds in Antarctica (Leventer *et al.*, 1993).

Recent *in situ* experiments designed to explore the effects of bottom water temperature on Halifax Harbour nearshore benthic foraminifera assemblages point to possible direct positive and negative responses by several arenaceous species (Schafer *et al.*, 1996). However, in Chezzetcook Inlet sediments, these biological responses are overprinted by those related to changes in tidal flushing. Flushing variation appears, in turn, to reflect the response of the local bay mouth barrier system to the forces of erosion and sediment transport. Consequently, in this particular coastal setting, the micro-palaeontological evidence for local LIA climate characteristics appears to be most vividly expressed by assemblage variations that reflect changes in the frequency and intensity of coastal erosion processes that modify those coastal features that control tidal exchange between inlets and the open ocean.

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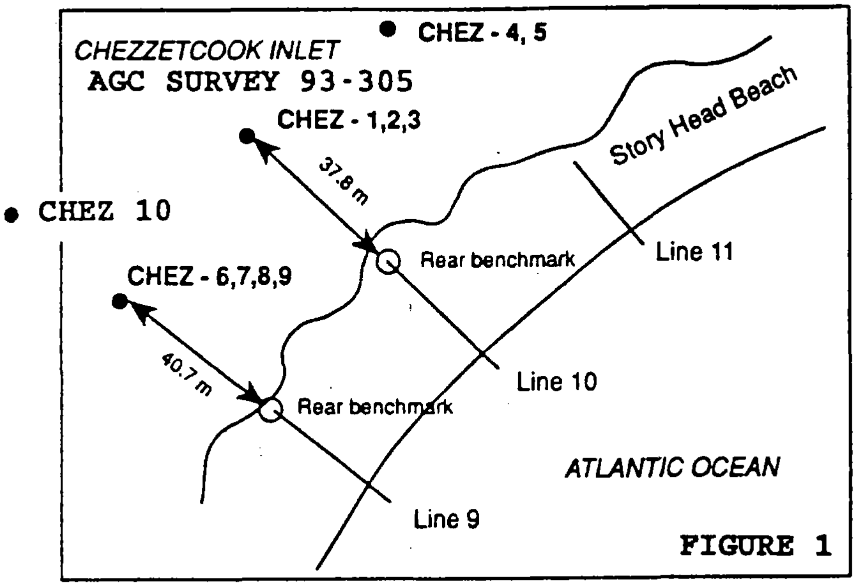

Figure 1. Locations of vibrocores collected during Geological Survey of Canada - Atlantic field survey 93-305. Core 10 is located about 10 m northwest of core 9 at latitude 44°40.63'N; longitude 63°13.27'W.

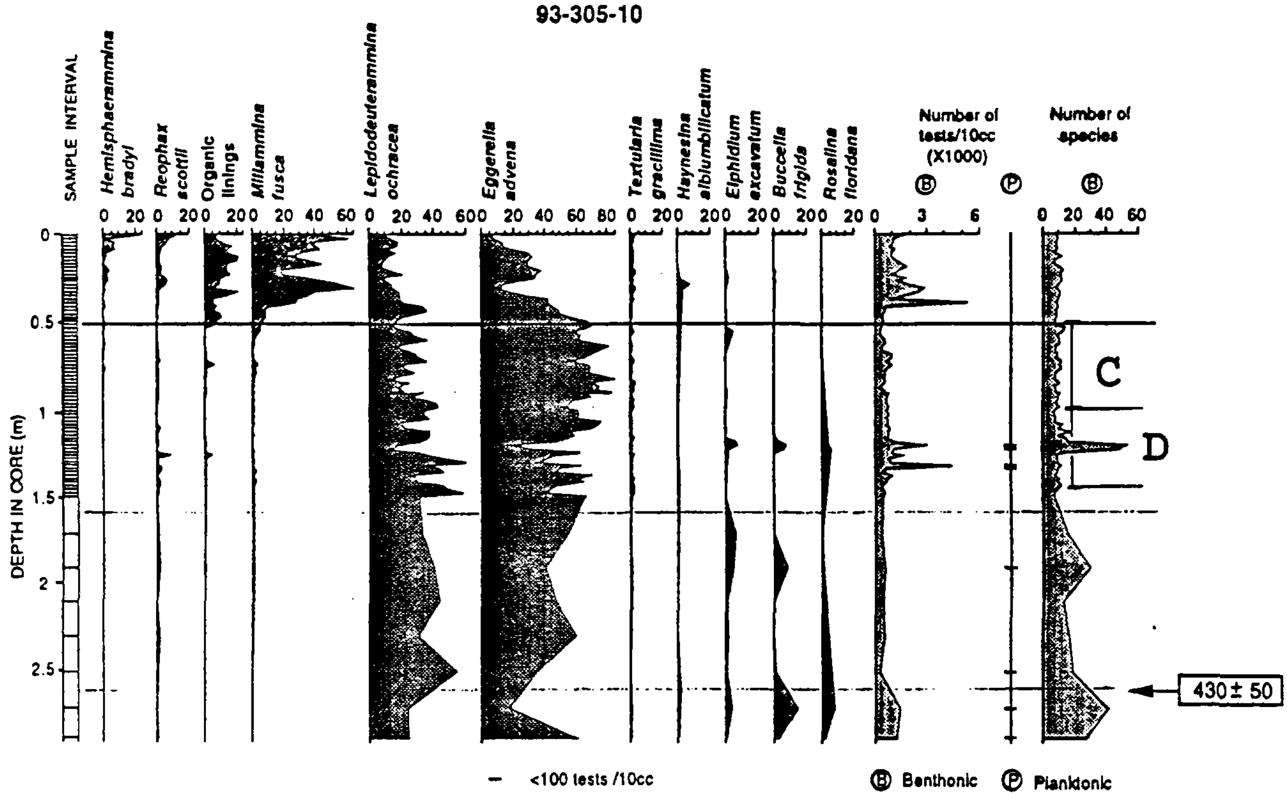

Figure 2. Temporal variation of foraminifera species in core 10. The temporal pattern of species abundance variation in this core is similar to that observed in core 9 except for an anomalous assemblage indicative of a storm event that occurs at about the 125 cm horizon in core 10. The C^{14} used to estimate the core depth of the LIA interval in core 10 was determined from shell fragments (Macoma balthica). The C^{14} date has been corrected for a presumed reservoir effect of 410 years (Isotrace Lab. No. TO 4250).

Table 1. Population statistics from the lower estuarine facies of cores 9 and 10.

CHEZZETCOOK INLET	CORE 9	CORE 9	CORE 10	CORE 10
INTERVAL	A	B	C	D
CORE SECTION (CM)	52-100	102-150	49-99	101-149**
C^{14} EXTRAPOLATED AGE (AD)	1820-1700	1695-1575	1827-1702	1697-1577
NO. OF SUBSAMPLES	25	25	26	23
MEAN NO. SPECIES (X_S)	7.9	9.6	9.8	10.8
STANDARD DEVIATION OF X_S	1.6	1.9	1.8	2.6
$X_{S,A} - X_{S,B}$; $X_{S,C} - X_{S,D}$	1.8		0.9	
STANDARD ERROR	0.5		0.65	
SIGNIFICANCE	3.6	DEFINITELY SIGNIFICANT	1.4	NOT SIGNIFICANT
MEAN NO. OF SPECIMENS (X_{FN})	598	700	598	749
STANDARD DEVIATION OF X_{FN}	270	152	199	260
$X_{FN,A} - X_{FN,B}$; $X_{FN,C} - X_{FN,D}$	102		151	
STANDARD ERROR	62		68	
SIGNIFICANCE		NOT SIGNIFICANT		PROBABLY SIGNIFICANT

**SUBSAMPLES 119 AND 121 OMITTED (STORM EVENT)

Development of an Environmental Index for the Detection of Climate Changes in the Gulf of St. Lawrence: Ecological Interpretation of First Results and Implications for Future Monitoring Programs.

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IMPORTANCE OF HISTORICAL DATA SERIES

The recent collapse of many fish stocks, a traditional backbone for the Atlantic economy, has brought our management practices into question. The oceans are not stable environments, as once assumed, but are constantly fluctuating in response to environmental variations, both of natural and of human origin. In the scientific community, a consensus has recently emerged to the effect that informed decisions concerning marine resource management will only be made when our science will have developed a better understanding of the interrelationships between climate variability and ocean ecosystem behavior, that is when our science will have developed the tools that are needed to forecast changes in ocean productivity.

One way to achieve this is to use information about the past to forecast the future. In fisheries and oceanographic research, long time series of observations have been used to correlate climatic indices of the ocean state to indices of ecosystem productivity (i.e., McGowan, 1990). Once a statistical relationship is developed, it can be used to forecast productivity based on current assessments of the marine climate, at least for a few months to a year in advance. The advantage of this approach is that it provides confidence intervals for the forecast, something that managers need to know in order to assess the risk of alternative policies. The disadvantage is that such empirical models may fail if the conditions under which the model was developed change. This has happened for the time series correlation between freshwater runoff and Magdalen Islands lobster landings (Drinkwater and Myers, 1987). As suggested by Mann (1993) this does not mean that the original correlation was invalid, only that another factor may have become of overriding importance. This supports the need to understand the mechanisms of interaction between the environment and the biological resources in all its complexity before we can understand the significance of correlations that change with time. With those considerations in mind, our main objective was to develop a robust environmental index that could be used to model interannual changes in ecosystem dynamics, and possibly, to forecast and explain changes in ocean productivity before they occur.

Among the myriad sequences of complex interactions in the marine environment, there is one which appears again and again in habitats as diverse as the open ocean, continental shelf waters, coastal upwelling areas, estuaries and so on, and it is a phytoplankton production burst (a diatom bloom) following a mixing event. The time scale of these burst can vary from wind or tidal mixing events, to seasonal or annual overturning events, but without consideration of the time scale, they all produce the same result, that is enhanced primary production which supports, on the long run, food chains leading to the production of important commercial fish stocks. It can therefore be expected that a better correlation will be found between primary production and exploited fish stocks in different environments, than with any other physical factor. In support of this assertion is the fact that phytoplankton is probably the best integrator of the general conditions in the aquatic environment. Indeed, if all the right environmental conditions are assembled, that is the favorable light and nutrients conditions, enhanced primary production is the immediate result. On the other hand, if only one among the set of physical variables changes, and that this change does not improve the overall growth conditions for phytoplankton, this change will not be followed by an enhancement of primary production. If a correlation is established between this particular physical factor and a fish stock, the result may very well be an unexplained failure in the correlation, while the correlation with primary production may still be holding.

An attempt was made to study these hypothesis using the Gulf of St. Lawrence as laboratory. One problem, however, was that no time series of primary production was available for the Gulf. But because it has been well established that nutrients are completely absent in the surface layer of the Gulf for most of the summer period, the assumption could be made that it should be possible to estimate the relative importance of primary production in the surface layer of the Gulf of St. Lawrence each year, just by measuring the relative importance of the nitrate pool (the limiting nutrient) in the mixed layer, just before the onset of the spring bloom. Once the size of the spring nitrate pool is known, it becomes a simple matter to use adequate conversion ratios to calculate the global carbon production potential that can be transferred to fish production each year.

CONSTRUCTION OF A TIME SERIES OF SPRING NITRATE CONCENTRATIONS FOR THE GULF OF ST. LAWRENCE

The rationale behind the above mentioned approach is illustrated in the conceptual model of Figure 1 which shows a typical vertical profile of nitrate concentration for the summer period in the Gulf. The most important characteristics of this profile is the existence of a linear increase of nitrate concentration with depth between about 45 and 205 m. The model suggests that only the knowledge of the depth of mixing is necessary to determine the size of the nitrate pool that is available for primary production each year. The possibility of using this characteristic to construct a time series of new nitrate concentrations in the surface waters of the Gulf, just prior to the spring bloom of phytoplankton, was then explored . First, nitrate data between 45 and 205 meters were extracted from the nutrient data bank that Peter Strain was maintaining at BIO. Then, a multiple regression analysis was carried out on these data to confirm that with the sole knowledge of the depth of mixing, it is possible to estimate the nitrate concentration in the mixed layer at the onset of the spring bloom with an accuracy of at least 70%. Since the nutrient data bank only contained data for a few years, it was not possible to construct a useful time series. But because the nitrate

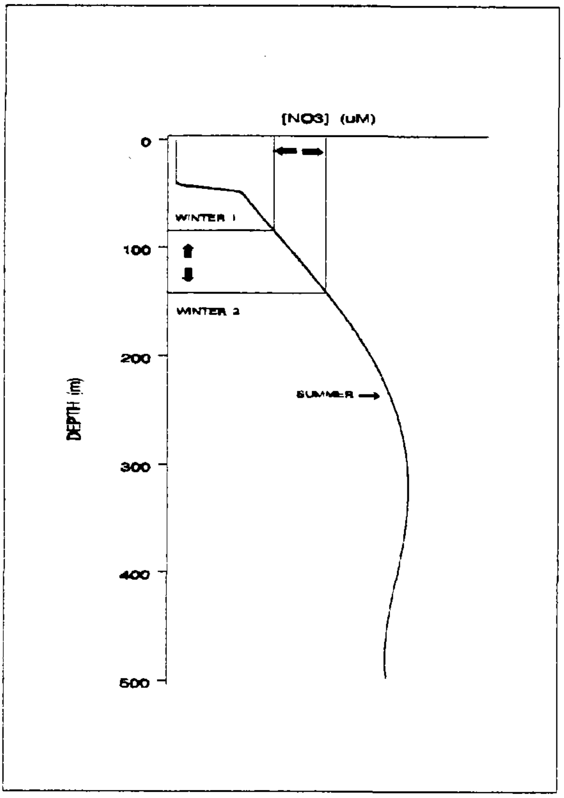

Figure 1. Conceptual model explaining the interannual variations in spring nitrate concentrations in the surface layer of the Gulf of St. Lawrence.

model only required the a priory knowledge of the depth of mixing, we examined the possibility of using the much more numerous temperature profiles from the AFAP data bank to determine that depth of mixing. By supplementing this data bank with data collected at the Maurice Lamontagne Institute for the more recent years, a temperature data series covering the period between 1947 and 1996 was obtained.

The temperature profiles were first examined to find out which characteristic of these profiles can be used to determine the depth of winter mixing with a good accuracy. The assumption was made that evidence of winter mixing is provided in a vertical profile when the difference between the surface and the minimum temperature is less than 1 °C. Temperature profiles responding to this definition were extracted from the data bank and this resulted in a selection of essentially winter-early spring profiles that had a surface layer temperature ranging between -0.5 to -1.79 °C. A multiple regression analysis was carried out on this data set and the results indicated that we could determine the depth of mixing on these late winter profiles with an accuracy > 87%, simply by estimating the lower depth of occurrence of 0 °C. This zero degree criteria was used to determine the depth of mixing for our nitrate model and the resultant nitrate (or primary production) data series showed significant decadal variations. While building up the mixed layer depth series using the zero degree criteria, it was noticed that a lot of vertical profiles were discarded because of the absence of a zero degree temperature in the profile, although a well defined intermediate cold layer (CIL) was apparent in the profile. We also noticed the absence of data points in the time series for some years, even though we knew that we had many temperature profiles in the data bank. We therefore reached the conclusion that the use of the zero degree criteria was potentially leading to the loss of important environmental information.

To correct this bias, the cold intermediate layer was redefined using different criteria (T_{min}, T_{bottom}, $\Delta T=T_{bottom} - T_{min}$, and Z_{max}) which allowed the inclusion of a greater proportion of temperature profiles. After analysis of this new data set, we reached the conclusion that an adequate correction of our data series can be obtained simply by multiplying the initial nitrate series by the following correcting factor : $W_i = n_i / N_i$, that is the ratio between the total number of profiles for which a zero degree temperature is detected for a particular year (n_i), over the total number of profiles having a well-defined CIL for that same particular year (N_i). The time series of this correcting factor is shown in figure 2.

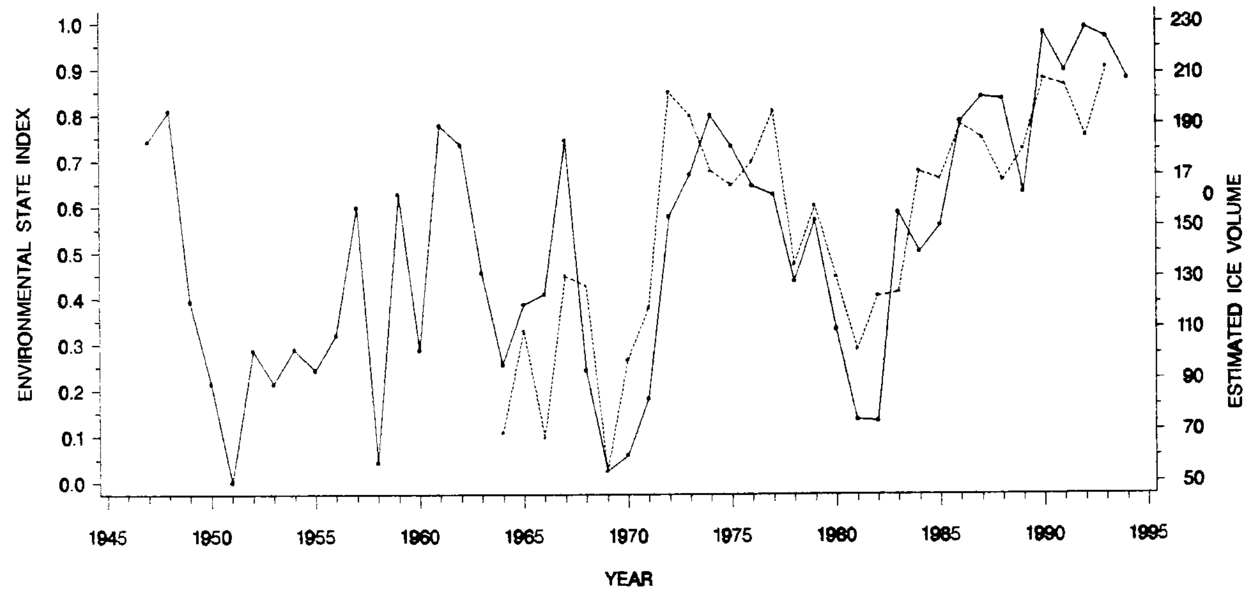

Figure 2. Relationship between the environmental state index W_i and an estimation of the annual ice volume (dotted line) in the Gulf of St. Lawrence.

Further analyses of the W_i data series showed that this series was well correlated with winter air temperature and particularly with ice conditions in the Gulf of St. Lawrence (see Figure 2). In fact, it was rapidly realized that the W_i ratio could be used as an environmental state index which was reflecting very well the variations in the general winter cooling conditions in the Gulf. Additional analyses indicated that this new environmental state index was highly correlated with various fish stocks such as, for example, the Esquiman channel shrimps, and that an interesting relationship could be established with the redfish recruitment success.

INTERPRETATION OF RESULTS IN A MORE GLOBAL ECOLOGICAL CONTEXT

The results of the present study suggest that over the last 40 years, important decadal variations in winter cooling conditions occurred, accompanied by consequent variations in the size of the nutrient pool that is available for primary production at the onset of the spring bloom in the Gulf of St. Lawrence. As suggested in Figure 3, this succession of cold and warm years can have profound consequences on the global productivity of the marine ecosystem by significantly affecting the global trophic structure and the efficiency of organic matter transfer to fish stocks. For example, it can be hypothesized that during cold years the fishery stocks that are directly linked to the benthic production (i.e. shrimps) will be favored because of a massive sedimentation of organic matter when the large diatom cells have exhausted the nutrient pool in the surface mixed layer. During warm years, little or no nutrient enrichment is occurring in the mixed layer and the organic matter is probably mostly recycled within the pelagic zone (the microbial loop). These warmer conditions associated with fundamental changes in the trophic structure of the plankton community may then create favorable conditions for other fishery stocks (i.e. redfish).

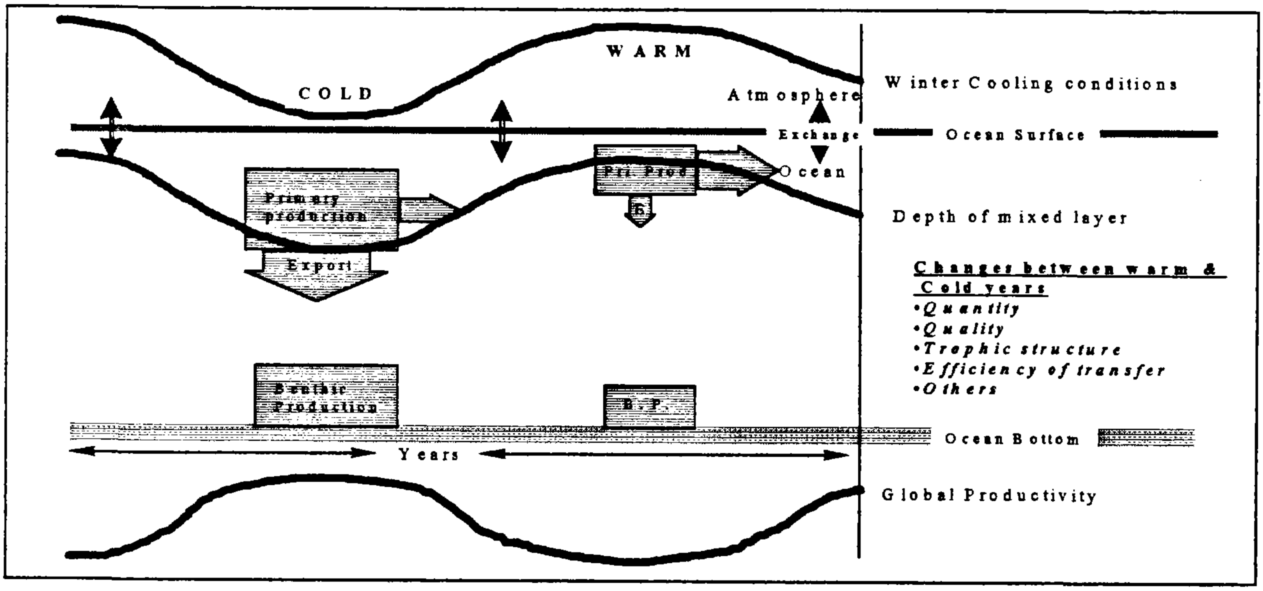

Figure 3. Conceptual model illustrating the difference in ecosystem productivity between warm and cold years in the Gulf of St. Lawrence.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study suggest (1) that to understand the impact of climate variations on the marine ecosystem, it is essential to monitor not only the quantity (biomass), but also the quality (i.e., species composition) of the organic production ; (2) that a good knowledge of the trophic structure is also essential for a better understanding of the efficiency of transfer from primary production to fish stocks ; and (3) that the use of representative environmental indices as the one proposed here can provide resource managers with important forecasting tools which may have important socio-economic impacts by allowing a better adaptation to climate changes.

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APPENDIX F

EXTENDED ABSTRACTS

COASTAL ZONE

Interdecadal Variation in Coastal Recession Rates: Climatic 'Motor' and Geological 'Brakes'

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INTRODUCTION

The coast is a dynamic boundary, constantly changing in response to variations in incoming wave energy and nearshore dynamics. Water level, an important factor controlling shoaling wave characteristics, varies over a wide range of time scales, from surf beat to semi-diurnal tides, to storm-scale wave setup and storm surge, to seasonal and long-term changes in mean relative sea level. Another critical element is the coastal geology, including shore-zone morphology and shoreface bathymetry, which influence the sedimentary feedback processes in the nearshore system. Distinctive coastal types can be recognised (Forbes *et al.*, 1990, 1995), including low, unstable, "type-3" gravel barriers, the focus of this study.

To what extent are coastal stability and position governed by long-term changes in mean water level? by singular storm events? or by changes in water level, storminess, or combinations of these, interacting with geological feedback processes at scales of a few years to decades? This paper addresses the evidence for decadal-scale variability and the processes that drive it along the Atlantic coast of Nova Scotia. This is the scale of historical records, both photographic and survey records of the coast and instrumental records of water levels, waves, winds and other climatic variables. Although necessarily empirical, analysis at this scale provides the only means of determining the coastal response under a wide range of recent environmental conditions. It is therefore a useful prerequisite to assessing the potential impact of future acceleration in the rate of sea-level rise or changes in the regional storm and wave climates.

ENVIRONMENTAL FORCING

The coast has retreated landward 20-40 km as relative sea level has risen by more than 50 m during the past 11 000 years (Shaw *et al.*, 1993, these proceedings). The tidal record at Halifax now spans an interval of 100 years, with a 13-year gap (1906-1919). A linear least-squares fit to the annual means indicates a long-term mean rate of sea-level rise [SLR] of 3.59 mm/a since 1920 (Orford *et al.*, 1990). An intriguing feature of the Halifax record is the remarkable reduction in SLR since the mid-1970s. If interpolation between 1905 and 1920 is valid, a similar hiatus in SLR seems to have occurred then.

In addition to mean sea level, we hypothesise that decadal-scale retreat of susceptible shore types will be governed by storm processes, in particular the probability of very high residual water levels associated with storm waves. The "surge index" used here is the same as the "forcing coefficient" of Orford *et al.* (1992) and Orford and Carter (1995). This is a measure of the relative frequency of large positive high-water residuals in any one year of the Halifax hourly tide-gauge record, after removal of a long-term polynomial trend. Orford *et al.* (1992) argued that the frequency of positive residuals conforms to a negative exponential distribution, which is represented by a straight line on a plot with log-transformed frequency f_{z+}. The slope of this line is the surge index (SI = b where $\log_{10}f_{z+} = a + b\Delta z$, Δz is the residual height to the nearest 0.05 m, and $b < 0$). The lower the slope (the smaller the absolute value of b), the higher the frequency of large positive residuals in the annual distribution and the higher the surge index. This may indicate more stormy conditions with a high frequency of cyclonic disturbances or the occurrence of a few high-magnitude storm events. The 11-year running mean of the surge index (Figure 1) shows a strong decadal signal, with high values in the late 1920s and early 1930s, consistently lower values through the late 30s, 40s, and early 1950s, and then a return to high values after 1954.

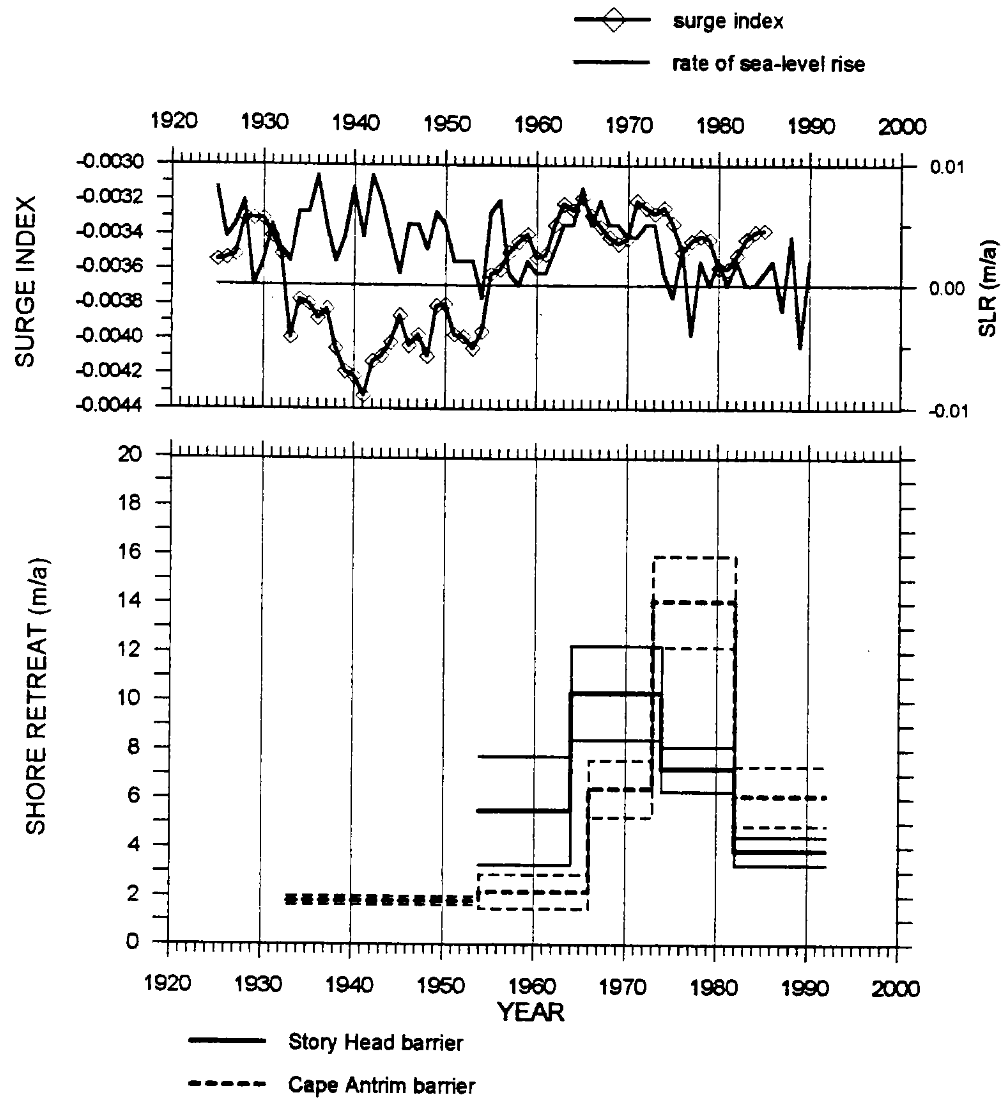

Figure 1: Rates of retreat (mean ± 1 std deviation) on the Story Head and Cape Antrim barriers (from Covill *et al.*, 1995). The upper panel shows the 11-year running mean of surge index and rate of sea-level rise [SLR] at Halifax.

COASTAL RETREAT

Digital rectification of sequential airphotos, supplemented by ground surveys, yields data on the varying retreat rates of gravel barriers at Story Head and Cape Antrim, on the Eastern Shore of Nova Scotia. These are similar "type-3" barriers developed on opposite sides of the entrance to Chezzetcook Inlet, and are therefore exposed to the same water level forcing and deepwater wave climate.

Data from early charts, maps, and the 1945 airphotos suggest that Story Head barrier was moving slowly landward at about 1.3 m/a between 1917 and 1945 (Orford *et al.*, 1990). The rate of retreat from 1945 to 1954 was about 2 m/a. Beginning in 1954, the barrier underwent a rapid acceleration in its rate of retreat, which peaked at more than 10 m/a between 1964 and 1974 (Covill *et al.*, 1995) and may have been as high as 15 m/a between 1966 and 1973 (Orford & Carter, 1995). The retreat rate diminished to 3.6 m/a from 1977 to 1982 and 3.9 m/a from 1982 to 1992 (Figure 1).

Initially, the barrier at Cape Antrim also had a consistently low retreat rate of 1.8 m/a between 1933 and 1954 (Figure 1). Unlike the Story Head barrier, it accelerated only slightly in 1954, retreating at 2.2 m/a until 1966 (Covill *et al.*, 1995). This is not significantly different from the pre-1954 retreat rate, indicating no response to the higher rates of sea-level rise and surge index prevailing through the 1950s and early 60s. Retreat of the Cape Antrim barrier accelerated significantly after 1966 and dramatically from 1973 to 1982, when it averaged 14 m/a (Figure 1), equivalent to the highest multi-year retreat rates documented for Story Head, which (by this time) had slowed down considerably.

At Story Head, we find a weak correlation with the 11-year rate of SLR, although there is some evidence for stronger correlation at rates of SLR >3 mm/a. In contrast, the 11-year surge index is a relatively good predictor of barrier migration at Story Head, where $r^2 = 0.66$ for the log-transformed retreat rates. At Cape Antrim, the migration rate was retarded until 1973, while the barrier remained anchored on the drumlin remnant headland. There was a significant increase in migration rate from 1966 to 1973, presumably a response to SLR and surge forcing, but the most rapid retreat occurred after 1973. The rapid migration of Cape Antrim barrier during the late 70s and early 80s may be attributed to a combination of still-high surge index (Figure 1), intense refraction around the remnant shoal at Cape Antrim, and exposure of estuarine muds in the nearshore. Nearshore scarp development in estuarine muds underlying and exposed in front of the Story Head barrier has been a marked feature of rapid retreat at that site, particularly during the 1990s (Taylor *et al.*, 1995), and could be considered a form of geological 'brake failure'.

WAVE CLIMATE

We have not addressed the issue of wave climate, for which the record at Halifax is now becoming long enough to be useful (1970-1996). We expect that the joint probability of high storm surge and large waves would be a promising predictor of barrier washover, cliff erosion, and coastal retreat (Taylor *et al.*, these proceedings). The wave records are non-directional, but the limited fetch in the landward direction suggests that all large-wave events are related to local or swell waves propagating onshore. Future work on both short-term and decadal instability on the Nova Scotia coast should explore the potential of combined wave and surge analysis.

CONCLUSIONS

- Classification of cliff condition and beach/barrier types enables the identification of shore segments most susceptible to coastal retreat.
- The retreat of an "unconstrained" type-3 barrier is weakly correlated with the low-pass rate of sea level rise and more strongly correlated with the low-pass filtered surge index.
- Coastal retreat (whether at cliff or beach/barrier sites) is strongly conditioned by the antecedent condition of the nearshore, beach, and backshore (barrier crest elevation, shoreface geology, or cliff condition). This introduces a significant complication in efforts to predict coastal response to changes in climate, sea level, storminess, or wave energy.
- Some sites will experience accelerated coastal retreat if the rate of sea-level rise accelerates without a change in the frequency distribution of storm surges or wave climate. Enhanced storminess, higher surge levels, and more energetic waves would contribute to more rapid erosion, with or without accelerated SLR.

NEEDS

- Maintain long-term tide gauges for monitoring rates of relative sea-level rise, perhaps in combination with satellite altimetry, absolute gravity, and other techniques. Tide gauges are required for detection and analysis of storm surges.
- Maintain long-term coastal wave instruments for analysis of wave climate, detection of trends, improvement of wave prediction, and documentation of storm waves.
- Maintain regular schedule of repetitive ($\Delta t \leq 10$ years), large-scale (1:10 000 or better), vertical aerial photography.
- Promote the analysis of historical data to derive reliable estimates of coastal retreat, sea-level rise, storm-surge climatology, and wave climate.
- Continue regular surveys of representative "indicator" sites along the coast.

Many of the foregoing recommendations are threatened by spending cuts, as well as by diminishing public confidence in the value of science to address societal problems. It is hoped that this symposium will highlight the necessity of environmental monitoring and help to support continuation of these extraordinarily important long-term records.

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The potential of satellite altimetry for monitoring coastal sea level in Atlantic Canada

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INTRODUCTION

A general rise in global mean sea level associated with global warming is a prominent prediction in global climate models under increased concentrations of greenhouse gases. For east coast Canada, the situation is complicated by the possibility that increased ice melt and a change in the coverage and timing of the seasonal ice cover could produce cooler coastal ocean conditions during a transient adjustment period. Monitoring of coastal sea level is an important tool for better understanding, detecting and predicting such regional aspects of global trends. The permanent Canadian water level network is a candidate for this monitoring task, but coverage is sparse and may be reduced even further in future due to budget pressures. Satellite altimetry offers a unique possibility for monitoring sea level change by virtue of near-global coverage and temporal sampling that resolves much of the sub-tidal variability in sea level.

We are beginning to develop the techniques and models necessary to use satellite altimetry to monitor sea level in Canadian coastal waters. This paper gives a general overview of how satellite altimetry could be used for this purpose in Atlantic Canada. The specific focus is on the technical challenges that must be addressed to use these techniques in coastal regions.

THE TOPEX/POSEIDON ALTIMETRIC MISSION

The joint U.S./ French TOPEX/POSEIDON (T/P) altimetric satellite mission was launched in August 1992 to study ocean dynamics through accurate measurements of sea level, and has produced more than four years of measurements to date. Sea level height is gauged by measuring the travel time of a microwave pulse sent by the satellite and reflected back to the satellite from the surface of the ocean. T/P offers an impressive system accuracy for height measurements of approximately 3 cm (Fu *et al*, 1994). This accuracy is limited not so much by the precision of the travel time measurement as by errors in the positioning of the satellite, by errors in the models used to correct for propagation delays, and by errors in supplementary geophysical models such as ocean tide models used to remove aliased tidal variability from the altimetric records. Even larger errors are introduced when the measured height is referred to the geoid, or terrestrial reference level surface.

TECHNICAL CHALLENGES FOR COASTAL APPLICATIONS

Every 10 days, TOPEX/POSEIDON gives measurements along discrete ground tracks separated by approximately 200 km at 45N latitude. Figure 1 shows the pattern of repeated ground tracks for Eastern Canadian waters. The altimeter footprint varies from approximately 2 to 10 km diameter as a function of sea state (Parke and Walsh, 1995), with larger values associated with higher wave heights. Operational products are smoothed to approximately 10 km resolution in the along-track direction to improve the signal to noise ratio and reduce the data volume. Measurements are not possible very close to shore because of contamination by the strong reflection of the radar pulse from the nearby land surface. The uneven space-time sampling characteristic of near-polar orbiting satellites means that the measurements must be interpolated in space and time to allow a comprehensive analysis of sea level or to produce spatial maps. Appropriate techniques must be developed to use available data. These techniques will include both statistical methods such as optimal linear interpolation and dynamical methods that assimilate the altimetric data into numerical models to produce dynamically consistent results. Better spatial coverage may be provided by combining data from several different altimetric satellites. Empirical mapping techniques will provide a first look, but a combination of numerical models and altimetric data holds the best promise for accurate sea level determinations in coastal regions.

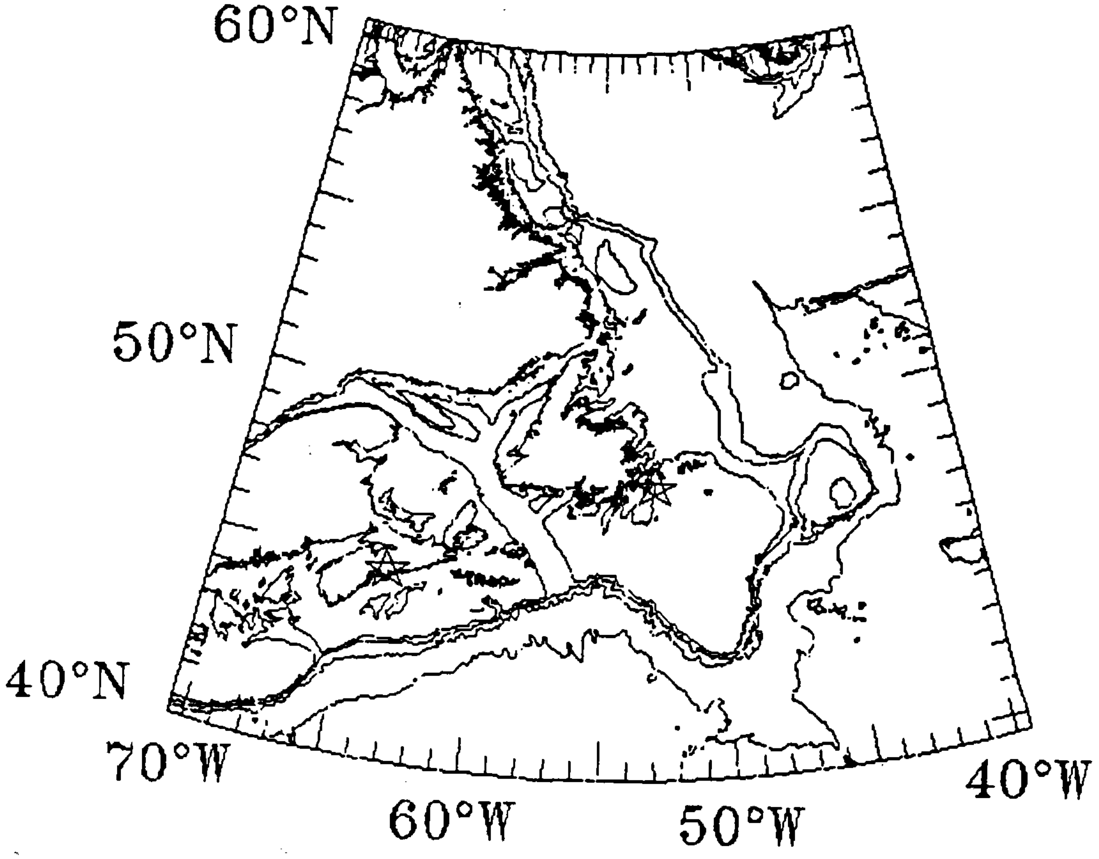

Figure 1 TOPEX/POSEIDON ground tracks in Eastern Canadian waters. Bathymetric contours (200, 1000, 2000 and 4000m) and positions of Halifax, N.S. and St. John's, Nfld. are also shown.

Tides generally show greater amplitudes and smaller spatial scales in coastal regions than offshore, and consequently tidal aliasing of altimetric measurements poses a greater problem for coastal applications. The sub-tidal sea level signals associated with variations in coastal currents, on the other hand, are small compared with variations in major ocean currents such as the Gulf Stream. The signal to noise ratio for coastal applications of altimetry is thus generally smaller than for deep-sea applications. Accurate and highly-resolved regional tidal models are required to use altimetry in coastal regions. These models require boundary conditions that must come from either observations or larger scale models. Tidal analysis of the altimetric height measurements is a useful way of improving the data base of observed tides for use in a variety of tidal models (e.g., Cartwright and Ray, 1991).

The seasonal march of sea ice down the Labrador and Newfoundland shelf hinders the use of altimetric measurements during part of the year, and optimal processing strategies must be derived to use available measurements.

LINKS TO GEODESY AND HYDROGRAPHY

The use of satellite altimetry for oceanographic study of the mean circulation requires a good knowledge of the marine geoid. The Geodetic Survey Division (GSD) of Geomatics Canada is the Canadian federal agency responsible for developing and maintaining an official Canadian geoid. They have compiled a regional geoid with high spatial resolution in Eastern Canadian waters that could be used to analyse the TOPEX/POSEIDON altimetric data instead of the low-resolution global geoids distributed with the data. We are interested in evaluating the usefulness of such regional marine geoids in our oceanographic study.

Safe navigation requires a knowledge of mean sea level and of the maximum deviations from mean sea level associated with tides and meteorological forcing. The Canadian Hydrographic Service (CHS) of Fisheries and Oceans Canada has traditionally relied on soundings and permanent water level gauges as the data base for compiling navigational charts. CHS plans to use Differential Global Positioning System (DGPS) measurements to reference the existing system of tidal bench marks on land to an ellipsoidal datum consistent with the T/P data reference frame. Measurements of mean sea level combined with numerical tidal models will yield the impact at the shore of climate-related sea level changes. A common datum for coastal benchmarks and mean sea level measured by satellite altimetry will allow a direct evaluation of relative sea level change at shore resulting from the combination of local ground subsidence and sea level changes.

OUTLOOK

We plan to map sea level in Eastern Canadian waters using presently available TOPEX/POSEIDON altimetric data. We will compare the resulting estimates of mean sea level and seasonal and interannual variations in sea level with *in situ* measurements from coastal tide gauges and offshore data to test the effectiveness of this approach for monitoring future sea level changes in Canadian coastal waters.

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Impact of Sea level Rise on the Coasts of Atlantic Canada

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INTRODUCTION

The threat of global sea-level rise

It is expected that the increase in global mean temperature predicted by the Intergovernmental Panel on Climate Change (Houghton *et al.*, 1995) will cause a rise in mean sea level because of thermal expansion of the oceans, melting of glaciers, and a variety of other effects. For the IS92a scenario the best estimate is a rise of 49 cm by the year 2100.

Long-term sea-level changes in Atlantic Canada

It is important to place the predicted change in context. The coasts of Atlantic Canada have been adjusting to sea-level changes for thousands of years (cf. Shaw *et al.*, 1993), due to the interplay between crustal motions and the level of the global ocean. Offshore from Halifax, for example, sea level has risen at least 40 m since 10 ka BP. Much of the mainland Newfoundland coast, on the other hand, experienced falling sea levels until the early Holocene (Shaw and Forbes, 1995), and rising sea levels thereafter, in contrast with the coast of Labrador, where sea level has been falling for the past 9000 years (Clark and Fitzhugh, 1991).

Recent sea-level changes

It is also worthwhile to consider more recent sea-level changes as recorded on tide gauges. South of a line from the St. Lawrence Estuary to the Strait of Belle Isle, tide gauge data for the past century indicate a sea-level rise. The Halifax gauge, for example, shows a trend of 36 cm/century (Carrera *et al.*, 1990). Most of this has been attributed to crustal subsidence; the remainder may be part of the globally coherent signal of rising sea level described by Peltier and Tushingham (1989), who speculated that this was due to the greenhouse effect. The anticipated global sea-level rise would be in addition to the crustal subsidence already occurring in Atlantic Canada.

Intermediate-scale sea-level changes

The rate of sea-level rise in this century, deduced from tide-gauge records, is greater than the average rate for the past few thousand years, deduced from radiocarbon-dated sea-level curves (Carrera and Vancek, 1988). This suggests that rapid sea-level rise is a modern phenomenon. However, peat layers found in the inorganic sediments underlying the Fundy marshes are indicative of alternating periods of rapid and less rapid sea-level rise during the past 3000 years. Similar trends have been discovered elsewhere (*cf.* Tanner, 1992, van de Plassche, 1991). Thus, the current more rapid rise may be part of a natural, non-anthropogenic cycle.

EVALUATING THE SENSITIVITY OF THE COAST TO SEA-LEVEL RISE

Methodology

An objective (and highly simplistic) method was used by Shaw *et al.* (1994) to evaluate the sensitivity of Canadian coasts to a future rise in sea level of the magnitude predicted by IPCC (Houghton *et al.*, 1990). Based on the assumption that the intensity of impact is related to seven quantifiable variables - relief, geology, coastal landform, coastal retreat rate, sea-level trend, wave energy, and tidal range - a dimensionless index was determined for each of 2899 NTS map sheets (1: 50,000 scale). Scores range from 0.8 to 57, with a mean of 5.1, and a strong mode between 2 and 4. Areas of low sensitivity (scores below 5) constitute 67 % of the total. Of the remainder, 30% have moderate sensitivity (scores of 5 - 15), and only 3 % are classified as highly sensitive.

Interpretation of sensitivity scores

As noted above, Canadian coasts have experienced changes over thousands of years, and changes - both cyclic and irreversible - are typical on decadal and annual scales also. The sensitivity score indicates the likelihood that rates of change will increase. The physical impacts predicted for the coasts by Shaw *et al.* (1994) include more rapid retreat of beaches and barriers, increased rates of erosion of coastal bluffs, more frequent overwashing and overtopping of beaches during storms, and inundation of coastal marshes and deltas.

However, when individual localities are considered, prediction of future coastal change is often difficult. This is partly because gravel beaches systems (which are common in glaciated regions) display long periods of self organisation that are punctuated by episodes of rapid reorganisation involving barrier breakdown and accelerated beach migration (Forbes *et al.*, 1995). In addition, sediment released by coastal erosion can arrest the process of coastal retreat (by forming beaches in front of eroding bluffs, for example). Fine-grained sediments can be transported by waves and currents into estuaries, and sequestered in salt marshes, allowing them to keep pace with sea level rise.

The emphasis in the sensitivity map (Shaw *et al.*, 1994) is on changes that may be experienced by natural coastal systems. This is because most of the Canadian coast is close to a natural state, and is unencumbered by the engineered structures such as sea walls, dykes, groynes etc. that proliferate in Europe, the most extreme example being the Netherlands. Nevertheless, when storms strike populated areas the type of change that attracts attention is the damage to infrastructure such as sea walls, piers, dykes, fishing shacks, houses, roads, etc. An assessment of the impact that future sea-level rise could have in this respect lies beyond the mandate of the Geological Survey of Canada. Later in this paper we will consider briefly how our organisation could play a role in that process.

IMPACT OF SEA-LEVEL RISE IN ATLANTIC CANADA

Newfoundland

The sensitivity map (Shaw *et al*., 1994) identified three areas at high risk from future sea-level rise. First, the northeast coast near Cape Freels, which consists of low, sandy barrier beaches, coastal dunes, and lagoons. Second, the coast of St. George's Bay, consisting of unconsolidated coastal bluffs, the Sandy Point barrier island, and the gravel strand plain at Stephenville. Third, the southwest Burin coast, comprised of low beaches that are often overwashed, eroding coastal bluffs, and including the gravel strand plain at Frenchman's Cove.

The method by which the map was produced overlooks very small areas that are more highly vulnerable to sea-level rise than surrounding regions. A good example is the settlement of Placentia (pop. 2204 in 1981), on the Avalon Peninsula, located in a region of steep rocky coasts that has moderate sensitivity overall. During the past several thousand years, successive storm beaches have accreted to form a low gravel strandplain. Because sea level has probably risen about 1-2 m since it began to form, the oldest beach ridges now lie below the high-tide level.

Placentia has a long history of flooding, and, in recent decades, as the settlement has expanded into successively lower areas of the strandplain, this has become more of a problem. A consultant's report published in 1985 showed that flooding occurred when high astronomic tides and storm surges coincided, and storm waves overtopped the beach. A high gravel berm was erected along the length of the beach in 1992, and a sea wall was erected in the northern part of the settlement. In order to protect lives and property at Placentia against storm waves and surges, coastal defenses will have to be maintained into the foreseeable future, a situation not unlike that in much of the coasts of Europe. Furthermore, maintenance costs and the risks of storm damage can only increase sharply if the global rise of sea level occurs in addition to the ongoing sea-level rise due to crustal subsidence.

Nova Scotia

The highly sensitive Atlantic coast is comprised of coastal bluffs, estuaries, and salt marshes. The already rapid pace of coastal change has been documented at a number of sites. For example, Story Head beach, 30 km east of Halifax, has migrated landward at rates of 4 - 11 m per annum since the 1950s (Covill *et al*., 1995). Migration takes place during storm surges, when the beach is overwashed and lobes of gravel are pushed landward (Forbes *et al*., 1991). Coastal bluffs in Nova Scotia are being eroded at rates typically <1 m per annum, but up to 12 m of retreat has been documented in a single storm (Shaw *et al*., 1993).

The salt marshes of the upper Bay of Fundy (including those in New Brunswick) have been neglected by coastal geomorphologists, yet this region is highly vulnerable to future sea-level rise. Extensive mudflats and salt marshes are situated in a region that has been submerging for thousands of years. The salt marshes have kept pace with the sea-level rise. During periods of more rapid sea-level rise, low salt marsh predominated, whereas during periods of slow sea-level rise, freshwater ecosystems spread outward across the marsh surface.

The Acadians first dyked and drained parts of the marshes in the late 1630s (Nova Scotia Department of Agriculture and Marketing, 1987), and today about 85 % of the former marsh lies behind dykes constructed at various dates. As sea level continues to rise (it has risen by 1.3 m since the Acadians arrived), the dykelands are at progressively lower levels in a relative sense. Provincial agriculture departments maintain the dykes at levels thought to be sufficient to stop flooding (and to compensate for dyke subsidence).

If sea level rises more rapidly due to global climate change, then the cost of dyke maintenance will obviously increase. Even more important than the financial consideration, however, is the hazard posed by a major storm, which could overtop the dykes and inundate the lowlands behind them. The most notorious storm to have occurred in this region is the Saxby Gale of October 5th 1869, during which the marshes were flooded. A repetition of the Saxby Gale would require two conditions: (1) an extra tropical low pressure with a northeast trajectory passing up the Bay of Fundy and along the Gulf coasts of New Brunswick; (2) a storm surge coincident with the passage of the tidal wave up the Bay of Fundy, at a time of high astronomic tides. The probability of recurrence of a similar surge remains to be established. Although dykes are constantly built up, sea level has risen 0.44 m since 1869.

New Brunswick

Apart from the Fundy marshlands (discussed above), the most sensitive coasts in New Brunswick fringe the Gulf of St. Lawrence. Barrier islands and spits extend across shallow, drowned embayments to form the longest barrier coast in Canada. During the Holocene transgression (Airphoto Analysis Associates Consultants Limited, 1975) the coast has retreated 14 to 19 km, which is an average rate of 3 m per annum. More recent rates are lower: about 5% of the coast is retreating at more than 0.6 m per annum, and about 50 % at 0.3 to 0.6 m per annum. The anticipated impacts include all the changes that accompany migration of a barrier coast: overwashing during storm surges, migration, opening and closing of channels. In many areas freshwater bogs are common in the coastal zone, mostly along the mainland coast behind the barrier islands. Further inundation and erosion of these bogs and adjacent woodlands are to be expected.

Prince Edward Island

The coasts of Prince Edward Island, except for some parts of the Northumberland Strait coast, are highly sensitive to impact from sea-level rise. The coastline is highly variable in character and includes bedrock cliffs, sandy barriers, coastal dunes, salt marshes, estuaries, and intertidal flats. Sea level has been rising rapidly (35.5 cm/century at Charlottetown), and coastal erosion is pervasive on the island's coastline. Parts of the Gulf coast lie at the heart of the PEI tourist industry, and could undergo even higher rates of coastal change than at present. Accelerated coastal retreat could increase the costs of maintaining a tourist infrastructure. Some of these additional expenditures will be in the Prince Edward Island National Park, in which a coastal highway has already been severed by migration of a tidal inlet (Forbes *et al.*, 1989).

Hillsborough Bay is a large drowned embayment, with low-energy intertidal flats and marshes up to 1 km wide; therefore, inundation of low-lying areas may occur here. P. Lane and Associates Ltd. (1988) attempted to determine the impacts of a 1 m rise in sea level at Charlottetown. The report itemised impacts in detail: the sewer station would be below high tide level; problems would be expected with low-lying parts of the sewage system and flooding of public and private buildings would occur. The report laid out the steps which must be taken in order to achieve a risk benefit analysis to produce guidelines for cost-effective development in Charlottetown.

FUTURE RESEARCH DIRECTIONS

1. With regard to the Bay of Fundy, an important objective must be to determine the probability of the dykes being overwhelmed by the coincidence of a storm surge and high tides. Consideration should be given to the extent of potential flooding, and the infrastructure at risk. When considering the costs of constantly maintaining dykes, and increasing their elevations, in order to accommodate the present sea-level rise, other issues arise. The most important is the question of whether or not some dyked areas would be more valuable to society if reconverted to salt marsh. In this regard the salt marshes and dykelands areas should not be considered in isolation from the remainder of the Bay of Fundy marine ecosystem. Had they not been dyked, the Fundy marshes could have sequestered up to 500 million cubic metres of mud since the 1600s. Most of this material is presumably somewhere outside the dykes.

2. We need to enhance our ability to predict the changes that would occur on wave-dominated coasts in the next century if accelerated sea-level rise were to occur. Towards this end, the Geological Survey of Canada intends to direct some of its research effort towards a study of some of the coasts that were highlighted by Shaw *et al.* (1994) as being highly sensitive. The Gulf coast of Prince Edward Island is being considered.

3. The Coastal Zone Management Subgroup of IPCC (1992) recommends that coastal nations adapt three strategies to cope with global sea-level rise: 1) retreat (abandon structures in developed areas and ensure that new developments are set back from the shore); 2) protect (defend vulnerable areas, especially population centres, economic activities, natural resources); and 3) accommodate (strike a balance between preservation and development). The Geological Survey of Canada could play a role in assisting policy makers consider which strategies to adopt in which

areas. Given that our coast is mostly natural, and has been experiencing sea-level change for thousands of years, and also that development pressures are increasing, then particular consideration should be given to the retreat and accommodation options. Arguably the optimum solution to the problem of continued sea-level rise in Canada is to allow our coasts and coastal ecosystems to function as close as possible to the natural state. To assist policy makers, the Geological Survey of Canada (Atlantic) is considering a second initiative: development of a manual describing natural changes in the coastal zone of Atlantic Canada.

4. In its 1992 report, the Coastal Zone Management Subgroup of IPCC described a common methodology for assessing vulnerability to sea-level rise. This methodology differs from that adopted for the Canadian study (Shaw *et al.*, 1994) in that it is focused on socio-economic impacts. Whether or not a similar approach should be adopted for all or parts of the Canadian coast, and how it would be integrated with coastal zone management, are matters for future consideration. The study of the vulnerability of the Fundy lowlands described above would undoubtedly consider socio-economic impacts.

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Shoreline Response To Major Storm Events In Nova Scotia

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ABSTRACT

This paper examines the impacts of two hurricanes and three extratropical cyclones on three types of barrier beaches along the Atlantic coast of Nova Scotia. The critical parameters controlling the magnitude of physical beach changes, given similar wave conditions and storm direction, are sea level and storm duration. The frequency of storm events, and whether or not a beach has recovered since the last storm, are also important considerations. Large swells generated by distant storms do not significantly erode the beaches. Intense storms such as hurricanes, that coincide with high water, have the greatest impact on the upper beach by lowering the crest and in some cases pushing the beach landward. Annual sea ice and shorefast ice may not exist very long, especially along the Atlantic coast of Nova Scotia but they can completely negate the impact of large waves on the shoreline. Under high water level conditions, low gravel (type 3) barrier beaches can be rolled 10-20 m landward during storms.

INTRODUCTION

The shoreline forms a natural buffer absorbing most of the energy directed against the land by the sea. Beaches are constantly changing shape and position in response to natural processes. During storm events they are forced to make larger scale morphological adjustments in order to absorb the dramatic increase in wave energy and must recover before the next storm strikes. It has been hypothesised by Forbes *et al.* (these proceedings) that decadal-scale retreat of susceptible shore types is governed by storm processes. The intent of this presentation is to examine the specific impacts of a few selected storms on barrier beaches of Atlantic Nova Scotia so that we will be in a better position to answer questions about the impacts of future changes in climatic patterns on coastal stability.

STUDY AREA

The Atlantic coast of Nova Scotia (Figure 1) has been identified as sensitive to sea level rise (Shaw *et al.*, 1994). It is also vulnerable to many large storms that track up the eastern seaboard of North America. Therefore, it is a prime location to monitor the effects of storms on shoreline stability. The Atlantic coast of Nova Scotia consists of a number of natural shoreline types including beaches, cliffs, and marshes. Within each of the main shore types there are several subtypes that can be defined on the basis of morphology and sediment composition. This paper focuses on the response of barrier beaches to five recent storms. Five barrier beach types were identified by Forbes *et al.*, (1990). We examine the impacts of storms on three of these: type 2 high gravel barriers, using observations from Miseners Long Beach (Figure 2); type 3 wave washover dominated gravel barriers, based on observations from Story Head Beach; and type 5 sandy barrier complexes using observations from Lawrencetown Beach. Although Lawrencetown Beach includes older gravel beach ridges (type 1, Forbes *et al.*, 1990), it is the modern sand beach that is discussed in this paper. Since type 3 gravel barriers are the most vulnerable to storms because of their low relief and frequency of wave overwashing (Forbes *et al.*, 1991), the text focuses on storm impacts to these beaches. The main study sites are all east of Halifax (Figure 1). Additional observations of the 1991 Halloween Storm were collected at Bakers Beach and Lockeport Beach, both of which are sand barriers located in southwest Nova Scotia (Figure 1).

STORM EVENTS

Two main types of storms affect Atlantic Canada; the tropical cyclone and the extratropical cyclone. Tropical cyclones develop in southern latitudes in the warmer months of June to November. These storms can track northward along the eastern seaboard where they usually weaken, but from time to time they affect Atlantic Canada as hurricanes, tropical storms or post-tropical storms. Extratropical cyclones (ET's) develop in mid- and northern latitudes and are most frequent and intense between October and March. Five major storm events have been selected for closer examination of their effects on the shoreline (Figure 1, Table 1). Wave and water level information was recorded during each of the events at the MEDS 037 wave rider buoy just off Halifax Harbour, and at the tide gauge within the harbour (Table 1). Wave information also was examined from offshore weather buoys, e.g., Buoy 44137 (41.2°N, 61.1°W).

Two of the three extratropical storms selected, the 1991 Halloween Storm and the 1993 "Storm of the Century", are well known because of their large-scale destruction of coastal properties in the northeastern USA. These two storms were selected because of their long duration and the large geographic area they affected. Both storms generated significant wave heights of ³1.5 m for six to seven days. Using the method of rating northeasters suggested by Dolan and Davis (1992a,b), these two storms were categorized as Class 5 (extreme). Additional information on the impacts of these storms in Atlantic Canada is provided by Bigio (1992) and Climatic Perspectives (1991, 1993), and in the USA by Dolan and Davis (1992c). The third extratropical storm called the "Saros" event is relatively unknown. It occurred in December 1995. Relative to the other two ET's, the "Saros" event generated much smaller waves (Table 1) and was only a Class 4 (severe) storm; however it coincided with a run of perigean spring tides.

Two tropical cyclones were selected, Hurricane Felix and Hurricane Hortense (Table 1). Nova Scotia lies in the pathway of hurricanes moving along the Atlantic coast of North America. However because of its northern location, hurricanes seldom strike it directly. The province is more often affected by large swells generated by hurricanes situated at lower latitudes. The most recent example of large swells generated by a remote hurricane was Felix (August 1995). It brought thousands of onlookers to the coast to watch the waves because they occurred during good weather.

Hurricane Hortense was barely a Category 1 hurricane when it reached Nova Scotia in September 1996 but it brought with it damaging winds, waves and high water levels. It was the first hurricane to make landfall in the province in 20 years. Furthermore it occurred close to a spring tide and caused the highest water level recorded in the period 1980-1996 at the Halifax tide gauge (Parkes, these proceedings).

SHORELINE RESPONSE

The impacts of the five storms listed in Table 1 are briefly described and the changes observed at a low gravel barrier (type 3), are illustrated in Figure 3. Water levels, wave run-up limits, and storm surge elevations are given relative to chart datum at Halifax (0.8 m below geodetic zero and 1.02 m below mean sea level).

Halloween Storm: Oct 28- Nov 2, 1991

For three days (Oct. 28-30) northeasterly winds of more than 54 knots (100 km/hr) lashed Atlantic Canada. Sustained high winds created unusually large deepwater waves. Offshore weather buoy 44137 measured a significant wave height of 17.4 m and maximum wave heights of 30.7 m (Climatic Perspectives, 1991). The waves were greater than the estimated 100-year extreme value (Perrie, 1993). Closer inshore off Halifax, the MEDS 037 waverider buoy recorded significant waves of 6.3 m and water levels in the harbour reached a maximum of 2.3 m by mid-day Oct. 30th (Table 1). The resultant storm surge was 1.05 m at Pictou and 0.95 m at Yarmouth whereas at Halifax the surge was only 0.68 m. The maximum wave height recorded by MEDS 037 was 8.9 m and waves of ^{3} 1.5 m significant height were sustained off Halifax for 165 hours.

At Story Head Beach (Figure 1) the beachface was combed down by waves, and the crest was lowered 0.5 m and pushed landward by 3 m as sediment was transported onto the backside of the barrier (Fig. 3). Toward the ends of the barrier, where the beach crest was 1 to 1.2 m lower, wave overwashing was more extensive. The beach crest was moved 7 to 8 m landward and the barrier lagoon shore shifted 2 to 5 m farther landward.

At Miseners Long Beach, a type 2 barrier, the long duration of attack enabled waves to comb down the beach face and narrow the barrier by 1 to 2 m which caused the collapse of the beach crest. The central part of the beach was not overwashed but the waves left the barrier in a very precarious state because of its narrow width. Nevertheless it was able to rebuild its upper beachface before being struck by waves from a subsequent major storm.

In southwest Nova Scotia, the lower dunes of Bakers Beach were overwashed by waves and dune vegetation was flattened and partially covered by a layer of gravel and debris. Where the sand dune was higher, the waves scoured the seaward duneline cutting it landward by 6 to 7 m. The eroded dune scarp was still present in 1995, showing little evidence of progradation.

"Storm of the Century": March 13-15, 1993.

This severe winter storm was called the "Storm of the Century" in the U.S. because of the large amounts of snow dumped along the eastern seaboard and because of the large amount of damage caused by high waves. The storm reached Canada on March 13th, bringing blizzard conditions with hurricane force winds in parts of Nova Scotia and heavy rainfall along the Atlantic coast. Significant wave heights reached 9.2 m late on the 14th off Halifax and waves of more than 1.5 m height continued for 148 hours. At Halifax water levels reached 2.3 m, similar to levels recorded during the Halloween Storm.

Higher snowfalls and cold temperatures that preceded the "Storm of the Century" were important controls on the impact of this storm on the Atlantic coast of Nova Scotia. Five days prior to the storm, perigean spring tides, drifting snow and cold air temperatures resulted in the formation of a large icefoot along most beaches. At Story Head, the beach crest was extended 10-12 m seaward and 0.5 to 1 m upward by ice (Figure 3). At the same time, strips of 3-9/10 sea ice extended along the Atlantic coast of Nova Scotia from Cabot Strait at least as far as Lunenburg and many bays contained brash ice (Ice Forecasting Central, 1993). During the storm, the waves initially attacked the lower beachface and threw debris up onto the icefoot. They were prevented from overwashing the beach by the increased elevation of the beach crest. Also, as the storm intensified, increased amounts of slush and brash ice were carried shoreward, dampening waves, and a second icefoot was built, extending 10-20 m offshore. The presence of shorefast ice shifted the wave breaker zone farther offshore and protected the shoreline from direct wave attack. Ice therefore completely negated the physical impacts of the "Storm of the Century" to most of the Atlantic shoreline of Nova Scotia. Within a week of the storm the embayments were cleared of brash ice and there were only small remnants of the icefoot which had been ablated by waves and warmer air temperatures.

Hurricane Felix: August 15-17, 1995.

As Hurricane Felix approached Bermuda on August 13th, it began generating large swells which reached Nova Scotia in the very early hours of the 15th. There was no associated storm surge, water levels were less than 2 m (Table 1), and wave heights were only 4.6 m (half those recorded during the 1993 "Storm of the Century"). Yet many of the beaches were closed for swimming for safety reasons. On the morning of August 15 as the tide rose, the waves extended farther up the beach until high tide when they extensively overwashed many parts of Story Head Beach (Figure 4a). However as the tide ebbed, the level of wave attack also fell and the waves only flowed through the washover channels (Figure 4b). Although the swells were spectacular, most of the physical adjustments occurred across the shoreface and lower beachface, in the washover channels and at the washover fans at the back of the barrier. In the next two days, the beach crest was actually built up by waves. Therefore this storm could be considered constructional rather than destructional.

At Lawrencetown Beach (type 5a), and Miseners Beach (type 2), sediment reworking and transport was restricted mainly to the shoreface and lower beach face (Figure 2).

"Saros" Storm Event: December 20-22, 1995

This storm in December 1995 was called the "Saros" event because it coincided with larger than normal perigean, spring tides which are associated with the "Saros" cycle, i.e., when the moon, sun and earth return to almost identical positions relative to each other, every 18 years 11 days and 8 hours (Desplanque (1974) warned of these high tides 21 years ago). Water levels at Halifax were the third highest recorded in the past 16 years. A low pressure system, which was positioned just off the Nova Scotia coast on December 21 and 22, produced strong easterly winds and significant waves of 4.8 m (Table 1). Although the significant wave height was higher than that recorded during Hurricane Felix, the duration was much less and the wave period differed. On the morning of December 22 coastal flooding was reported at several locations along the Atlantic coast near Halifax and surveys of the low gravel barrier at Story Head showed it was pushed landward by as much as 16 to 20 m (Figure 3). The large movement of the gravel barrier was in part facilitated by the occurrence of a smaller storm 10 days before. It produced the fifth highest water levels recorded at Halifax in past 15 years, reaching 2.38 m. This storm eroded the beach face, thinned the crest in some places and flattened it in others and produced large washover channels making the beach more vulnerable to the storm on December 20 to 22.

At the low east end of Lawrencetown Beach (Figure 2, type 5b) and at several other low sand barriers, gravel clasts and debris were washed over the beach crest and into the dunes or backshore. Where inlets or deeper washover channels existed there was flooding of backshore areas; however unlike the low gravel barriers, no significant landward migration of the beach crest was observed.

Hurricane Hortense: September 14-15, 1996

Hurricane Hortense made landfall east of Halifax at 0600 UTC September 15, 1996. The first major impacts to the coast occurred between 0000 and 0300 UTC when the peak storm surge of 1.03 m coincided with astronomical high tide at Halifax (Table 1, Figure5). Flooding of houses at the east end of Lawrencetown Beach began after 0130 UTC which just preceded the largest significant wave heights of 8.69 m recorded at the MEDS 037 waverider buoy at 0250 UTC. The storm tracked through central Cape Breton Island where the peak storm surge of 0.76 m coincided with high tide at North Sydney on the morning of the 15th. The storm then moved out to sea south of Newfoundland.

Story Head Beach was submerged completely and debris reached elevations of 2.9 m on the headland behind the beach. The crest of the low gravel barrier was shifted landward 13 to 14 m and in some places by as much as 22 m. Sequential cross-sectional profiles showed that there was little physical change to the shoreface and most of the change occurred above high tide level (Figure 3). Closer to Halifax, the lagoon shore of Silver Sands Beach, was also shifted 14 m landward by construction of cobble washover sheets and cobble-boulder fans.

At Miseners Long Beach, a high gravel barrier (type 2), waves from Hortense reached elevations of 4.4 m (Figure 2). Only the highest point of the beach, at 4.6 m was not overwashed. Sequential surveys of the beach before and after the storm show that the crest was lowered by 0.5 to 0.7 m and became much more irregular because of the increased number of washover channels.

At the larger sand barriers (e.g., Lawrencetown), water washed through or over dunes that were less than 4.5 m elevation. As much as 0.2 m of gravel was deposited over the dune vegetation along the east end of the beach. Where the dunes were higher, as at the west end of Lawrencetown (Figure2, type 5a), there was only minor scouring of the duneline. The lack of dune scouring is attributed to the short duration of the storm.

DISCUSSION

The magnitude of coastal change resulting from a storm depends on the type of shoreline and its shoreface, the characteristics and direction of the storm and the sea conditions during each event. The key parameters that influenced the magnitude of coastal change along Atlantic Nova Scotia during the five events described here included: water level, storm duration, wave energy, frequency of storms and the presence of shorefast ice or sea ice.

Field surveys at a number of sites have shown that low gravel (type 3) barriers are subject to major adjustments during most storms but are particularly vulnerable to storms that coincide with high water, e.g. "Saros" and Hortense events. The crest and backshore of the high gravel (type 2) barriers are only affected during events that coincide with high water levels but storms with a long duration can cause substantial thinning of the barrier ridge and retreat of the crest through sediment collapse, e.g. Halloween storm. Similarly sand (type 5) barrier complexes are only overwashed at high water levels. They can be severely cut back when waves attack for several tidal cycles, e.g. the Halloween storm. Large waves by themselves rework the lower beach face and shoreface but need to coincide with high water levels to severely impact the subaerial part of the beach. Weather anomalies such as very cold temperatures, high snow falls or the influx of sea ice alongshore can completely negate the erosional impacts of waves on the upper beach but can re-focus the wave attack farther offshore, e.g., the "Storm of the Century". The type 3 and type 5b shores lie at or just below the elevation of wave runup during the five storms hence they were subject to larger physical changes and backbarrier flooding (Figure 2). The plot also illustrates the importance of a high stable dune complex (type 5a) such as at the west end of Lawrencetown Beach in preventing flooding of the backshore and in absorbing wave attack. Wave run up is controlled by shoreface character and sediment composition of the lower beachface. A simple comparison between observed water levels at the Halifax tide gauge and the height of wave runup at Lawrencetown Beach shows that wave runup reached 2.4 to 2.6 m above the maximum water levels recorded at the tide gauge during the five storms (Table 2). Wave runup was greatest during Hurricane Hortense, when it reached elevations of 5.3 m above Halifax chart datum (4.5 m above geodetic zero). When water levels at the Halifax gauge reached to within 1m of the crest elevation of Story Head Beach, it was nearly completely submerged, e.g. the "Saros" event and Hurricane Hortense.

The importance of water level in determining the elevation at which waves strike a coast is illustrated in the comparison of the storm surge profiles from the Halloween Storm, which coincided with perigean neap tides, and Hurricane Hortense, which coincided with spring tides (Figure 5a, b). The impacts of the Halloween storm would have been much larger if the storm had occurred a few days earlier or later (Parkes *et al.*, these proceedings). The impact of Hurricane Hortense also would have been much more severe if it had occurred over several tidal cycles because it quickly lowered the beach crests making them vulnerable to further overwashing. This highlights the importance of storm frequency. If a beach is unable to rebuild or recover before the next storm, it is more likely to experience larger magnitude changes than if no previous storm had occurred. Likewise, a small storm can comb down a beach face and make it vulnerable to much larger physical changes than one would normally expect from such a small storm. Such was the case in December 1995 when the "Saros" event quickly followed another storm-generated high water event. The importance of antecedent beach conditions has been recognized by others including Carter et. al. (1987) and the topic is further discussed by Forbes *et al.* (these proceedings).

SUMMARY

1) Storms provide the primary mechanism for causing episodic beach migration.

2) Large waves alone may have limited impact. Instead, it is the cumulative effect of sea level, wave power, and storm duration (number of tidal cycles), offset or enhanced by local conditions that determine the magnitude of physical shoreline change.

3) Low gravel barrier beaches are significantly impacted by most storms and can move as much as 10-20 m landward if completely submerged under storm waves for several tidal cycles.

4) High sand and gravel barrier beaches are overwashed less often than the low barriers, consequently they migrate landward at much slower rates. High, stable sand dunes can withstand short periods of wave attack at high water levels but can recede 5 to 10 m if the duration of wave attack is extended over several days. The crest of a high gravel barrier may retreat less than 2 m during a similar long-duration storm, e.g., Halloween Storm, by erosion of the beachface rather than through overwashing.

5) Along the Atlantic coast near Halifax, wave runup was observed to extend to maximum elevations of 5.3 m above Halifax chart datum (4.5 m above geodetic zero), which was 2.6 m above the water level recorded at the Halifax tide gauge. The maximum wave run-up occurred during Hurricane Hortense.

6) Ranking the five storms, Hurricane Hortense, Halloween and "Saros" caused the most property damage and most significant beach changes. Hurricane Felix caused disruption in the recreational use of the beaches but less physical change. The "Storm of The Century" despite its large size and high waves did the least damage to beaches in Atlantic Nova Scotia because of the protective role of ice.

FUTURE NEEDS

1) Closer links need to be established between shoreline monitoring crews and storm surge forecasters who have access to real time marine measurements. The forecasters could provide storm alerts to the survey crews who could measure shoreline changes sooner, obtain better post storm observations which could be used to develop a better relationship between wave heights, water levels and beach response. Once the beach response to specific storms is established, storm warnings could be developed for specific shore types along Atlantic Nova Scotia.

2) It is critical that the network of wave buoys, especially inshore buoys (e.g., MEDS 037), and the network of tide gauges along our coasts, be maintained, not abandoned. These observing tools allow forecasters to monitor the movement of storm surges alongshore and allow a better documentation of the marine conditions responsible for the physical changes observed onshore.

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DEFINITIONS

Barrier beach: An elongated sand, gravel or mixed sand and gravel beach with one or more ridges extending generally parallel to shore but separated from it by a lagoon, lake ,wetland or low land.

Beach Crest: A berm or ridge marking the highest portion of a barrier beach reached by waves. The crest often coincides with the seaward edge of the backshore slope or foredune.

Chart Datum: A plane below which the tide will seldom fall. Canadian Hydrographic Service has adopted the plane of lowest normal tides. At Halifax mean sea level is presently 1.02 m above chart datum and geodetic zero (to which Canadian Geodetic survey control points are referenced) is presently 0.799 m above chart datum.

Cyclone: An atmospheric low pressure system with a closed, roughly circular wind motion that is counterclockwise in the northern hemisphere; tropical cyclone: intense cyclone that forms over the tropical oceans, ranges from 100 to 1000 km in diameter; extratropical cyclone: found in middle and high latitudes, commonly has much larger aerial extent, but less intensity, than tropical cyclone.

Hurricane: A tropical cyclone with winds of 64 knots or greater but rarely exceeding 130 knots. A Category 1 hurricane has winds of 64 to 82 knots.

Icefoot: A narrow strip of ice formed along and firmly attached to the coast, unmoved by tides; formed by freezing spray, swash, snow, ice cakes, and / or brash ice. Usually forms above low tide.

Perigean Tide: A tide of increased range occurring when the moon is at or near the perigee (point nearest earth) of its orbit. In this study perigean tides were defined when the moon in perigee coincided with, or was within 2 days after the new or full moon.

Storm Surge: An abnormal rise in sea level during a storm, usually generated by onshore wind stress or less frequently by atmospheric pressure reduction, resulting in water piled up against the coast. It is most severe when it coincides with high tide. Surge height is defined as the observed water level minus the predicted astronomical tide.

Wave Height, Significant: The trough to crest height of the highest one-third of waves that pass a point.

Wave Period, Peak: the wave period associated with the maximum energy (variance density) in the frequency spectrum of waves that pass a point.

Table 1. List of storms discussed in the text and their associated water level and wave conditions. Data is derived from hourly observed values from the tide gauge in Halifax Harbour and the MEDS 037 wave rider buoy located in 56.7 m of water (44.489 °N 63.416°W) offshore of Halifax Harbour (Marine Environmental Data Service (MEDS), Ottawa, 1996.

Storm Event	**Date**	**Water**	**Level**	**Conditions**	**Wave**	**Conditions**	
		Storm Surge Height (m)	Storm Surge Duration (hrs)*	Max. Sea Level Elevations (m)# Time (UTC) / Date	Max. Signif. Wave Ht (m) Time (UTC) / Date	Duration (Hrs) Signif. Wave Ht (□1.5 m)	Wave Peak Period (sec)
"Halloween" Storm (Extratropical)	Oct. 28-Nov. 2 1991	0.68	13	2.3 (16:30/30th)	6.3 (18:50/30th)	165	16.7
Storm of the Century (Extratropical)	Mar. 13-15 1993	0.60	2	2.3 (04:00/14th)	9.2 (23:50/14th to 00:20/15th)	148	16.7
Hurricane Felix (Tropical)	Aug. 15-17 1995	0.15	0	1.8 (15:15/15th)	4.6 (14:50/15th)	83	16.7
"Saros" Storm (Extratropical)	Dec. 20-22 1995	0.71	9	2.5 (10:15/21st) (11:00/22nd)	4.8 (04:20/21st)	56	14.3
Hurricane Hortense (Tropical)	Sept. 14-15 1996	1.03	4	2.7 (00:15/15th)	8.7 (02:50/15th)	63	11.4

* Duration includes only storm surges where the water level equals or exceeds predicted tide levels by 0.6 m.
# elevation above chart datum, Halifax.

Table 2. Maximum elevations (m above Halifax chart datum) of wave runup recorded at three barrier beach types. Type 5 is represented by Lawrencetown Beach (except for Halloween Storm); Type 2 by Miseners Long Beach; Type 3 by Story Head Beach. Original beach elevations were surveyed relative to geodetic zero, therefore elevations have been increased by 0.8 m to allow direct comparison with water level elevations which are relative to Halifax chart datum.

Storm Event	**Max. Water Level Elevation (m)** Halifax Tide Gauge	**Max. Elev. of Wave Run-up (m)**		
		Type 5 High Sand Dune Barrier Complex	Type 2 High Gravel Barrier Beach	Type 3# Low Gravel Barrier Beach
"Halloween" Storm	2.3	4.9*	4.5	3.5
Storm of the Century	2.3	icefoot	icefoot	icefoot
Hurricane Felix	1.8	~4.3	~4.1	3.1
"Saros" Tide	2.5	>4.9	>4.1	3.4
Hurricane Hortense	2.7	5.3	5.3	3.3

* Elevation from Bakers Beach, SW Nova Scotia;
# Represents beach crest elevation overwashed by waves; not maximum elevation of wave runup.

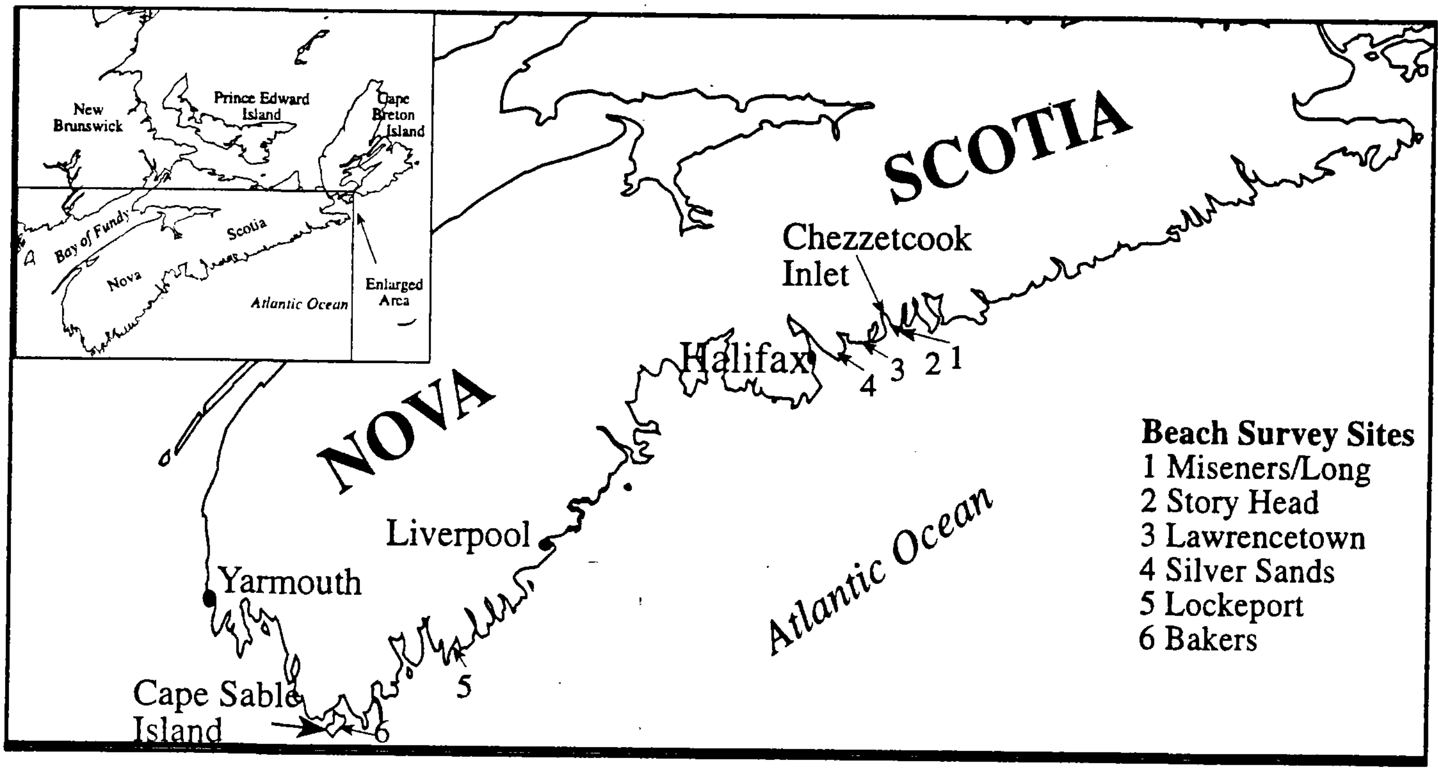


Figure 1. Place names and location of the barrier beaches along the Atlantic coast of Nova Scotia where the impacts of the five storms, discussed in the text (Table 1), were documented.

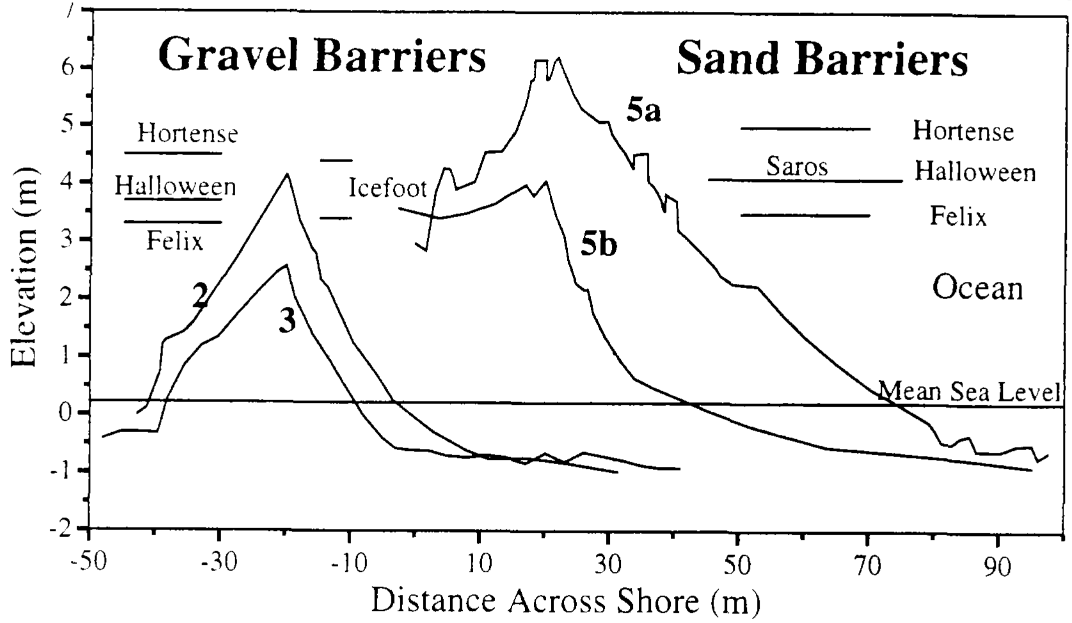


Figure 2. Profiles of three barrier beach types (2, 3, and 5) from the Atlantic coast of Nova Scotia illustrate the difference in their physical character and the maximum elevation (relative to geodetic zero) of wave run-up during the storms discussed in the text. The sand barrier (type 5), is represented by Lawrencetown Beach (Fig. 1); 5a is from the west end and 5b is from the east end where the beachface is gravel and the sand dune occurs farther inland. Waves, during the storms listed, extended to elevations above the crest of the type 3. The elevation of the gravel barriers was temporarily raised (as marked) by an icefoot, just prior to the 1993 "Storm of the Century ". The profiles of each beach type have been offset: the ocean is to the right of each profile.

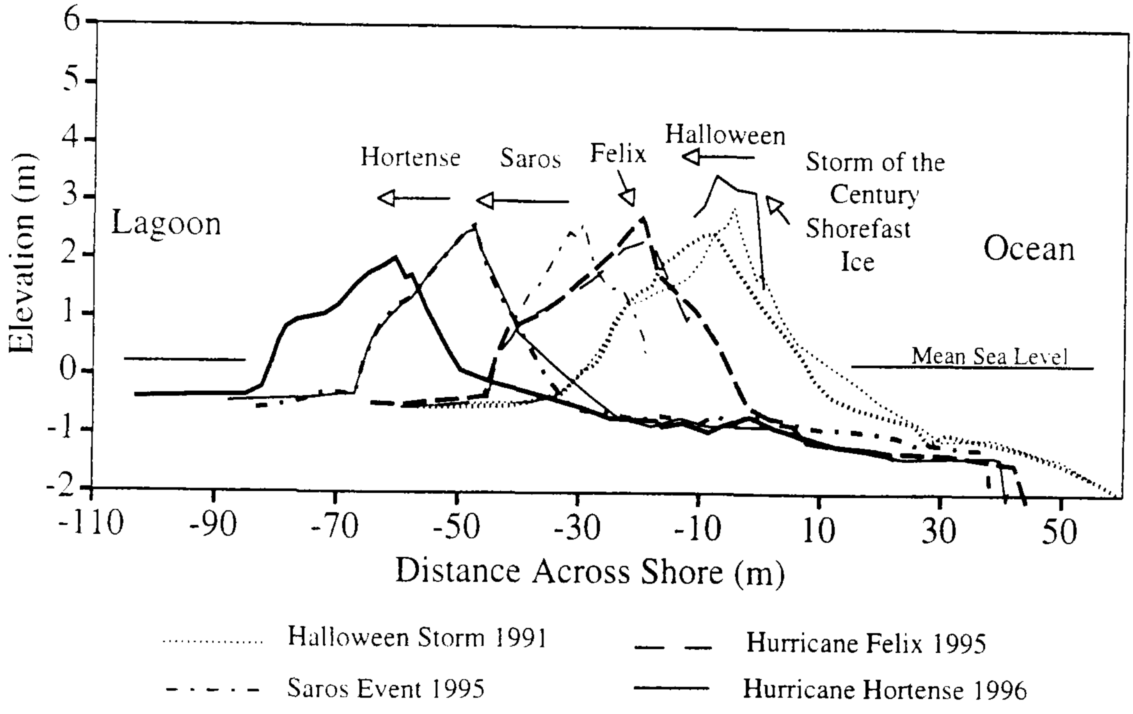
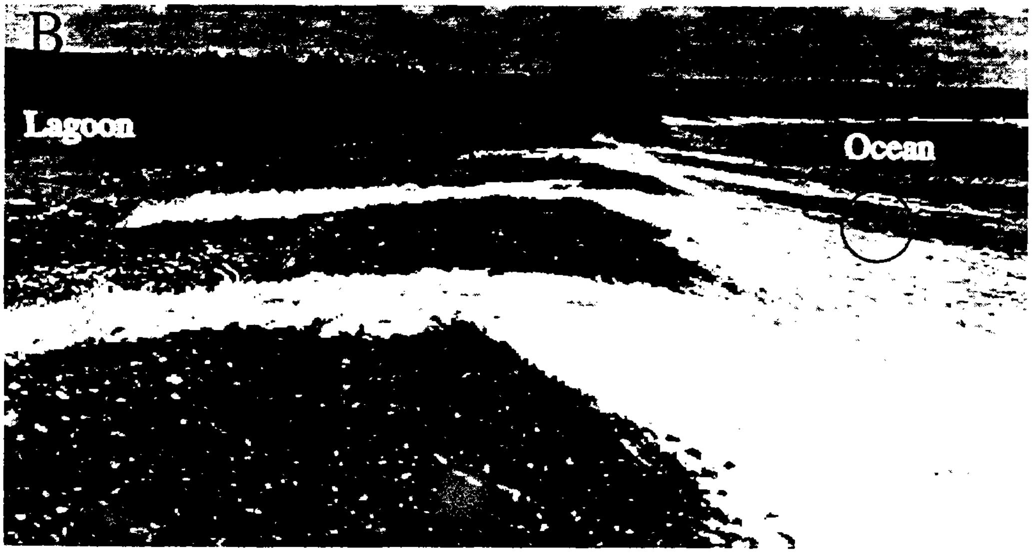


Figure 3. A composite of cross-sectional profiles measured at Story Head Beach following the 1991 Halloween Storm, Hurricane Felix (1995), the "Saros" event (1995) and Hurricane Hortense (1996). Each storm is represented by two lines, the pre-storm line is thinner than the post -storm line: arrows mark the zone of change during each event. The icefoot that temporarily raised the beach crest during the 1993 "Storm of the Century " is also marked. The diagram does not show the intermediate positions of the beach between storms. Elevation is relative to geodetic zero.

Figure 4. Views looking east along the crest of Story Head Beach during Hurricane Felix (August 15, 1995) showing the importance of water level. Just before and at high tide (A), the waves surged over much of the beach crest but an hour later, as the tide fell, the flow of water was restricted to the overwash channels (B). A t-bar, marking the survey line shown in Fig. 3, is circled on each photo for reference. The width of the beach from its crest to the lagoon shore is 20 to 22 m.



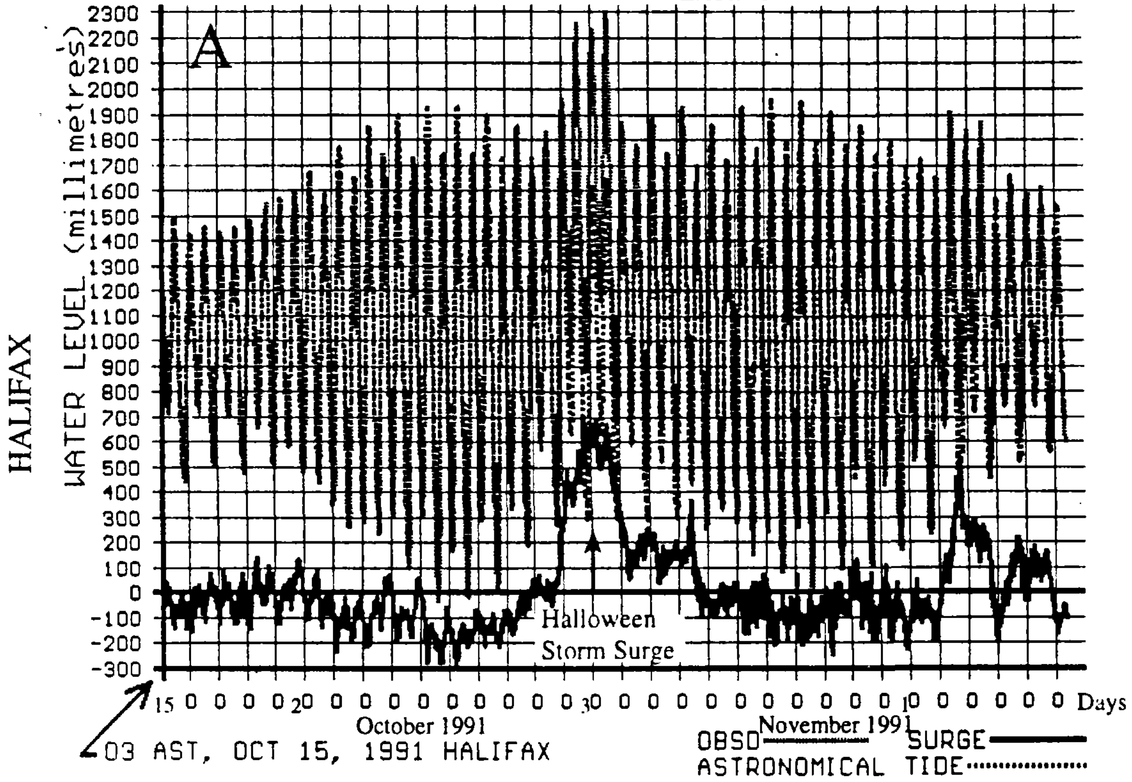
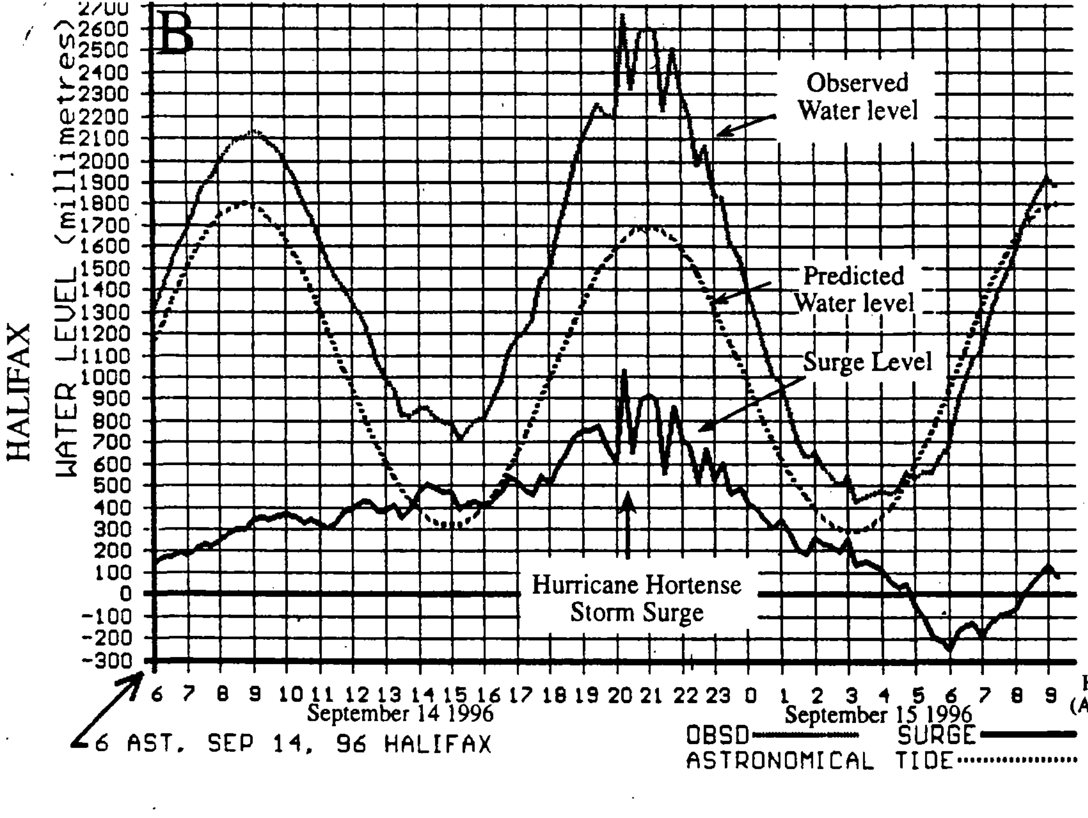


Figure 5. Graphs of the observed and predicted tides for Halifax, Nova Scotia showing the storm surges produced during the 1991 Halloween Storm (A) and Hurricane Hortense (1996)(B). The Halloween Storm occurred at perigean neap tide and the surge lasted 13 hours. The impact of the Halloween Storm would have been much greater if it had been a few days earlier or later, when it would have coincided with higher tides. Hurricane Hortense coincided with a spring tide and the storm surge only lasted 4 hours. Despite its short duration ,the higher water levels caused severe overwashing of all but the highest barrier beaches. Note the difference in time scales for each plot, (A) is daily and (B) is hourly.



APPENDIX G

EXTENDED ABSTRACTS

ECOSYSTEM SCIENCE AND WATER RESOURCES

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Potential Ecosystem Effects of Atmospheric Change: a Precautionary Tale

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ABSTRACT

Climate change, UV-B, acidification and persistent organic pollutants pose ongoing threats to our Canadian well-being through their direct effects both on our natural resources and on related industries such as agriculture, fisheries, forestry, tourism, power generation and outdoor recreation.

There is also a more immediate risk of severe impacts which may result from the influence of changing climate on the number and severity of extreme events (droughts, floods, ice-jams, fires, storms, etc). Recent flooding in the Saguenay was only the latest event in a year of weather vagaries throughout Canada and the rest of the world.

The risk is not only of disasters. It is also of an ongoing drain on the economy from reduced production, increased costs for infrastructure maintenance and repair, a greater incidence of business failures and increased risk associated with investment.

Canadians can act to minimize these risks through programs involving the identification and assessment of regional patterns of atmospheric changes, their effects and the potential means of adapting to them. Such means might include, for example, selecting resistant tree or crop species; altering standards for dams, building construction or land-use; early development of irrigation capabilities; protection of critical habitat; water supply management and allocation; altered energy development strategies; and anticipatory actions to offset economic disruptions. Such programs at present include the Canada Country Study and the Regional Ecosystem Effects of Atmospheric Change program.

While scientists and others will continue to debate the reality and exact nature of atmospheric changes, Canadians can ill afford to remain unprepared for possible impacts which may well be severe, widespread, long-lasting and difficult to reverse. The risks posed to our Canadian society, economy and environment by atmospheric changes urgently require assessment in order that appropriate policies and actions can be undertaken to minimize or adapt to impacts.

APPENDIX H

EXTENDED ABSTRACTS

AGRICULTURE

A Spreadsheet Model as a Framework to Examine The Effect of Climatic Uncertainty on Agriculture

Roderick W. Shaw[1] and Bo R. Döös[2]

INTRODUCTION

Research will in all likelihood result in improved estimates of the impact of climate caused by increasing concentrations of greenhouse gases, but reliable predictions of climatic change on a regional scale are still some time away. Therefore, it would be prudent to assume that the management and use within the next several decades of natural and man-made resources such as forests, agriculture and coastal structures may have to be carried out in the face of climatic uncertainty. This uncertainty would manifest itself not only with respect to changes in climatic means, but also with respect to the frequency and severity of extreme events such as hurricanes and droughts.

A valuable approach in a examining regional vulnerability to climatic change is systems analysis, which affords one the opportunity of looking at a problem in a holistic, integrated fashion by including as many of the important components as is practicable, and the linkages among them. Systems analysis often begins with a conceptual model which can then be "operationalized" by quantification (using the best available scientific knowledge) of the stocks and flows of the relevant components, and the processes that are involved. Common tools for operationalization are computer models, spreadsheets, databases, and display mechanisms such as geographical information systems.

STRUCTURE OF A SPREADSHEET MODEL OF FOOD DEMAND AND PRODUCTION

Figure 1 shows a spreadsheet model for the human demand and supply of crops and biomass. This model was initially developed at the Stockholm Environment Institute by Bartholomew *et al* (1994a, 1994b). Each box in Figure 1 represents a database which is linked to the others by the arithmetic operation that is indicated. At the beginning of the Demand Chain for crops and biomass are the "drivers": population, nutrition, and diet structure. Added to the regional demand for agricultural commodities consumed directly as human food are the demands for trade; stock change; losses in harvesting, transportation, etc.; recycling of agricultural commodities for seed and eggs; processing into secondary commodities; use of crops for animal feed; and biomass to be used for other purposes such as energy and industrial raw materials.

The total demand for a crop or biomass commodity must be satisfied by the Supply Chain which depends upon a combination of cultivated area, cultivation pattern (fraction of cultivated area assigned to each crop), cropping intensity (number of crops per year) and yield per unit cultivated area. Yield in a given area is determined by factors such as the soil characteristics, climate, and inputs including water, seed and fertilizer. In attempting to satisfy demand in a given scenario, various factors affecting yield can be adjusted (within realistic limits) and land use can be altered,

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including the use of cultivable land not presently being used.. Of course, an important part of the analysis will be the establishment of realistic limits on the factors that affect agricultural production. Inadvertent changes in production factors can be brought about by atmospheric stresses such as climatic change, tropospheric ozone and increased UV-B radiation.

It is obvious from the above that one can use a model such as that shown in Figure 1 as a framework for examining the sensitivity of crop commodity production to uncertainties brought about by climatic change affecting factors such as cultivated land and yield.

GLOBAL APPLICATION OF THE SPREADSHEET MODEL

Shaw (1997) describes the use of the spreadsheet model to examine the effects of various scenarios of atmospheric change (climatic change, tropospheric ozone, increased UV-B radiation from stratospheric ozone depletion) on whether or not supply might be able to meet the demand for crop commodities in the year 2025. Food demand was based upon projections of population by the United Nations Population Division (e.g., UN, 1992); changes in diet structure in various regions of the world were based upon extrapolation of trends, taking into account saturation of food calorie intake in developed regions. Changes in crop production factors such as cultivated areas and yields were based upon an extrapolation to the year 2025 (within limits of maximum cultivated areas and yields) of projections by FAO (1993) to the year 2010.

One result was that the particular scenario of climatic change assumed in the analysis could by 2025 cause a global shortfall (supply less than demand) of 18% in grains, 13% in roots and tubers, and 8% in oilcrops. It should be stressed that results such as the foregoing are scenario results only, *not* predictions. The model results are of course dependent upon assumptions about factors such as cultivated area and yield; it is the uncertainties in these factors brought about by environmental change which makes the planning of the management of these resources such a challenge. However, models such as the very simple spreadsheet version described above can help one gain some insight into the sensitivities of the crop commodity system to uncertainties in the input factors.

SUGGESTIONS FOR SENSITIVITY ANALYSES

Because the food production in the model is calculated as a product of cultivated area, cropping intensity, cultivation pattern and yield, an uncertainty of ± x% in any of these factors would result in the same percentage uncertainty in production. It is, therefore, essential to assess the uncertainties in each of these factors brought about by uncertainties in climatic change; the uncertainties in each factor may in turn be the result of several effects. For example, in the case of yield Y_{ij} (t) for crop commodity *i* in region *j* for a year *t* in the future, $Y_{ij}(t) = (1+c_{ij}t)Y_{ij}(0)$, where $Y_{ij}(0)$ is the present yield for crop commodity *i* in region *j* and c_{ij} is the net annual rate of change of yield due to: (1) CO_2 fertilization; (2) changes in mean values of climatic variables such as temperature and precipitation; (3) changes in climatic variability such as droughts, floods and early frosts; (4) changes in cropping intensities due to changes in the number of growing degree days. Parry (1990) has attempted to estimate values for c_{ij} on a world region basis but it is obvious that, for an analysis in the Atlantic Region, these factors would have to be estimated locally.

Yield could also affected by biotic stresses such as increases in insect pests and weeds brought about by climatic change, and decreases in yield due to soil degradation. To the effect described in the foregoing paragraph would be additional factors $(1-b_{ij}t)$ and $(1-d_{ij}t)$, where b_{ij} and d_{ij} would be the annual rate of change in yield due to pests and to soil degradation, respectively. Yield could of course be increased through the application of fertilizers and irrigation but here there may be a technological limit Y^*_{ij} which the yield may approach asymptotically with time.

In addition to the effects of climatic change on yield would be its effects on factors such as cultivable land. Sea level rise could affect dyked marshlands used for agriculture, and erosion of topsoil due to increased precipitation. The available cultivable land area $A_{ij}(t)$ for crop commodity *i* in region *j* for a year *t* in the future could be expressed in a manner similar to that used above for yield: $A_{ij}(t) = (1+e_{ij}t)A_{ij}(0)$, where e_{ij} is the annual rate of change of land area from various factors linked to climatic change.

It is important to realize that the *rate of change with time* of each of the above factors may, in the next two or three decades, be as important as the final state in determining our sensitivity to climatic change.

CLOSING REMARKS

A spreadsheet model such as that described here will not in itself be able to assess our vulnerability to climatic change. It serves merely as a framework for organizing the various climatic effects on yield and land area. The rate of change of these effects, and their possible limits, must be determined by research specific to this region.

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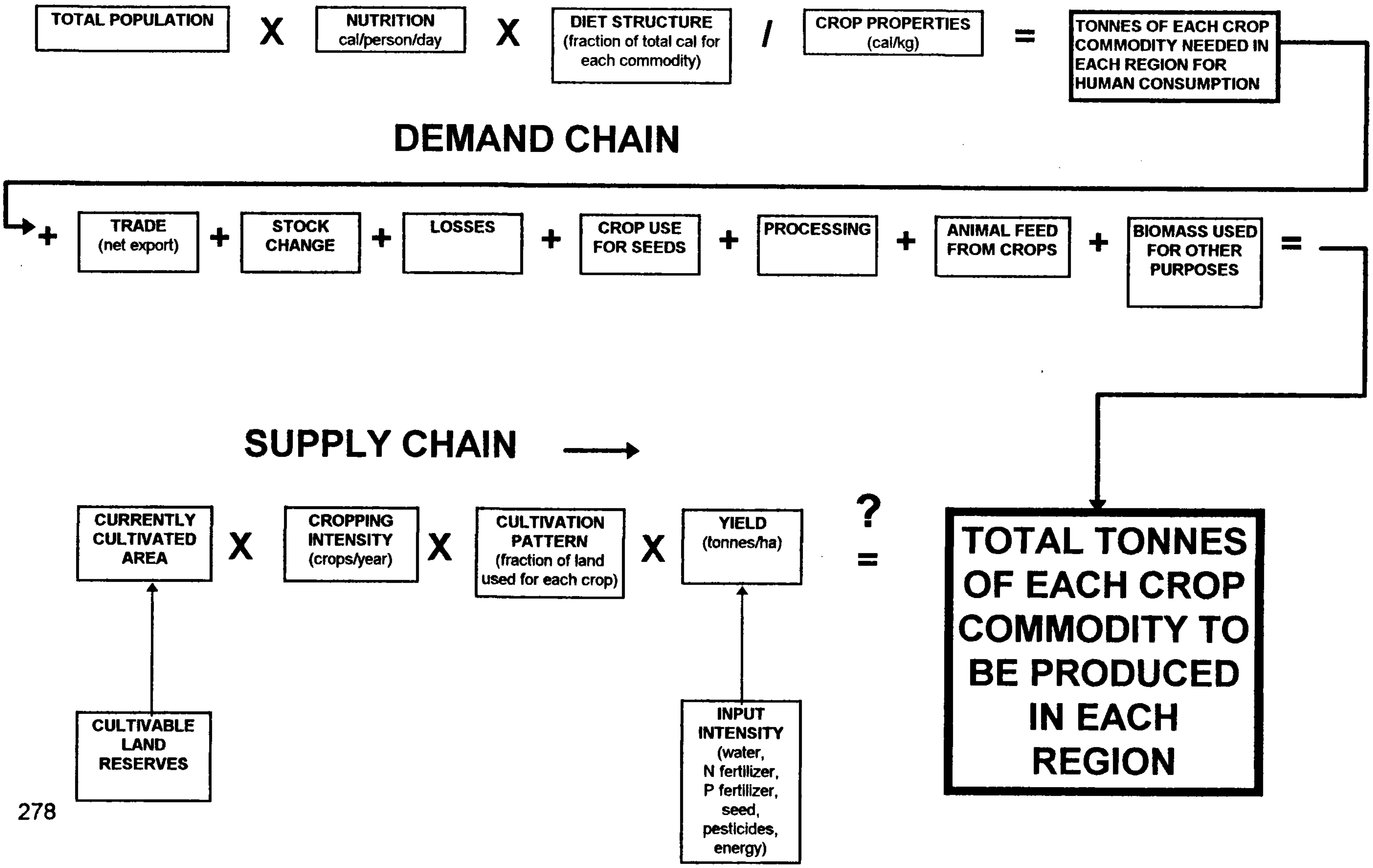
Figure 1: A spreadsheet model of the production and consumption of crop commodities.



APPENDIX J

EXTENDED ABSTRACTS

FORESTRY

Accounting for Variable Terrain in Landscape Scale Forest-Climate Models

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INTRODUCTION

Fundamental to all terrestrial ecosystems is the quantity of solar radiation (energy) available for photosynthesis and for plant and animal functioning. Regional distribution of solar energy amounts is highly variable and is controlled to a large measure by the underlying topography and vegetation cover which make up the regional landscape. The intent of this presentation is to explore numerical ways of addressing these topographic and vegetation effects as they relate to the spatial distribution of solar radiation and surface temperature across entire forest landscapes.

The climate model is created from first principles (i.e., solar geometry, radiation laws, energy balance) so that it can be applied to a broad range of topographies and vegetation conditions. Model calculations proceed in one hour time intervals so high-frequency processes affecting ecosystems, like the dispersion of gases (CO_2, SO_2, NO_x, etc.), pollen, spores, insects, and wild-fire can be addressed. Addressing these ecological processes, however, would require that the model be adapted to accommodate the hour-by-hour effect of atmospheric turbulence and mixing heights according to the daytime and nighttime distribution of meteorological conditions and the distribution of vegetation surface roughness. Aspects of this work have already started, but mostly in relation to flat terrain (Bourque, 1992; Bourque & Arp, 1994a, 1994b, 1996). Long-term climate information may be derived from this model by integrating model calculations to the desired time interval (e.g., week, month, year).

The model is to be used to generate maps of land-surface irradiance and temperature for several regions in northern New Brunswick and for the Cape Breton Highlands. A landscape-level assessment of surface energy fluxes and temperature at this stage will prove helpful later with developing a forest-landscape model for predicting natural and human-caused landscape changes. Because the adopted approach is based on energy-exchange processes, the model can potentially be used to investigate the distribution of solar energy and surface temperatures for a broad range of land surfaces.

MODEL

Solar Radiation

The adopted modelling approach is based on a spatial treatment of solar radiation and temperature applied across a gridded domain (digital elevation model) representing a 4300-ha. land area in north-central New Brunswick (Fig. 1).

The solar radiation model calculates hourly insolation values for every node of the digital elevation model according to the point-calculation of solar zenith angle, direct and diffuse solar radiation, aspect, slope, horizon angle, view factor (proportion of sky that is unobstructed from one's view), terrain configuration factor, and surface albedo (proportion of incoming solar radiation reflected by the underlying surface). Procedures used to calculate the solar zenith angle, and direct and diffuse solar radiation are based on equations given in Sellers (1965) and Bourque & Arp (1994a). Node values of slope, aspect, horizon angle, and view and terrain configuration factors are obtained according to the methods outlined in Dozier et al. (1981), Dubayah et al. (1990), Nikolov & Zeller (1992), and Dubayah and Rich (1996). Example calculations for three of these quantities, i.e., aspect, slope, view factor, are provided in Fig. 2. Note that for the view factor, a value of 1.0 occurs predominantly along the ridges of the modelled land surface. Low view factor values as a rule occur in land-surface depressions (e.g., near the centre of Fig. 2C). Point-calculation of surface albedo is based on a mathematical treatment relating albedo to the orientation of the sun to the land surface (Pielke, 1994). An example calculation of albedo is given in Fig. 3A. The albedo is greatest where the angle of the sun to the land is smallest. Finally, an example calculation of solar irradiance for 0830 is given in Fig. 3B.

Temperature

An important aspect of this work relates to the calculation of surface temperatures given input about the surface-energy fluxes. A classical approach to obtaining surface temperature is by solving the energy balance by an iterative procedure based on a Newton-Raphson expression of the energy balance (Bristow, 1987). A more recent approach to obtaining temperature (Bourque & Arp, 1994a) uses a differential form of the energy balance and associated energy flux equations. Solution is obtained by solving the linear system of differential equations by Gauss elimination. These methods, although practical for one-dimensional problems, fail to be practical concerning the calculation of temperature for two and three-dimensional spaces because of the computational effort (number of iterations) required to obtain a single temperature value. The artificial neural network approach uses one equation evaluation to derive the same information. As a result, this approach can be used to calculate temperature for whole gridded surfaces with minimal computational cost.

The temperature component of the model, based on a tested artificial neural network adaptation of the energy balance, calculates surface temperatures from estimates of incident and outgoing energies determined in part by the solar radiation module. The artificial neural network developed here does not address sensible and latent heat fluxes directly, but uses surrogate variables like wind, relative humidity, air density, partial water vapour pressures (based on calculated temperatures and relative humidity), estimates of vegetation cover stomatal resistance, etc., to account for the effects of surface ventilation (forced convection) and evapo-transpiration on the simulated energy balance and on the calculation of temperature. Obtaining values for these surrogate variables is not a trivial matter since they themselves respond to changes in the landscape. Work on this has yet to be fully developed, but conceivably the procedure will be based on estimating these variables from meteorological data obtained from local weather stations.

Actual daytime energy fluxes, namely incoming and outgoing solar radiation and incoming longwave radiation, and related weather conditions (wind, relative humidity, water vapour pressures, etc.) for three significantly different days in the summer of 1989 (Fig. 4) were used to build and train the artificial neural network. Results of the training and subsequent testing of the neural network are depicted in Fig. 4. Clearly, the neural network reproduces observed temperature trends very well ($r^2 = 0.992$, Sum of Square Error = 0.008). To generalize the approach further, the artificial neural network will be re-trained, this time with both daytime and nighttime energy-flux and temperature data. Arrangements have been made with researchers with Agriculture Canada to obtain the necessary data to train and test the artificial neural network.

FUTURE MODEL ENHANCEMENTS

Nighttime drainage of cold air resulting from radiative cooling of the land will be simulated by mathematically tracking the hour-by-hour movement of hundreds of thousands of individual simulated air parcels placed on top of the modelled land surface (Bourque, 1992). Tracking of the individual air parcels will be done by way of Lagrangian air parcel trajectory calculations, whereby changes in air parcel co-ordinate positions will be expressed as function of parcel temperature and density (see Bourque & Arp, 1996). To ensure reasonable representation of night-time conditions, the simulated air parcels will be placed evenly across the land surface.

Initially, before the air parcels are affected by gravity, air parcel temperature (Bourque, 1992) will be adjusted downwards according to the calculated surface air temperature determined with the artificial neural network expression of the energy balance. The equation of state (Hewson & Longley, 1951) will be used to determine the new air parcel densities. With time, gravity will cause the simulated air parcels to move downward to regions of lower elevation. As air parcels descend, adiabatic compression of the air parcels will cause the individual air parcels to warm 1 C. deg. for every 100 metres of descent. Early-morning distribution of simulated air parcels will then be used to obtain vertical and horizontal mappings of temperature distributions.

MODEL APPLICATION

The model will be adapted to several regions in northern New Brunswick and the Cape Breton Highlands so that the micro climatology of these areas may be studied in greater detail. Maps depicting spatial distribution of surface temperatures will be generated for each of the study areas for selected times during selected days in the growing season. Also, maps depicting degree-day accumulations for typical growing seasons will be generated with the model. These summaries will be helpful with developing the forest-landscape model referred to earlier.

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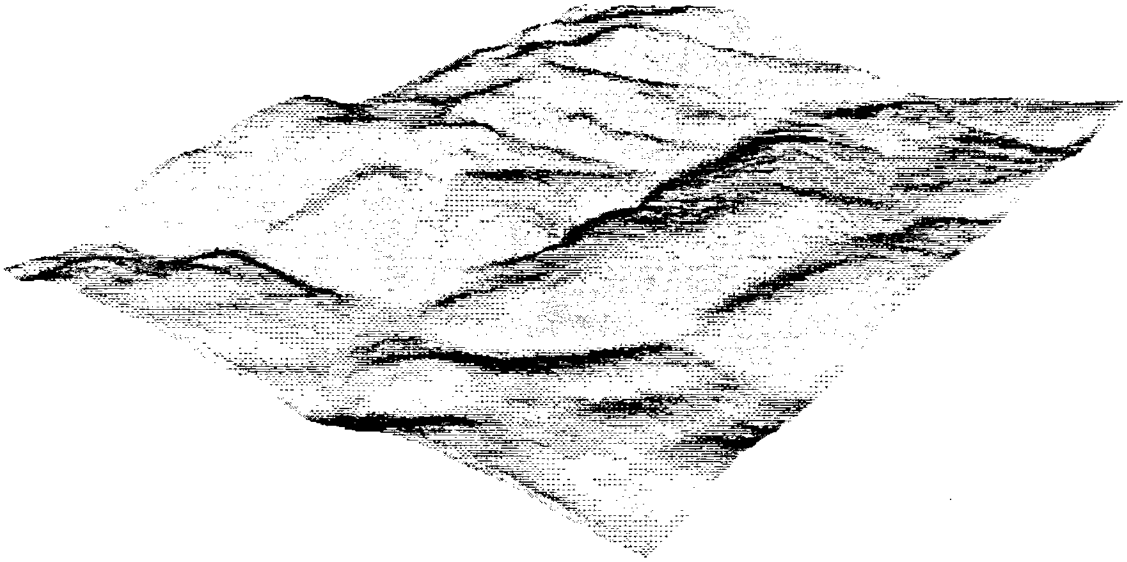

Figure. 1. Digital elevation model for a northern New Brunswick region. The model constitutes a 112 × 152 rectangular grid with 50-m spacing between points.

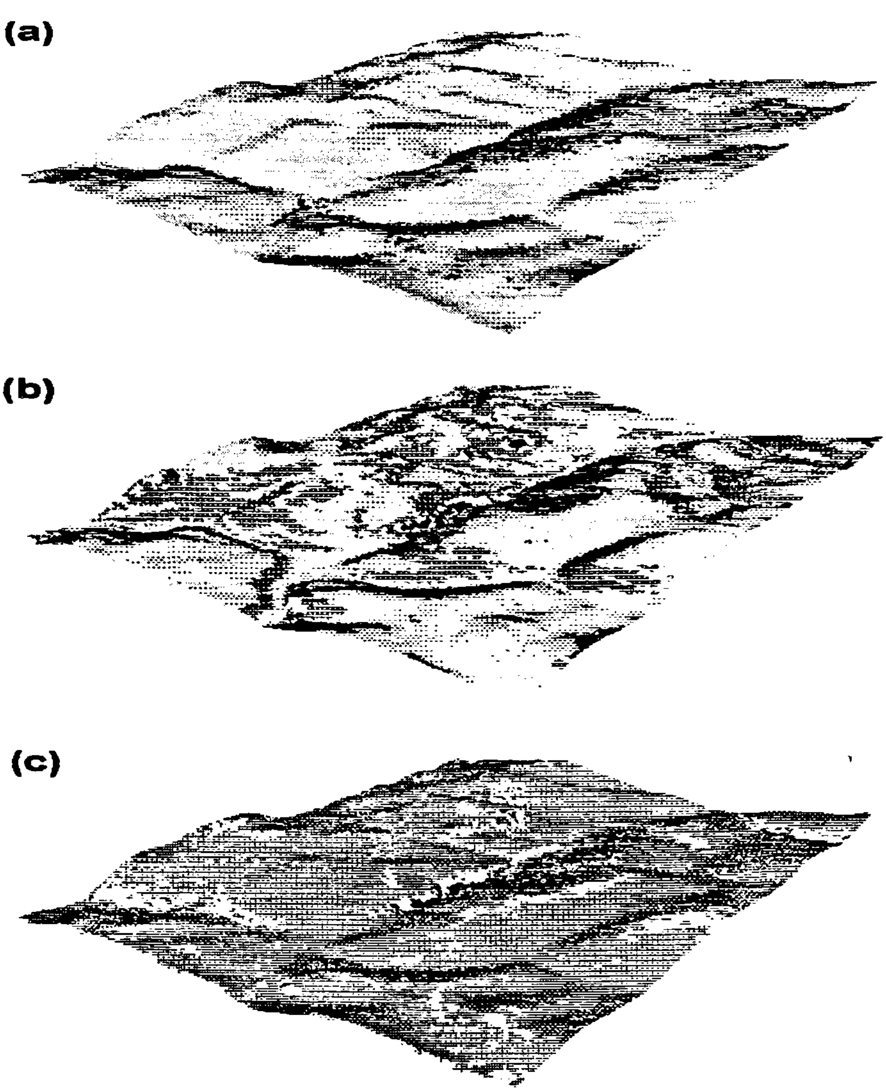

Figure. 2. Aspects (a), slopes (b), and view factors (c) calculated from the digital elevation data of Figure. 1: (a) The dark shading represents the west-facing direction, while the lighter gray represents the east-facing direction; (b) Slopes greater than 15° are depicted in dark gray; (c) Lowest view factor values, <.95, occur in the depression near the centre of the land surface. The light grays along the ridges represent view factors of 1.0.

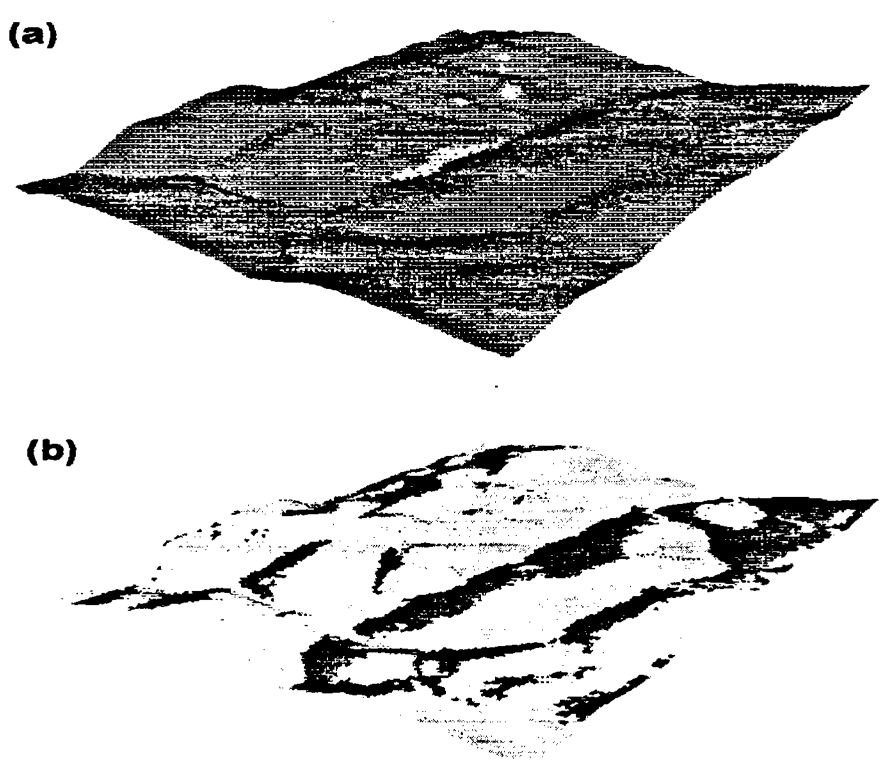

Figure 3. Surface albedo (a) and solar irradiation (b) for 0830. (a) The lighter grays represent albedoes close to .10, the darker grays in the fold of the land surface represent albedoes of greater than .18. (b) Light grays represent insolation levels greater than 600 W·m^{-2}. The darker grays represent lower insolation levels.

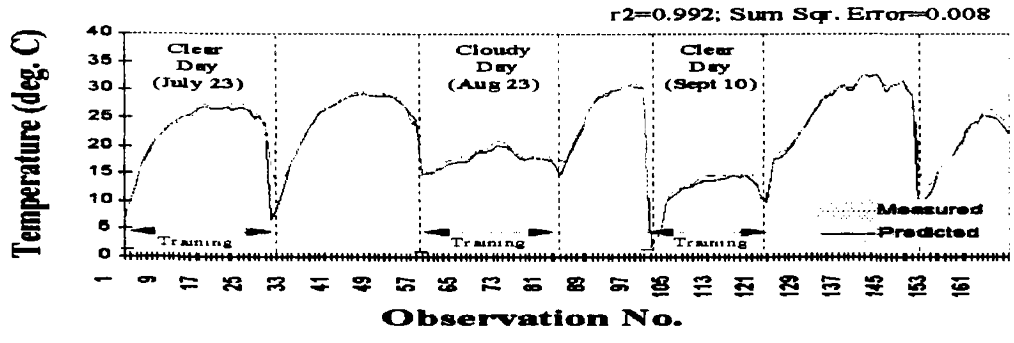

Figure 4. Results of the trained and tested artificial neural network. Segments of the time series depicted by observation number 1 through 33, 59 through 86, and 103 through 124 represent target temperatures used in the training of the neural network. Other segments represent temperatures used in testing the network.

Winter Climatic Anomalies, Xylem Conductivity and Birch Die-back: An Experimental Approach.

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ABSTRACT

Current evidence suggests an increase in mean global surface temperature of 0.5 °C has occurred since 1860, with a greater increase recorded during winter than summer. It has also been suggested that climate warming will be greater at higher latitudes, approaching 3-4 °C in parts of Canada. This together with the cooling, due to increases of a sulphate aerosol from northern hemisphere pollution sources, led to a scenario of increased climatic instability, and an increase in the frequency of winter thaws. The suggestion that winter thaw may have caused the birch decline of the 1930's has prompted experimental examination of the potential role of such events on die-back of birch species and the underlying physiological and biophysical mechanisms.

Climate-controlled chambers were used to simulate winter thaw conditions in the field. Stems, or stems and roots of potted 2 year-old paper and yellow birch were subjected to different periods of a simulated winter thaw. Simulated thaw of various durations induced dieback on the treated plants. The stem thaw treatments increased variation in dieback responses of paper birch but showed no statistically significant effects. However, some significant ($P < 0.05$) correlations were found relating GDD (>4°C) with both % reduction in conductive xylem and die back in these treatments. All paper birch trees which had received >60 GDD (Growing Degree Days >4°C) died back to some extent. Paper birch with roots and stems thawed for > 60 GDD, showed a significant ($P<0.05$) amount of dieback. In addition these trees had a significant ($P<0.05$) loss of conducting xylem after a period of growth and recovery in the greenhouse, especially, in the xylem of the one-year-old stems. Furthermore correlations between GDD of a thaw and both loss in conductive xylem and dieback yielded higher coefficients ($p<0.05$) than for the stem thaws. Thawing roots and stems also yielded highly significant relationships ($p<0.05$-0.001) between loss in conductive xylem and dieback. Comparisons between paper birch and yellow birch indicated that the yellow birch roots are more sensitive to thaw damage.

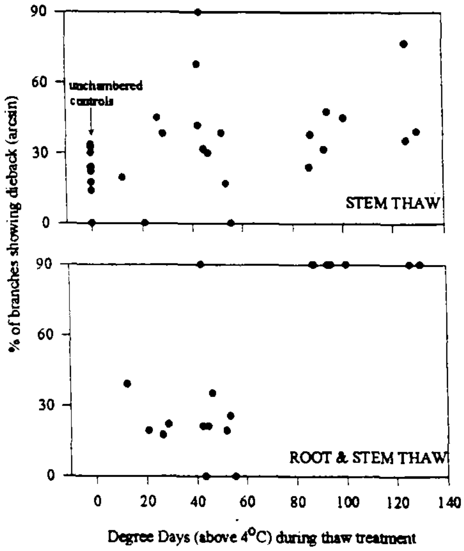
The occurrence of dieback in response to winter thaws, and losses of xylem conductivity due to winter embolisms, coupled with an inability to refill the xylem due root damage, supports the view that these processes may be key inciting factors in birch declines. These mechanisms will be discussed in relation to passed and present birch health in the Maritimes.

METHODS

This is the first time that an experimental regime has been put together to study effects of simulated winter thaws in a field plot. Twenty automated climate controlled field chambers were developed to simulate different thaw durations (a natural thaw day profile) to either just the stem or to the stem and roots of 2-3 year old trees. This was carried out in a split plot random block design of 4 blocks and 5 treatment durations. Unchambered controls were also included. Soil and air temperatures were logged every minute. After each thaw treatment, the plants in their pots were removed from the plots, and exposed to a standard refreeze treatment down to -12 °C. Shoot segments, sampled from plants on their removal from the freezer, were tested for % conducting xylem, and or xylem conductance (Sperry et al. 1988), while other shoot segments from plants that were allowed to recover in the greenhouse and had been scored for dieback were also tested. For details of methods see Cox and Malcolm (1997).

RESULTS

Winter thaws of different durations have been successfully simulated using 20 specially designed field chambers in which 2-3 y-old trees can be subjected to root and stem thaw and thawing of only the shoots. Major investigations are completed on two species, paper birch and yellow birch. Dieback has been induced in both species (figs. 1 & 2) and their response thresholds been obtained for both stem thaw and stem and root thaw conditions.



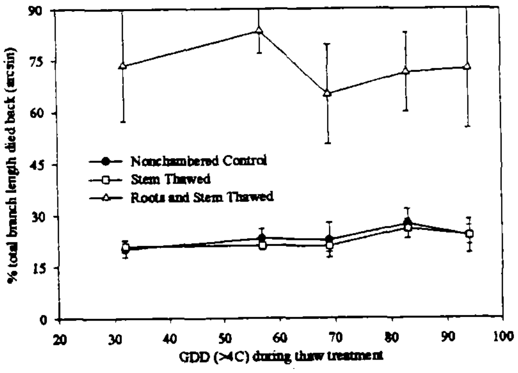


Figure 1. Dieback on paper birch treated with different durations of simulated winter thaw of known growing degree days >4 °C. Each point is one tree.

Figure 2. Dieback on yellow birch treated with five durations of simulated winter thaw of known growing degree days (GDD) >4 °C. Data are means ± 1 S.E.

Significant correlations were obtained for the relationships between % non conducting xylem (cavitated xylem) two measures of dieback (Table 1). Stem and root thaw was most damaging to both species due to root damage caused on refreezing after roots became dehardened after a critical duration of thaw, these damaged roots were unable to produce sufficient root pressure to refill the xylem cavitations accumulated prior to the thaw treatments. Yellow birch was more sensitive to thaw duration than paper birch.

CONCLUSIONS

This preliminary work has demonstrated the efficacy of an experimental approach and has generated a testable hypothesis for birch dieback (Cox and Malcolm, 1997). The implication of such a hypothesis would be that dieback in paper birch would be greatest in winters when there were large numbers of thaw/freeze events, which would maximize development of xylem embolisms, followed by a prolonged thaw, which would maximize damage to the roots, thus preventing refilling of the cavitated xylem. Such prolonged thaws prior to a -5 °C frost and their distribution are described by Braathe (1995) for 1936, 1944, 1945 and 1954; he linked them to birch dieback. These decade events may become more frequent and occur over wider areas under climate warming, a scenario which increases risk to northern adapted hardwoods generally in eastern Canada.

Table 1. Values of 'r' determined for the relationship between % stem cross section not stained (non-conducting xylem) in upper and lower sections of 5 cm segments sampled from 1 year old and 2 year old stems, and two measures of die back in same experimental plants (n).

Stem Section		All plants scored for dieback		Plants treated with thawed roots and stem	
		% of branches with dieback (arcsin)	% of total length died back (arcsin)	% of branches with dieback (arcsin)	% of total length died back (arcsin)
1 year old	Top	0.461^{**}(46)	0.516^{***}(46)	0.561^{*}(18)	0.590^{**}(18)
	Base	0.499^{***}(46)	0.563^{***}(46)	0.695^{***}(19)	0.731^{***}(19)
2 year old	Top	0.567^{***}(42)	0.597^{***}(42)	0.678^{**}(18)	0.687^{**}(18)
	Base	0.513^{***}(41)	0.526^{***}(41)	0.607^{**}(17)	0.595^{*}(17)

*P<0.05, **P<0.01, ***P<0.001, No correlation for the plants treated with just thawed stem were significant at the 0.05 probability level.

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Red Spruce - Bud and Shoot Mortality - 1993

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EXTENDED ABSTRACT

Foliage reddening of red spruce, associated with bud and shoot mortality, was widespread in southern New Brunswick in the spring of 1993 (Magasi and Hurley, 1994). Similar damage was reported from Maine, Vermont and as far west as the Adirondack Mountains in the state of New York (Manion and Castello, 1993).

Widespread damage to red spruce was common in southern and especially southeastern New Brunswick (Figure 1). Foliage reddening affected mainly the 1-year-old (1992) needle complement but, in the worst cases, caused damage to foliage as old as that produced in 1990. Those trees with more than 1 year's needle complement affected often had bud- and shoot-mortality as high as 70%. Entire crowns of red spruce had this striking damage, but the damage was more frequent and severe on the top third. Trees affected ranged in age from young to mature trees, growing within stands, at stand edges or in open areas. Red spruce in plantations and thinnings were affected as well. Often, there were many unaffected red spruce interspersed with damaged trees. Red spruce was found to be the only tree species affected.

Foliage reddening due to winter drying, ocean salt spray, roadside salt spray, etc. is common in the Maritime Provinces. Such damage is usually localized on one or more species with only the previous year's foliage affected. The current year's bud remains healthy and current shoot growth is normal. In 1993, red spruce buds and shoots were killed outright and the extent and severity of the damage does not fit the patterns of previous injury events we have recorded.

Manion and Castello (1993) noted that the red spruce damage observed in the Adirondack Mountains of New York state, was not related to elevation or aspect and referred to a similar event in 1948 reported by Curry and Church in 1952.

It seems likely, given the geographic scale of this event and the species specificity, that damage was the result of a unique and perhaps complex weather anomaly. If these particular weather conditions, capable of creating this type of tree damage, are characteristic of climate variability/climate change, it may well be that they will occur more frequently and/or with greater intensity over time.

The natural range of red spruce extends from near sea level in the Maritime Provinces southward along the Appalachian Mountains to high elevations in North Carolina and Tennessee. In the Maritimes, as a species at the northeastern edge of its natural range, red spruce is potentially vulnerable to climate variability/climate change. Therefore, we propose red spruce as a biological indicator.

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Carbon cycling in Atlantic Canadian forests in relation to climate change

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ABSTRACT

A significant body of evidence suggests that terrestrial ecosystems in northern latitudes are currently net sinks for carbon, and hence are slowing the rise of atmospheric CO_2 concentrations. Three questions arise that are relevant to the forests of eastern Canada. First, to what extent are the temperate deciduous and mixed forests of the globe (of which the Acadian Forest Region is a part) acting as a carbon sink. Second, what mechanisms are controlling the carbon cycling of these forests, and lastly, how will these forests perform as climate change progresses. Answers to these questions have global and regional implications; regionally we must be concerned with economic and ecological impacts of a changing forest resource, and future rates of global change will depend on the performance of these forests. We provide a brief literature review of the current roles of terrestrial ecosystems, particularly temperate forests, in the global carbon cycle. Then we use this outline to assess the current and future carbon sequestration by the forests of Atlantic Canada. The evidence suggests that the forests of Atlantic Canada are currently net sinks for carbon and have the potential to become stronger sinks as climate change progresses, but these conclusions are very uncertain. It is not possible to quantify the current and future sink activities with the present state of knowledge. Moreover, possibilities clearly exist for disturbances and regeneration failures to prevent the forests of Atlantic Canada from realizing its potential as a carbon sink during the upcoming period of transition to the altered climate.

INTRODUCTION

About 7 Gt of carbon are emitted annually by fossil fuel burning and tropical deforestation, approximately half of this amount remains in the atmosphere, and at least 2 Gt y^{-1} of carbon are taken up by oceans (Schimel 1995). Uncertainty persists about where the remaining 1 - 2 Gt y^{-1} of carbon are sequestered, but a large body of circumstantial evidence suggests that some, or all, of it is absorbed by the biosphere and particularly forests of the northern hemisphere (Tans et al., 1990, Sedjo 1992, Dixon et al. 1994, Gifford 1994, Sundquist 1994, Ciais et al. 1995, Denning et al., 1995). The controversy over the current role of the biosphere in the global carbon balance will continue until irrefutable evidence is gathered, but, for the sake of argument, we proceed by assuming that the circumstantial evidence is correct.

Forests have sequestered carbon because of land use changes during the past 100 years (~0.5 Gt C y^{-1}), the CO_2 fertilization effect on growth rate (~1Gt C y^{-1}) and the nitrogen fertilization effect of industrial pollution on growth rate (~0.6Gt C y^{-1}) (Schimel 1995). Canadian forests behaved as a sink primarily because a comparatively low disturbance frequency during much of the 20th century permitted the standing stock of carbon to increase (Kurz et al. 1995). No studies have focused on carbon sequestration by the forests of Atlantic Canada although estimates may be made for the processes referred to above. Land use changes, disturbance frequencies, CO_2 fertilization and nitrogen deposition will not create the same sink activity among forests in the future as they have in the past, and so future rates of carbon sequestration are uncertain. Moreover, increasing temperature, changing precipitation and increasing climate variability will only begin to impact forests as climate change progresses further. An understanding of processes involved in carbon cycling by terrestrial systems is required to (1) determine the current role of the Acadian Forest in the global carbon cycle, (2) accurately predict its future role, and (3) develop forest management plans to maximize its carbon storage while maintaining its contribution to the regional economic well-being.

CARBON CYCLE OF TERRESTRIAL ECOSYSTEMS

The basics of the terrestrial carbon cycle and its interactions with the atmosphere are shown in Figure 1. Carbon is acquired by photosynthesis and the products of photosynthesis are used for plant growth and autotrophic (plant) respiration. Parts of trees die annually, and enters the soil organic matter pool where it is decomposed by soil microorganisms. These microorganisms respire (heterotrophic respiration), thereby giving off CO_2 which is emitted to the atmosphere. Forests are sinks for carbon when photosynthesis is greater than the sum of autotrophic and heterotrophic respiration, and sources when photosynthesis is less than the sum of autotrophic and heterotrophic respiration. Autotrophic respiration consumes 40 - 70% of photosynthetic production (Ryan and Lavigne 1997). The large majority of annual plant growth in forests is by foliage and fine roots. These components are short-lived; tissues live less than one year for fine roots, and one growing season to several years for foliage depending upon whether it is a deciduous or evergreen species. Most of the carbon in short-lived components is returned to the atmosphere by heterotrophic respiration within several years of its capture by photosynthesis.

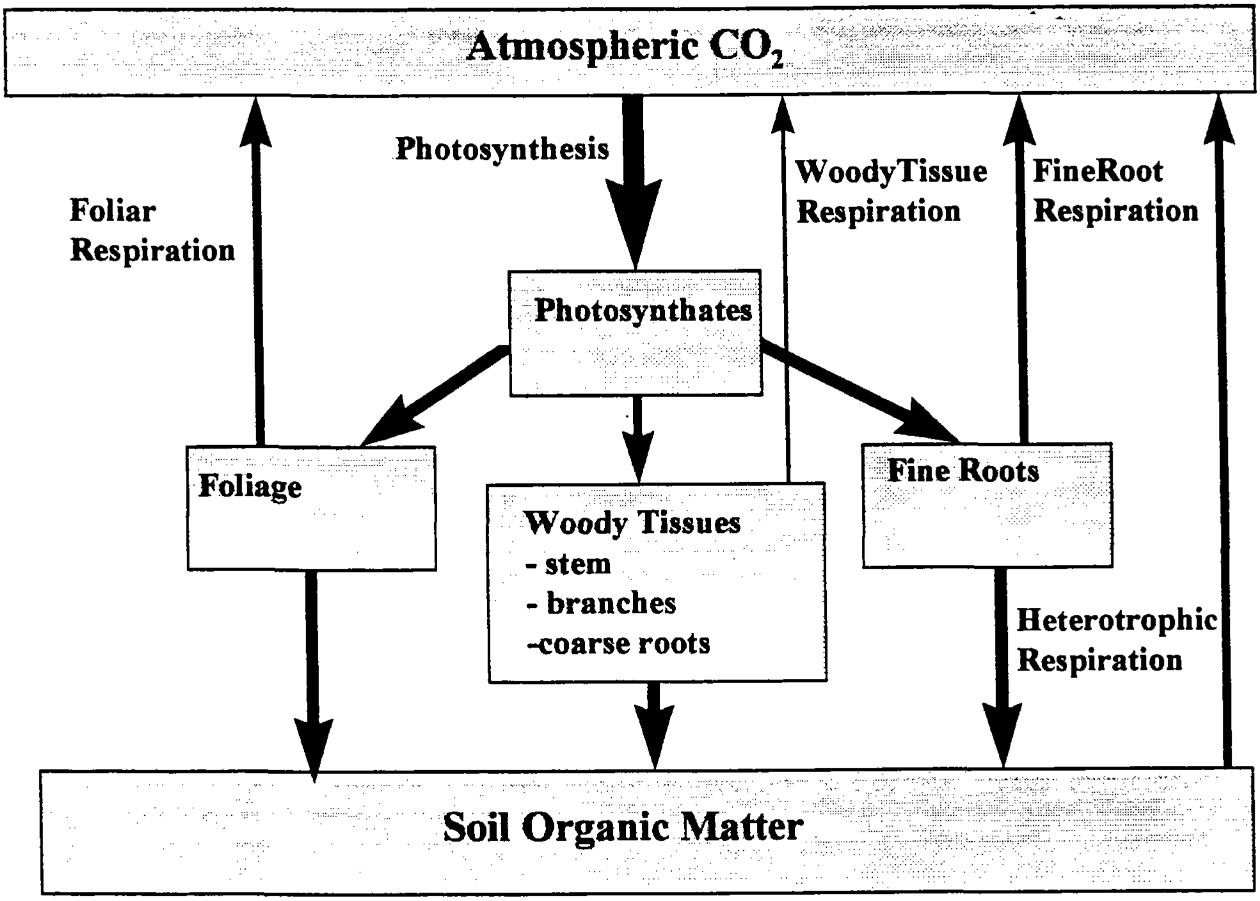

Figure 1. Processes and pools of the terrestrial carbon cycle.

It is the accumulation of carbon in the live-woody and soil components of an ecosystem that largely determines its activity as source or sink. Annual production of woody tissues represents a small proportion of annual photosynthetic uptake of carbon, and the net increment must account for shedding of branches and large roots, and for tree mortality. Large woody debris decomposes more slowly than does foliage and fine roots, and this also contributes to the capacity of forests to perform as sinks.

Carbon dioxide exchange between forests and the atmosphere depends upon characteristics of the forest, attributes of the environment, and complex interactions among these factors (Table 1). This can be illustrated with one example. The amount of foliage in the canopy is the single most important determinant of annual photosynthetic carbon uptake. Leaf area index (LAI) is the one-sided leaf area per unit of land area. Maximum LAI varies between climatic regions and within regions it varies between sites. If all else is equal, the maximum LAI is greater in humid regions than in arid regions, it is greater on nutrient rich sites than on nutrient poor sites, and it is greater on sites with higher moisture holding capacity than on sites with lower moisture holding capacity.

Table 1. Factors influencing carbon dioxide exchanges between forests and the atmosphere.

	Photosynthesis	Autotrophic Respiration	Heterotrophic Respiration
Ecosystem State	LAI species age/height	living biomass species growth rate	chemical composition of annual input size of soil organic matter pools
Site Characteristics	mineral nutrition soil moisture holding capacity slope and aspect		soil moisture holding capacity
Climate Characteristics	length of growing season incoming PAR vapor pressure rainfall air temperature atmospheric [CO_2]	air temperature rainfall	soil temperature rainfall

Maximum LAI varies between species; early seral stage communities, usually dominated by intolerant species, have lower potential LAI than do late seral stage communities dominated by shade tolerant species. LAI varies over the life of a stand; recently disturbed stands are not capable of maximizing LAI, polestage stands that exceed some minimum density and have reasonably regular spatial distribution can display the maximum LAI, while mature and overmature stands may not be able to display as much LAI as immature stands. Site characteristics influence species composition, photosynthetic properties of foliage and growth allocation patterns, thereby affecting all of the carbon flows through ecosystems. Climate and weather affect all processes, and this gives rise to substantial interannual variation in carbon cycling due to climatic variability (Goulden et al. 1995).

Rates of carbon cycle processes change predictably as forest ecosystems age. Recently disturbed stands may have high rates of heterotrophic respiration because large quantities of recently dead biomass enters the soil pool, due to the disturbance, and soil temperatures are higher without the closed canopy above. Immature stands have relatively large annual increments of woody biomass, the production of new woody biomass is approximately balanced by mortality in mature stands, and usually there are greater losses from the living woody pool in overmature stands than there is production of new woody biomass. Therefore, very young stands are often sources of carbon, immature stands sequester carbon, and mature stands are weaker sinks than immature stands. Overmature stands become net sources of carbon when heterotrophic respiration rises, because of the increasing supply of detritus, to exceed net increases in the woody biomass pool. The carbon sequestration by a forested landscape depends on the age class distribution of the forest, which is the net result of past disturbance patterns (Kurz and Apps 1994). When the highest percentage of stands are immature, the landscape is performing as a sink for carbon, but when the highest percentage of stands are overmature the landscape is performing as a source for carbon. Past disturbances significantly influence the current carbon sequestering by existing forested landscapes, and future disturbances will significantly influence carbon sequestration in the future.

CURRENT SINK ACTIVITY OF ATLANTIC CANADA FORESTS

Leaf area index of the Maritime provinces is as high as, or higher than those elsewhere in the country (Hunt et al. 1996). Moreover, LAI of the Maritime provinces is greater than that of most other regions in the global temperate forest zone. The comparatively high LAI values for the Maritime provinces exist because relatively little land is used for agriculture or settlement, and the moist climate and productive soils (for forests) provide a favourable physical environment. Hunt et al. (1996) determined that the net primary production of the Maritime provinces was as great as that of all other regions of Canada, but that some other temperate regions on the globe had greater NPP. Combining information concerning LAI and NPP, we inferred that the net primary production per unit of leaf area in the Maritime provinces was somewhat lower than that of the Great Lakes/ St. Lawrence Forest Region, and some other temperate regions in the world. We explain this by the Acadian Forest Region being cooler, and hence having shorter growing season, than the Great Lakes/ St. Lawrence Forest Region, and most other temperate regions globally. High values of NPP do not necessarily mean that the Maritimes have performed as a sink for carbon. It is necessary to consider losses from the living woody biomass to determine net change in that pool of carbon, and also to account for heterotrophic respiration before coming to conclusions about carbon sequestration rates. Hunt et al. (1996) attempted to estimate heterotrophic respiration rates but judged the results as unreliable.

Approximately half of the New Brunswick forest is mature (Figure 2), and hence is at most a weak sink for carbon, and more likely is neither sink nor source. Much more of the forest of New Brunswick is immature than is overmature. Immature forests are sinks for carbon, and overmature forests are usually net sources of carbon. Therefore, the age class distribution of New Brunswick probably favours this province being a net sink for carbon. We assume that the age class distribution of the Nova Scotia forest is similar to that in New Brunswick, and hence that it also is currently a net sink for carbon. Age class distributions are created by historical patterns of forest fires, insect outbreaks and harvesting. In contrast to national statistics which indicated that fires and insects disturbed much greater areas than did harvesting (Kurz et al. 1995), statistics for the Maritime provinces indicated that harvesting was responsible for much more than half of the annually disturbed area, and fires caused less than 1 % of the disturbance during the 1980's (Pendrel 1991). The moist climate and aggressive protection programs have minimized impacts of fire and insects. Reversion of farmland to forest has not contributed to the sink activity and influenced age class distribution in the Maritimes as it has in the northeastern United States and Europe (Dixon et al. 1994). We think that the long history of forestry activity in the region has influenced the current carbon sequestration rate more than have natural disturbances.

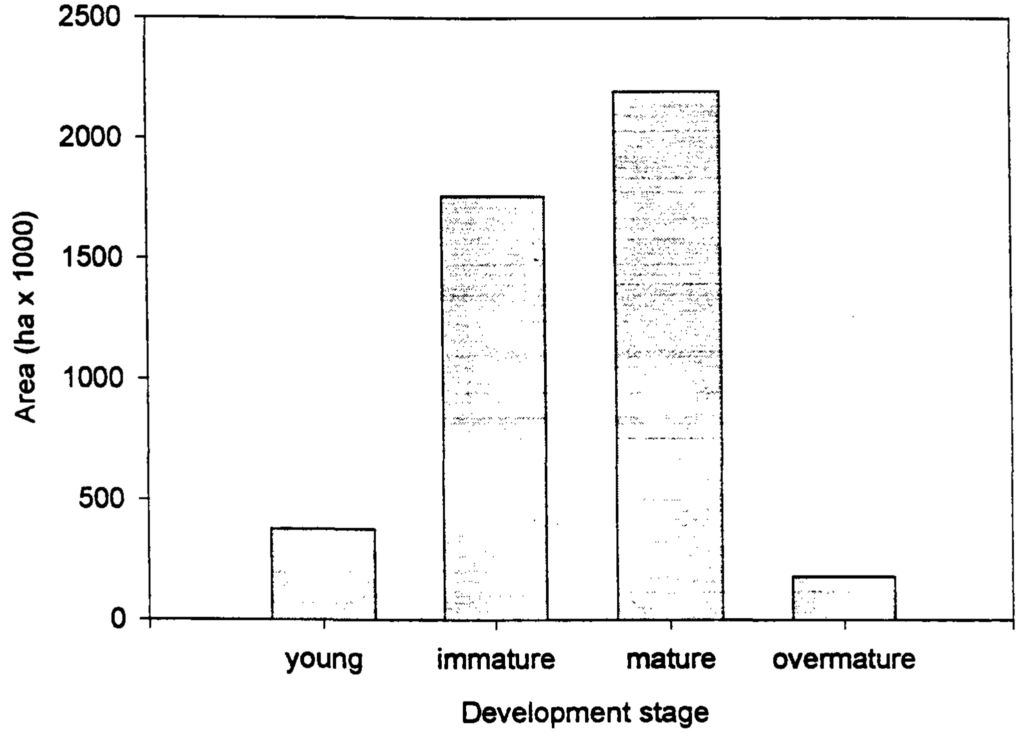

Figure 2. Age class distribution in the forests of New Brunswick in 1986 (source: Anonymous 1989).

Townsend et al. (1996) estimated annual nitrogen deposition rates of 2.5 - 4 kg N ha^{-1} for the Maritimes in 1990, an estimate similar to values measured by Hughes (1991) in New Brunswick during 1988-1990. Higher deposition rates have been measured elsewhere in Canada, but Maritime rates are about average for the industrialized regions of the northern hemisphere (Townsend et al. 1996). This nitrogen deposition increased annual sequestration of carbon by 25 - 45 g C m^{-2} (0.25 - 0.45 Mg C ha^{-1}) in the Maritimes (Townsend et al. 1996), a large response made possible because forests dominate the landscape in the Maritimes. As a result, carbon sequestration due to N deposition was nearly as great in the Maritimes as that estimated for south-central Canada and greater than most other temperate forest regions.

No studies have reported on regional variation of the CO_2 fertilization effect on sink activity of the biosphere. This effect has been estimated to contribute substantially to global carbon sequestration, but a concern exists that the response to CO_2 fertilization might be limited in ecosystems whose productivity is limited by nutrient supply (Schimel 1995). In contrast, Gifford (1994) showed that nitrogen supply would probably not limit responses to CO_2 fertilization in most ecosystems. In the absence of direct evidence we assume that the forests of Atlantic Canada have responded to increased atmospheric CO_2 concentrations by becoming stronger sinks for carbon in the same way as other northern forests.

In summary we believe that the forests of Atlantic Canada are currently performing as a carbon sink because the forest is aggrading, and growth is stimulated by nitrogen deposition and increasing atmospheric CO_2 concentration. The response is partly due to past, and current harvesting, silviculture and protection activities of forest management agencies. The sink activity of Atlantic Canada has been possible because it is predominantly forested. Our belief in the sink activity of Atlantic Canada biota is subject to a number of uncertainties, however, and the current state of knowledge does not permit quantifying the rate of carbon sequestration.

FUTURE SINK ACTIVITY OF ATLANTIC CANADA FORESTS

Future carbon sequestration by the forests of Atlantic Canada will depend on the extent to which the regional climate changes, the levels of harvesting that are sustained, frequency and severity of insect outbreaks, the frequency and types of other disturbances, and the level of forest protection. With the possible exception of harvesting, the future of these factors affecting carbon sequestration are very uncertain. Moreover, carbon sequestration during the immediate future, say the next 100 years, could depend upon the rate of environmental changes, and this is clearly uncertain. If the climate warms to that expected for an atmosphere with doubled CO_2 concentration then the vegetation in the Maritimes will change from being cool temperate and moist boreal vegetation to being moderate temperate and cool temperate vegetation (Rizzo and Wiken 1992). This is a so-called 'steady state' prediction that is intended to indicate the general direction and magnitude of change and not to predict the precise rate of change, or the exact magnitude of the change. The prediction of Rizzo and Wiken (1992) indicates that eventually the forests of Atlantic Canada will have the capacity to store more carbon than they can at present, but it does not predict when this will be the case nor how the forest will perform during the transitional period.

Forest productivity should increase substantially with increases in atmospheric CO_2 concentrations. The extent of this productivity gain, however, is difficult to predict because of uncertainty about interactions with rising temperature, and future rates of nitrogen deposition (Thornley and Cannell 1996). For example, rising temperature might partially offset responses to increasing CO_2 concentration by increasing moisture stresses and nitrogen losses from soils, or effects of rising temperature and increasing CO_2 concentration might depend on the richness of the site, the rate of nitrogen deposition, and change in rainfall regime. If the temperature rise is modest in Atlantic Canada, then it should not negatively impact the responses to rising CO_2 and continued nitrogen deposition. The level of harvesting will probably maintain a forest age class distribution that is capable of performing as a sink for carbon. Wood products sequester approximately half of the harvested carbon for extended periods of time (Kurz and Apps 1994), and so harvesting leads to more long-term sequestration than do other types of disturbances.

Two aspects of possible environmental changes will affect the shorter-term forest response in the Maritime provinces. The first is the rate of change. The second is the increase in climatic variability associated with these changes. The rates of environmental change will be particularly important, because rapid changes might exceed the capacity of some processes, such as species migration, to keep pace (Smith and Shugart 1993). If species migration does not keep pace with environmental change then regeneration failure may occur more frequently following harvesting and natural disturbances. Changes in the climate might affect the patterns of natural disturbances, such as the frequency of insect outbreaks and the species of insects causing major damage to forests. These disturbances might reduce forest health and thereby prevent increases in forest productivity induced by changing climate while they are recovering, or they might create new challenges for forest protection.

Climatic variability will also affect forest growth and carbon sequestration. Disturbances caused by unusual weather have occurred occasionally in the past and these types of disturbance could occur more often as climate change progresses. The dieback among sugar maple trees during the 1980's is an example. Robitaille and colleagues (Bertrand et al. 1994, Robitaille et al. 1995, Boutin and Robitaille 1995) replicated the dieback experimentally by preventing the accumulation of snow around the roots of trees. They showed that the snowpack protected roots from being exposed to damaging cold temperatures. Trees suffering fine-root mortality experienced crown dieback to tree death the following spring. Because this sort of disturbance is not catastrophic, like fire or clearcut logging, it is more difficult to quantify the extent of areas affected. These sorts of disturbance reduce forest health and prevent forests from being as productive as might be expected from climatic norms. More climatic variability is expected as climate change continues, and therefore, midwinter thaws that melt snowpacks and expose root systems to unusually cold soil temperatures might occur more frequently in the future than they have in the past.

Much of the current understanding about forest functioning suggests that the capacity of the forest of Atlantic Canada to sequester carbon should increase as climate warming and atmospheric change progresses. However, it is not possible to predict the magnitude of the increase in sink activity to be expected because the degree of environmental change is uncertain, and the understanding of forest functioning is incomplete. Also, the predictions of increased sink activity do not take into account the possibility of disturbances such as dieback, or the possibility of regeneration failures. These would prevent the forest of Atlantic Canada from achieving its potential as a sink for carbon during the transitional period.

DISCUSSION

Forest responses to climate warming are predicted to differ among regions of the country (Rizzo and Wiken 1992). For example, forests are predicted to disappear from much of the area currently covered by dry, boreal forests, causing northern parts of Prairie provinces and northwestern Ontario to become sources of carbon because of climate change, whereas the Atlantic provinces are predicted to become stronger sinks. All predictions of source/sink activity are subject to much uncertainty, and the regional disparities in predicted responses argues strongly for reducing uncertainties on a regional basis.

There is much uncertainty globally about how processes involved in primary production will respond to increasing atmospheric CO_2 concentrations, in combination with rising temperature, changes in precipitation, and uncertain nitrogen deposition rates (Kirschbaum et al. 1994, VEMAP 1995, Thornley and Cannell 1996), and these concerns are relevant to predicting responses by forests in Atlantic Canada. It is very uncertain how patterns of growth allocation to foliage, fine roots, and woody-tissues will change, but it is clear that sink strength depends on these patterns (Medlyn and Dewar 1996). Uncertainty exists concerning whether carbon storage in soils will increase of decrease as climate changes, and whether more nitrogen or less nitrogen will be made available to roots. In addition to these concerns about production processes, there are other concerns about forest health and vigor as climate change progresses. We identified a concern that crown dieback among sensitive species might occur more frequently in the future. The possibility of more frequent regeneration failures in the future has also been recognized. If forest health and vigor are reduced by climatic variability and the rate of climate change, then Atlantic Canada forests will be incapable of taking advantage of the more favourable conditions for primary production processes. The uncertainties about production processes and forest health need to be addressed so that future carbon sequestration rates can be predicted with confidence.

It is clear that climate change will create new challenges for forest management. In fact present-day forest resource managers should already plan with the uncertainty associated with climate change because the response to activities, such as harvesting, planting, thinning and forest protection will be sensitive to changes in the physical environment during the next 100 years.

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Carbon Cycling in Atlantic Canadian Forests In Relation to Climate Change: Outline of a New Project.

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ABSTRACT

A significant body of evidence has accumulated to suggest that terrestrial ecosystems in northern latitudes are currently net sinks for carbon, and hence are slowing the rise of atmospheric CO_2 concentrations. Three questions arise that are relevant to the forests of eastern Canada. First, to what extent are the temperate deciduous and mixed forests of the globe (of which the Acadian, and Great Lakes and St. Lawrence Forest Regions are a part) acting as a carbon sink. Second, what mechanisms are controlling the carbon cycling of these forests, and lastly, how will these forests perform as climate change progresses. Answers to these questions have global and regional implications; regionally we must be concerned with economic and ecological impacts of a changing forest resource, and future rates of global change will depend on the performance of these forests. We provide a brief literature review of the current roles of terrestrial ecosystems, particularly temperate forests, in the global carbon cycle. Then we outline two functional frameworks, one at the stand level and one at the landscape level, for evaluating forest performance in relation to climate change. Critical processes in forest responses to climate change in this region of the country are identified. Finally we describe a new project that will investigate some of the key issues.

APPENDIX K

EXTENDED ABSTRACTS

EXTREME EVENTS

Analysis of Climate Variability in Ocean Waves In the Northwest Atlantic Ocean

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INTRODUCTION

During the past 5-6 years or so there have been a number of extreme storm events on either side of the North Atlantic Ocean. In 1990, extreme waves crushed the superstructure of the drilling platform Ekofisk in the North Sea. In 1992, a "3000-year return period storm" severely damaged west Norwegian coastal settlements, while in 1993 the master of Ocean Weather Ship "Mike" reported that in 35 years experience in the Norwegian Sea he had never before encountered such severe wave conditions.

In the western Atlantic, on Halloween day 1991, a moored buoy south of Nova Scotia reported the highest waves ever measured by an instrument (17.3 m significant wave height, with maximum waves estimated at more than 31 m). On March 15, 1993 the "Storm of the Century" produced record high waves at buoys along the U.S. and Canadian east coasts, including a significant wave height of 16.3 m at the buoy south of N.S. Then in September 1995, Hurricane Luis hit the liner *Queen Elizabeth II* with estimated 29 m maximum waves, corroborated by a nearby buoy which reported significant waves of 17 m, and estimated maximum waves exceeding 30 m.

These events caused many questions to be asked. Foremost among these were: (1) Is the climate changing?; and (2) Are storms becoming more frequent? more severe?

The offshore oil and gas industry adopted a wait-and-see attitude; the insurance industry in Europe raised premiums.

These questions were also being addressed at an international meeting of scientists and offshore interests in Reykjavik Iceland in March 1993. As a result of the Reykjavik meeting the WASA (Waves and Storms in the Atlantic) project was established with European Community funding and the participation of external experts. At the same time a Canadian program (smaller) was established in parallel with WASA.

WAVE DATA

The first major concern in looking at the long-term trend and variability in ocean waves was that there were no long term reliable *wave* data sets. Ships definitely did not provide the necessary observational quality, nor the stationary location. Drilling platform data were of better quality, but were spatially and temporally extremely restricted. Moored buoys provided the best source of quality data, and in some locations along the U.S. continental margin, included more than 10 years of data. However, this period was still far too short for analysis of trend and variability, and in Canadian waters the length of the buoy record was far less than that.

As a result of the lack of reliable observed data, Canada and other countries turned to wave hindcast models to provide the data for engineering design as well as climate trend and variability analysis. A recently produced CD-ROM contains the wind and wave data for the 82 most severe wave-producing storms in Canadian Atlantic waters from 1957-1995.

The hindcast quality versus measurements is very good for storms, as has been shown in many hindcast evaluation studies (Cardone and Swail, 1995). Recent hindcasts for the North Sea, using newly-developed state-of-the-art techniques, show virtually unbiased results with a scatter index for a 6-year continuous hindcast of 17%, over a wide range of sea states. Similar results have been consistently obtained for other ocean basins, including the northwest Atlantic off Canada.

A caveat to hindcast quality statement relates to the modelling of very high sea states, i.e. significant wave height greater than 12 m. There seems to be a tendency for all classes of wave model to underpredict these extreme storms (Cardone et al., 1995). This may be due to mesoscale effects (jet streaks), wave model deficiencies, scaling relationships of the wind in fully developed seas, or a combination of the above. Overall, however, hindcasting has provided a very good estimate of storm waves, using a *consistent* methodology.

ANALYSIS OF THE TREND AND VARIABILITY OF STORM WAVES OFF THE EAST COAST OF CANADA

Examination of the storm wave data for 1957-95 off the east coast of Canada shows some interesting results. On the Scotian slope, for example, there is an apparent trend towards increasing wave heights in storms when a simple linear trend line is fitted to the entire data record (see Figure 1). This apparent trend is also evident in data from other points along the Scotian Shelf extending to the southwest Grand Banks. However, on the northern Grand Banks near the Hibernia location there is no trend at all, and farther to the northeast in the Labrador Basin, the trend, if any, is towards reduced storm waves. On the Scotian Shelf the apparent increasing trend in wave heights is accompanied by a similar increase in wind speed, while on the Grand Banks the wind speed trend line was as flat as that for the waves. This is in contrast to the findings of Bacon and Carter (1991) in the eastern Atlantic, who found a trend in mean wave heights over a 20-year period, with no corresponding increase in wind speeds.

Further examination of the Scotian slope data reveals that the apparent trend to increased wave heights over the 40-year period is entirely due to 2 or 3 events in the past 5 years. A linear trend line fitted to the 1957-90 data alone shows no trend, or even a slight decrease in storm wave heights (Figure 1). This points out an inherent danger in applying simple linear trend analysis over a long time span which may contain significant interdecadal variability. It is not evident that these 2 or 3 recent events fall outside the natural variability of waves over the past century. Resio et al. (1995) showed, at least in a qualitative sense, that similar large waves may have occurred in the early part of this century. Preliminary WASA results (WASA, 1995) showed similar findings.

EXTENDING WAVE CLIMATE VARIABILITY ANALYSIS TO THE CENTURY TIME SCALE

In order to further investigate wave climate variability on a century time scale a 40-year continuous wave hindcast is presently being carried out at AES, based on the NCEP (U.S. National Centers for Environmental Prediction) global re-analysis for 1957-96 (BAMS reference). The objective of this "Reference Wave Climatology for the North Atlantic Ocean" project is: "To produce a high-quality, homogeneous, long-term wind and wave data base for assessment of trend and variability in the wave climate of the North Atlantic Ocean. The results of the wave hindcast will be related to large scale features of the general circulation and via a downscaling approach used to infer wave conditions back to 1900.

The reference wave climatology will cover the domain from the equator to 75°N, from 20°E to 80°W; the grid spacing will be 0.625° latitude by 0.833° longitude, giving 9076 sea grid points. The time period will be 1957-1996. The wave hindcast will use a 3rd generation deep water wave model. All wind and wave fields will be archived at every grid point each 3 hours for 40 years on CD-ROM; wave spectra will be archived at a few selected points.

The key to the wave hindcast will be the wind fields used to drive it. The NCEP re-analysis wind fields should provide an unbiased forcing field over the 40-year period, using all available data and a consistent numerical model for the complete period of analysis. This should remove the problems encountered by WASA in attempting to use archived Fleet Numerical Meteorology and Oceanography Center (FNMOC) wind fields; the inhomogeneities encountered in that data set were so severe that removal of them was found to be impossible.

The results from this reference wave climatology will give us, finally, the information we need in order to properly investigate the spatial changes in the wave climate over the past 40 years, and through the downscaling approach, to investigate variability over the past century.

CONCLUSIONS AND GENERAL OBSERVATIONS

- There is no discernible trend in magnitude or frequency of extreme wave heights on the east coast of Canada, but there is significant inter-annual variability (as was found in WASA).

- Any apparent trend is all caused by two or three recent events on Scotian shelf (since 1991); this illustrates the real danger in using simple linear trend analysis over a long time period which contains cyclical behaviour.
- The extreme events of the early 1990's on the Scotian shelf may represent a change in large-scale circulation patterns, but are not inconsistent with events experienced earlier in the century.
- The NCEP re-analysis project, and the Canadian reference wave climatology project deriving from it, are critical components of wave trend and variability research.
- A statistical downscaling approach is required to extend trend and variability analyses to 1900.
- It is essential that we maintain (or enhance) the moored buoy network and validate offshore platforms for long term wind/wave monitoring.
- Wave hindcast models (including wind aspects) still need work in relation to extreme conditions; mesoscale effects may be important.
- The tropical storm population must be revisited in light of Hurricane Luis experience.
- The use of historical synoptic weather maps creates a bias towards more extreme conditions in recent years due to increased observational densities, satellite observations and improved numerical models.
- Experimental results from strap-down accelerometers shows waves are underestimated by about 10%; "maximum" waves reported until at least 1997 are incorrect and should be avoided.

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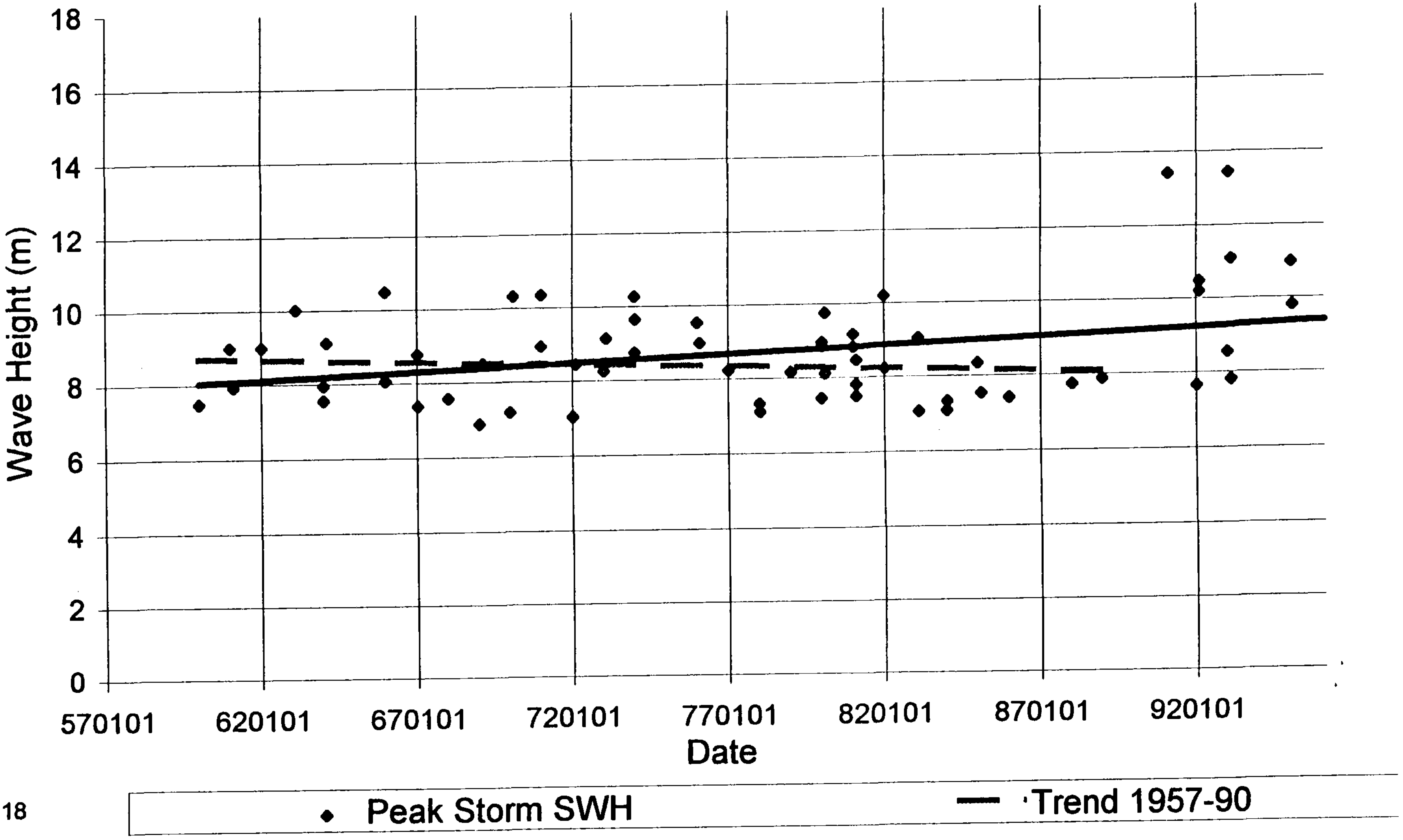
Figure 1. Variability of Scotian Slope Storm Waves



APPENDIX L

EXTENDED ABSTRACTS

POSTER AND OTHER PRESENTATIONS

Satellite Measurement of Sea-Surface Temperatures and the Study of Ocean Climate

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ABSTRACT

Satellite measurements of sea surface temperatures may be obtained from The Physical Oceanography Archive Center of the Jet Propulsion Laboratory. We have used their product of weekly global 18 km gridded multichannel sea-surface temperatures (MCSST) derived from the daytime NOAA Advanced Very High Resolution Radiometer (AVHRR). The data is available as a global set (2048x1024 pixels) and covers the period October 1981 to present. Each data file contains a weekly map of gridded SST with a spatial resolution approximately 18 km by 18 km at the equator. A buoy match-up data set was used by NOAA in computing calibration coefficients used to calculate sea surface temperature. Data were provided to us in UNIX Tar format on 4mm tape - and may also be downloaded from an ftp web site - http://podaac-www.jpl.nasa.gov. There is no charge.

The MCSST product consists of weekly composites; for each grid point, the average of all MCSST measurements for one week are computed. We have extracted and archived a time series of SST maps for the Scotian shelf. The weekly data sets have been combined into monthly averages based on the value for each point and the number of measurements for that week. (Values and number flags from the JPL set). To assist in visualizing the region we have overlaid coastline and bathymetry plots.

Three long term open ocean monitoring sites provide a time series of ship based temperature measurements. These sites are occupied more or less monthly and a measurement of a one meter depth temperature is obtained. Measurements since 1981 have been collected with calibrated profilers (Conductivity-Temperature-Depth). Location of each of these sites and the coordinates of the nearest MCSST pixel are given below.

Station:	Latitude	Longitude	MCSST	Latitude	Longitude
Prince 5	44.95	66.81		44.82	66.62
Station 27	47.55	52.58		47.46	52.38
Emerald	43.88	62.88		43.95	62.93

Time series of monthly temperature measurements have been obtained from the MCSST product and compared with the coincident ship measurements. The Prince 5 and Station 27 sites are relatively close to shore and for those sites we selected the nearest pixel for which the satellite obtained data. For each of the three stations there is good agreement between the two data sets with no temperature offset. The three data sets were then combined to form a total of 205 duplicate measurements. There is no apparent difference between the two data sets.

Regressions - In-situ and MCSST

Station	Slope	Error	Intercept	Error +/-	Std. Dev.	No.(a)	No.(b)
Prince 5	1.04	0.03	-0.03	0.2	1.03	94	98
extrapolated	1.08	0.03	-0.2	0.24	1.24	126	131
Emerald	1.03	0.03	-0.3	0.4	1.45	45	124
Station 27	1.05	0.03	0.1	0.3	1.45	66	71
All three	1.04	0.02	0.08	0.15	1.27	205	

No(a) - coincident measurements
No(b) - MCSST measurements

We have also calculated a time series of annual average temperatures for these sites. There is good agreement between data sets when the averages are calculated using only those months for which there are duplicate measurements.

The MCSST data are incomplete, some months having no measurements. There are no data for the first 15 months from October 1981 through 1982. From 1983 to 1996 (13 years) we have a possibility of 156 measurements. We are able to enhance the number of measurements by utilizing data from pixels adjacent to the site pixel. This was done for the Prince 5 site by calculating the regression with each of two adjacent pixels which had data and then calculating the temperature for months with a missing value. This increased the number of MCSST measurements from 98 to 131 or about 1/3. These enhanced data improved the calculation of the annual average temperature at Prince 5.

We now intend to examine the night time MCSST data set to determine if the temperature measurements are as accurate as the day time values. There may be a problem with the night time values because there will be no data for cloud cover. If these values are useable, this may further increase the number of available measurements. There are already a greater number of measurements at the Emerald site from the MCSST data than from the insitu observations.

We are encouraged that the MCSST data appears to constitute a time series of monthly temperature measurements for the Scotian Shelf which is equivalent in accuracy to the much smaller data set of ship measurements. We intend to further investigate the agreement between ship and MCSST values.

We thank Brian Petrie for useful discussions and for providing the data base of ship measurements.

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Ecosystem response to late-glacial climate change in the Maritimes, Canada

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EXTENDED ABSTRACT

Some of the first observations of late-glacial fossils in Atlantic Canada were made by Abraham Gesner during his geological survey of New Brunswick in 1840. Continuing research, especially over the past decade, has greatly enriched paleontological study of late-glacial ecosystems in the region. Nineteenth century records documented mostly marine faunas, primarily molluscs, echinoderms, arthropods (Miller and McAlpine, 1991), whales, seals and walrus (Miller, 1990), with little emphasis on understanding ecosystems. However, the introduction of radiocarbon dating, paleoclimate analysis using stable isotopes, and refined models of late-glacial climate and glaciation have made it increasingly possible to study not only species occurrence, but ecosystem response to climate change. Over the past few decades terrestrial records of pollen and plant macrofossils (Cywnar *et al.*, 1994; Mayle, *et al.*, 1993a; 1993b; Mayle and Cwynar, 1995; Mott, 1994), and arthropods (Miller, 1995; 1996; in press-a; Miller and Morgan, 1991; Walker *et al.*, 1991; Wilson *et al.*, 1993) have added to the overall picture. Changes in vegetation, and to a lesser extent arthropods, are reasonably well known during late-glacial times (Figure 1). The vegetation of the deglaciated landscape by herb tundra, then shrub tundra and finally forest is well documented at a number of sites in Atlantic Canada. The corresponding development of components of the arthropod fauna is beginning to be understood. In the beetle fauna for example the establishment of a subarctic fauna, followed by northern boreal and boreal species has been recorded across Nova Scotia and in parts of New Brunswick. Records are sparse or non-existent for other terrestrial animal groups. Only a few records exist for mammals, birds, reptiles or amphibians in older Wisconsinan deposits.

Among the most significant contributions to understanding climate variability and climate change in Atlantic Canada have been studies showing evidence of the younger Dryas event in North America (Mott *et al.*, 1986; Stea and Mott, 1989; Mott and Stea, 1993; Mott, 1994). The Younger Dryas is likely the most significant rapid climate change in the Late Wisconsinan, and is a main focus of the International Geosphere Biosphere Programme Past Global Changes (PAGES) project. During the Younger Dryas temperatures, at least in the North Atlantic region, may have decreased by 5 to 7°C in as little as a decade (Lowe *et al.*, 1994; Broecker, 1995). The Younger Dryas event is among the best analogues for studying future rapid climate change, of the magnitude predicted under a doubling CO_2 scenario. Data gathered from buried organic sites in Nova Scotia and New Brunswick provide stratigraphic interpretation, radiocarbon chronology, pollen and arthropod records that together present a picture of late-glacial environments from about 14,000 to 10,000 years BP. Combined with recent summaries of marine invertebrate (Miller and McAlpine, 1991; Dyke *et al.*, 1996) and vertebrate faunas (Harington and Occhietti, 1988;

Harington *et al.*, 1993; Miller, 1990; in press-b), a more comprehensive picture of late-glacial paleoenvironment and biotic response to climate change is emerging (Figure 1).

The record of late-glacial, and to a lesser extent, interglacial, climate and ecosystem components is well represented in Atlantic Canada. Considering the region's geographic importance in unravelling questions about the Younger Dryas event, efforts should continue to be made to exploit proxy climate records archived in the terrestrial and marine sediments. Many of the fossil sites are vulnerable to natural erosion or are only temporarily exposed through construction activity. While protecting the sites may not be practical, sharing information and samples is important. Some sites might deserve protection as reference sections. Much of the late-glacial paleo-record is dominated by palynological research generated by university and Geological Survey of Canada scientists. Rare specimens of less studied groups are often found in museums, where decades of collecting have accumulated significant records. Use of these collections will help fill in knowledge gaps. However, research funding, especially at regional museums, is scarce. NSERC funding, for example, does not generally support museum based researchers. For example, AMS radiocarbon dating of fossil walrus is costly, but is the only way to build a chronology of the response of walrus populations to climatic change (Miller, in press-b). Multi-sector, interdisciplinary perspectives of climate variability and climate change and partnerships among government departments, academic institutions and the private sector should attempt to bring together and support all partners.

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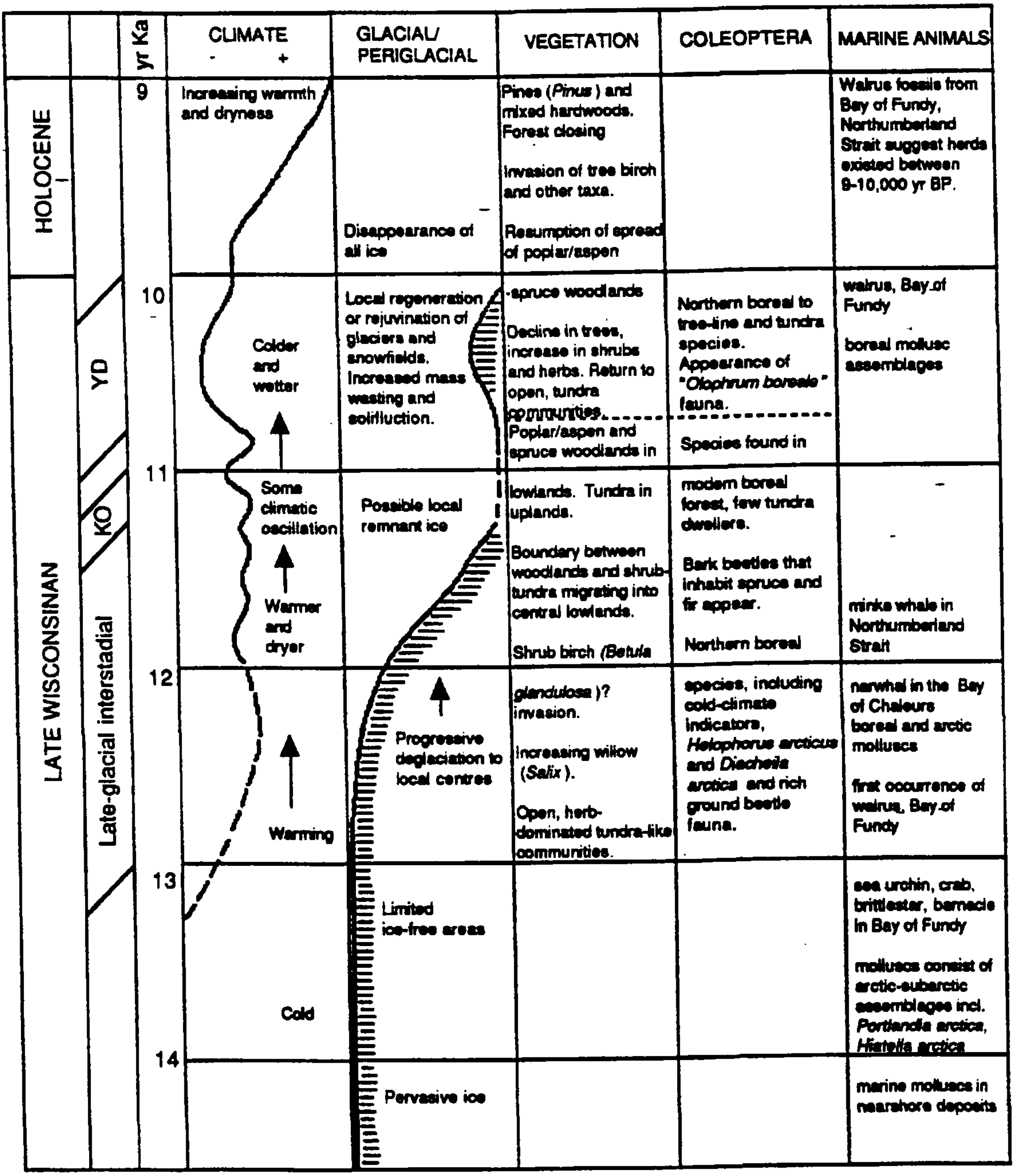
Fig. 1. Wisconsinan late-glacial environmental change template for Nova Scotia, Canada, from IGCP-253 North Atlantic Seaboard Programme. Climate and vegetation data redrawn from Mott (1994) supplemented with Coleoptera and marine animal evidence. YD = Younger Dryas. KO = Killarney Oscillation.



Cooling in the North Atlantic Region in relation to Secular Climate Change

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ABSTRACT

Trends of surface air temperature (updated to 1995) for stations in and around the extra-tropical North Atlantic Ocean continue to confirm our earlier conclusion (Morgan and Pocklington, 1995) that cooling, rather than warming, has prevailed in the region during the latter half of this century. Trends at stations in northwest Europe - some with records going back to the eighteenth century - additionally show that such warming as has occurred in the present century is not exceptional in an historic context. The North Atlantic region is not participating in the same manner as continental regions with respect to climate change in the Northern Hemisphere.

INTRODUCTION

The Working Group I (WGI) of the Intergovernmental Panel on Climate Change (IPCC) in the Summary for Policymakers of their Second Assessment Report (p.4) stated that "... analyses of meteorological and other data over large areas and over periods of decades or more have provided evidence for some important systematic changes." (Houghton *et al.* 1996). For some time now we have looked for important systematic changes in the North Atlantic region (Morgan *et al.* 1994, Morgan and Pocklington 1995). In this study we focused upon surface air temperature trends on islands in the North Atlantic Ocean (N of 32 deg. N) and from stations on land adjacent to the ocean in northwest Europe and eastern Canada. These enable us to examine whether the propositions concerning systematic warming contained in the latest IPCC report are applicable to our region.

DATA AND METHODS

Monthly mean surface air temperature records for individual stations were initially obtained from World Data Center-A as an updated global grid point surface air temperature anomaly data set (NDP - 020/R1 (Rev. 1990)). This is the land-surface air temperature data base developed by P.D. Jones and colleagues (Jones *et al.* 1994) and used by them to produce the global and hemispheric anomaly time-series featured in the IPCC Climate Change reports. We updated our stations to the end of 1995 using "Monthly Climatic Data for the World", the official publication of the World Meteorological Organization, as supplied by the National Climatic Data Center (Ashville, NC, U.S.A.). We calculated the annual means as simple averages of the 12 monthly values, and the annual anomalies as departures from the long-term mean at each station.

In the Figures, annual anomalies in deg.C (y-axis) are plotted against year (x-axis) beginning in 1890, or earlier where possible. For stations that had data only within this century, a uniform starting year of 1900 was adopted. The trend of annual means is shown by the lighter line; the five-year running mean by the heavier trend-line.

When individual station data needed to be combined into regional sets (e.g. for Paris - Budapest), the latest WMO "Standard Normal" period of 1961-90 was used to calculate the individual station anomalies; these were then combined by simple averaging.

RESULTS

Atlantic Canada (Fig 1: Charlottetown, P.E.I.; Sable Is., N.S.; St. John's, Nfld.)

The most obvious feature of these records - a warming trend from the 1920s to the 1950s - was substantial, amounting to ca. 2 deg. C at Sable Island, the location least likely to suffer any anthropogenic heating ("urban warming"). All stations had their warmest decade in the 1950s. The cooling that followed was interrupted from the mid-70s to the mid-80s, but resumed through the latter half of the 1980s to the present. All stations are cooler now (in the mid-90s) than they were in the 1890s at the beginning of the instrumental record.

Labrador (Fig 2: Cartwright (Labrador), Nfld.)

The data-base for this sub-region is slight prior to 1940. Nevertheless, the pattern of trends at in the second half of this century is not dissimilar to that in Atlantic Canada. Warming to a peak in the 1950s was followed by cooling to the present. This is also consistent with stations in west Greenland (Godthab) during the same period.

Greenland (Fig 3: Godthab; Angmagssalik)

An increase in temperature through the first decades of this century culminated in the 1930s as the warmest decade in both west and east Greenland. Since that time both coasts have cooled. In the west, to the lowest values in the record at Godthab; in the east, to a minimum in the 1970s followed by warming to the mean at Angmagssalik.

Iceland (Fig 4: Reykjavik; Akureyri)

Two cold decades at the beginning of this century were followed by a rapid rise through the 1920s to the 1930s (warmest decade at Akureyri) and 1940s (warmest decade at Reykjavik). Subsequent cooling until the late-60s at Akureyri and early-80s at Reykjavik was followed by warming to date. At Reykjavik the temperature is still cooler than it was at the beginning of the instrumental record; at Akureyri, it is warmer than 100 years ago, but still well below its values at mid-century.

North Atlantic Islands : polar (Fig 5: Bjornoya; Jan Mayen; Svalbard)

The first two of these island stations in the polar North Atlantic (N of 70 deg. N) share two cool periods - in the 1940s and the 1960s. Though the latter was followed by warming that continued to the present, current temperatures are no warmer than at the start of the record. Further to the north, Svalbard shares the feature of a cold decade in the 1940s, but warmed through the 1950s and 1970s to a peak in the 1980s, since when it has cooled to the present.

North Atlantic Islands : boreal (Fig 6: Lerwick; Stornoway; Thorshavn)

These island stations in the boreal North Atlantic (S of 70 deg. N) all have short series begun only in the 1930s. All cooled to a minimum in the 1980s, since when they have warmed but are still cooler than at the start.

North Atlantic Islands : subtropical (Fig 7: Ponta Delgada (Acores))

At these latitudes in the subtropical North Atlantic (S of 45 deg. N) the range of interannual temperature variation (+/- 1 deg.C) is much less than it is to the north. Even so, the pattern of warming through the first half of this century to a maximum in the 1940s followed by cooling to a minimum in the 1970s, then warming to date, is remarkably similar.

Norway (Fig 8)

According to Hanssen-Bauer *et al.* (1996), the temperature series for the North Atlantic Climatological Dataset (NACD; includes Norway) during the period 1891-1990 show generally the same periods of warming and cooling as the series of mean temperatures for the northern hemisphere (Jones *et al.* 1994). However, the main period of temperature increase in their series is 1920-1935 in most regions and there is no significant increase during recent decades in the northern parts of their area of study. This confirms our findings as shown in the trends for Tromso and Vardo.

United Kingdom and Ireland (Fig 9)

The time-series at Plymouth (U.K.) during this century shows general warming to the 1940s, interrupted an interval of cooling to a minimum in the 1960s, followed by warming to date. Were this the only data available, we would deduce a steady warming at this location. But a longer record is available: it shows that from the 1860s to the 1890s temperature decreased, and that temperatures today are no higher than they were at the beginning of the series.

At the Valentia Observatory off southwest Ireland, the time-series is similar to the one at Plymouth. From the 1860s to the 1890s temperature decreased, then increased from the 1890s to a peak in the 1940s that has yet to be surpassed by recent warming which has not yet exceeded the initial values.

Northwest Europe (Table 1; Fig 10)

In this region where the first instrumental measurements of temperature were made, time-series extending back over more than 200 years can be found at selected locations (Table 1). The warmest decade on record for the majority of these stations was not the 1980s, but either earlier in this century, or in the late 18th century. Notably, no station had its warmest decade in the 19th century, but all stations had their coldest decade in the 19th century.

Figure 10 is a composite of the data from those stations in Table 1 that lie in a narrow latitudinal belt (47 - 49 N, 2 - 20 E) across northwest central Europe. This is a continental region that should be showing warming to an unprecedented degree. It does not. Though the warmest individual year in the record was in the 1990s, this decade so far is no warmer than the 1940s, and little warmer than the 1770s. What is clear is that the 19th century was, with the exception of the 1820s, well below the long-term average. Thus any time-series beginning in the mid-to-late 19th century and continuing to the present day (as the global and hemispheric time-series shown by the IPCC do) cannot fail to show an overall warming to date. This warming, however, is not exceptional when the full > 200-year record is considered, being comparable in rate and magnitude to the cooling that occurred earlier.

CONCLUSIONS

Surface air temperatures around the northern North Atlantic are currently close to (or below) their long-term means, and below the values reached in the warmest decades of this century. In northwest Europe, the warmest decade in the record at a majority of long-term stations came before the 1990s, in many cases before this century. Global and hemispheric mean surface air temperature time-series for the period 1850-1995 are commonly used to support the argument that the world is warming at a rate - and to a degree - not seen before. This thesis is poorly supported by our analysis of time-series of surface air temperatures.

ACKNOWLEDGEMENTS

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Table 1 : Stations in northwest Europe with a > 200-year record

Station / Nation	record from	no. years	Warmest Decade	Coldest Decade
BASEL* / Switzerland	1755	236	1940s	1880s
BERLIN / Germany	1730	265	1980s	1810s
BUDAPEST* / Hungary	1780	215	1790s	1880s
COPENHAGEN / Denmark	1768	227	1980s	1830s
GENEVA / Switzerland	1753	242	1940s	1850s
HOHENPEISSENBERG* / Germany	1781	214	1790s	1880s
KREMSMUENSTER* / Austria	1767	224	1780s	1830s
MUNICH* / Germany	1781	214	1790s	1880s
PARIS* / France	1764	231	1770s	1880s
PRAGUE / Czech Republic	1771	224	1790s	1850s
ST.PETERSBERG / Russia	1753	242	1770s	1890s
STOCKHOLM / Sweden	1756	239	1930s	1860s
TRONDHEIM / Norway	1761	219	1930s	1830s
VIENNA / Austria	1777	218	1980s	1850s

* stations on the PARIS - BUDAPEST line (Fig. 10)

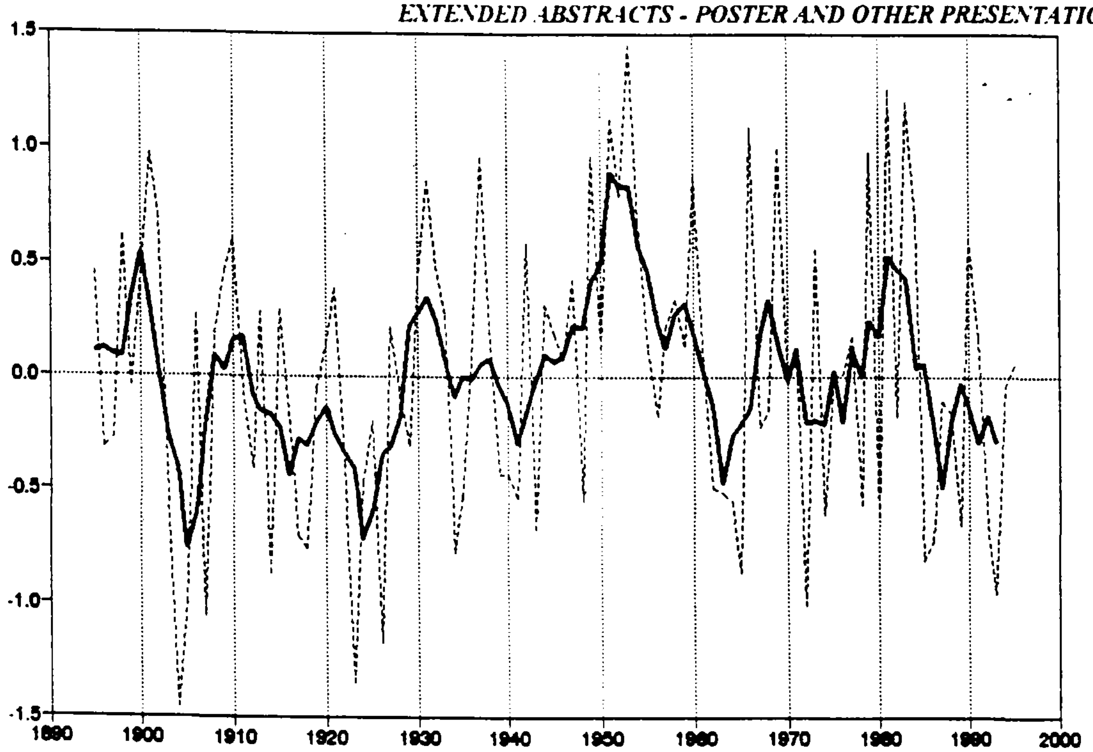

Figure 1 (a) Charlottetown, P.E.I.

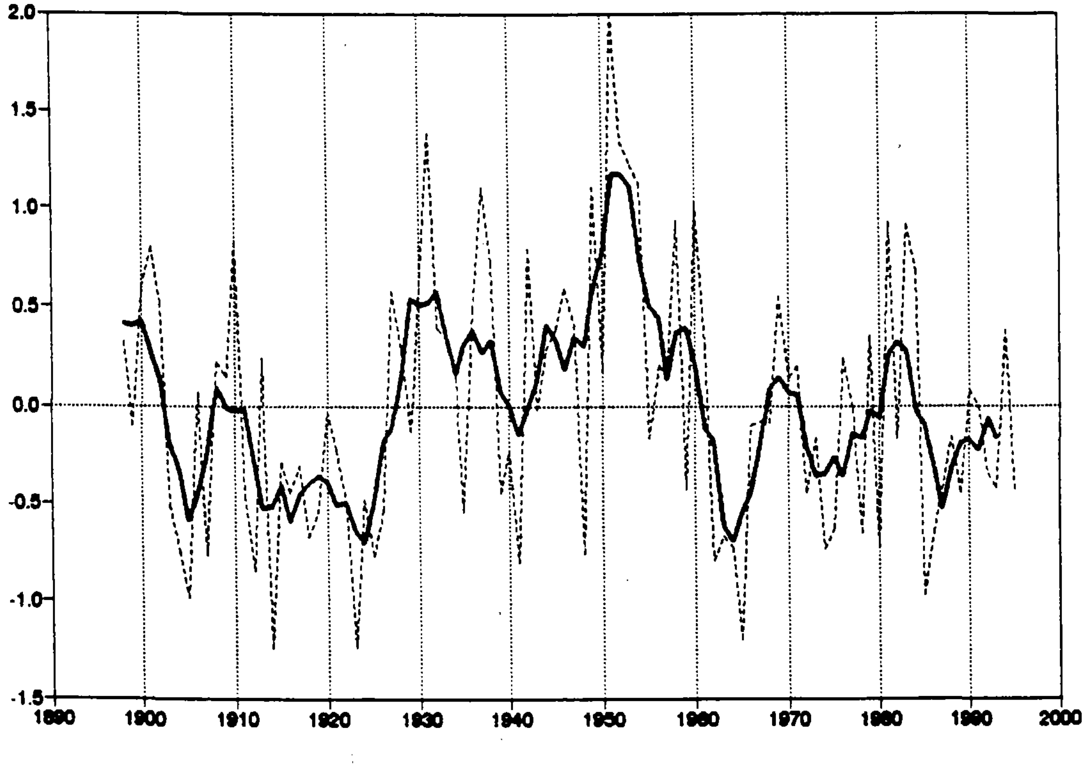

Figure 1(b) Sable Is., N.S.

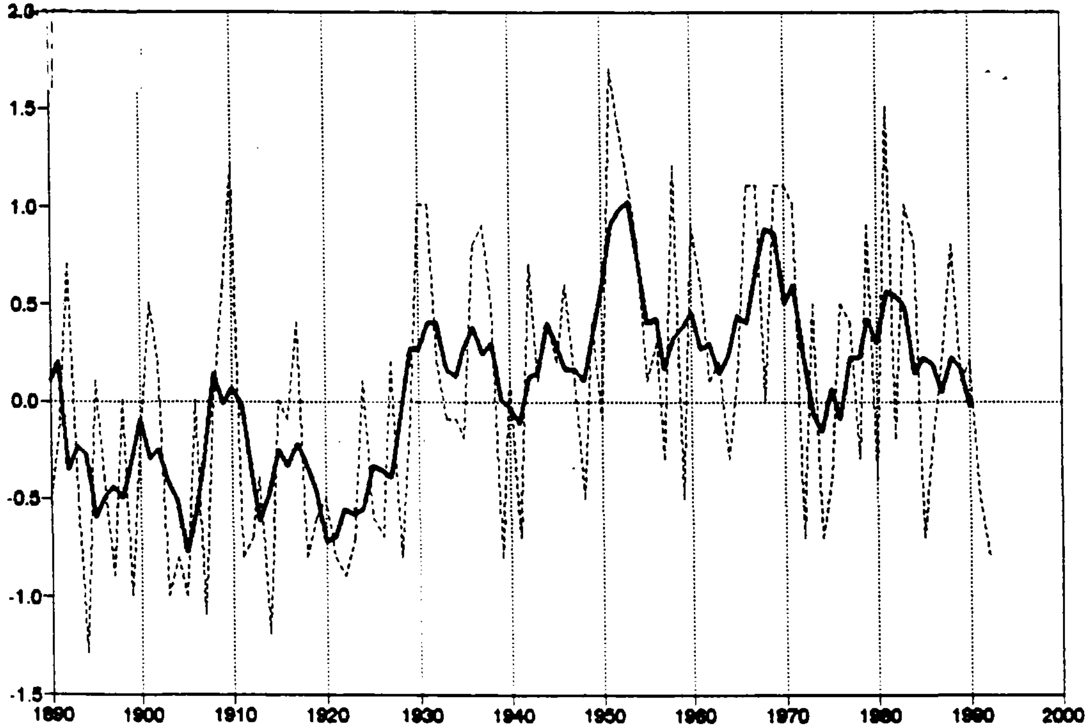

Figure 1 (c) St. John's, Nfld.

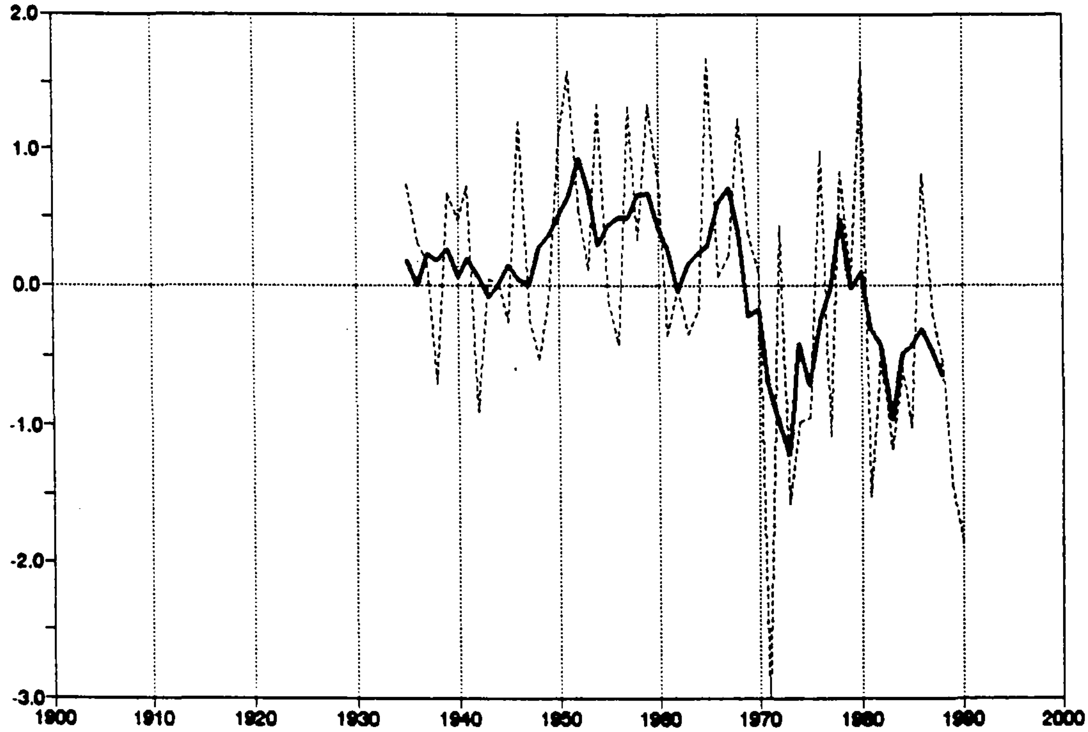

Figure 2 Cartwright (Labrador), Nfld.

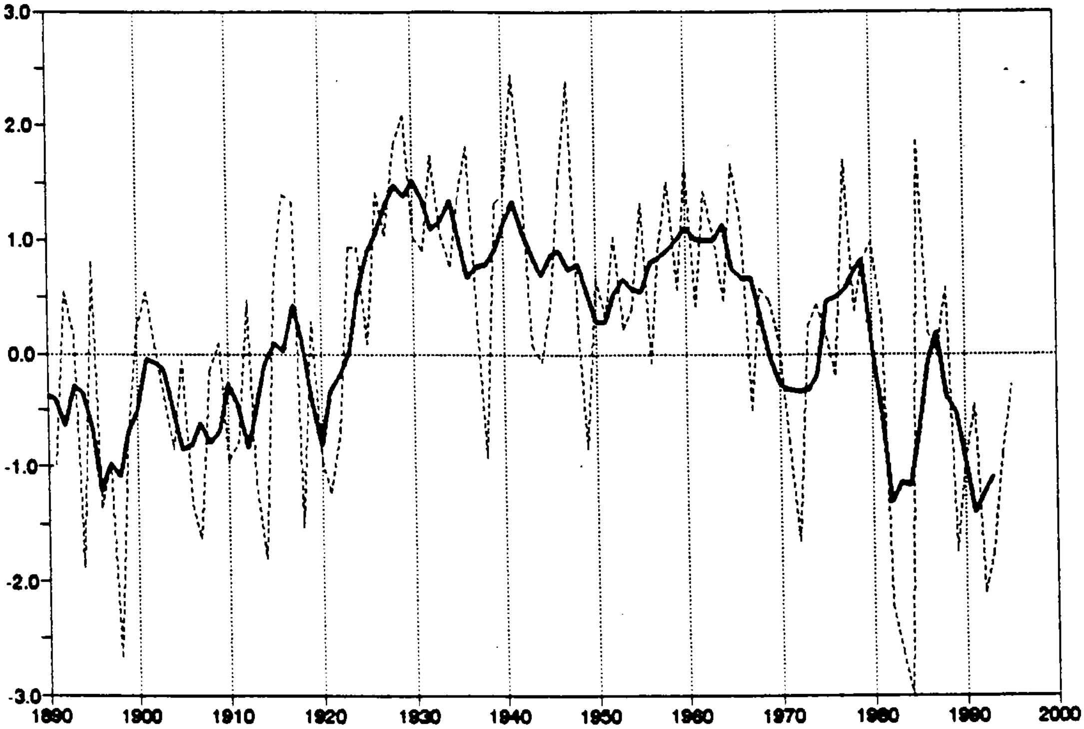

Figure 3 (a) Gothab

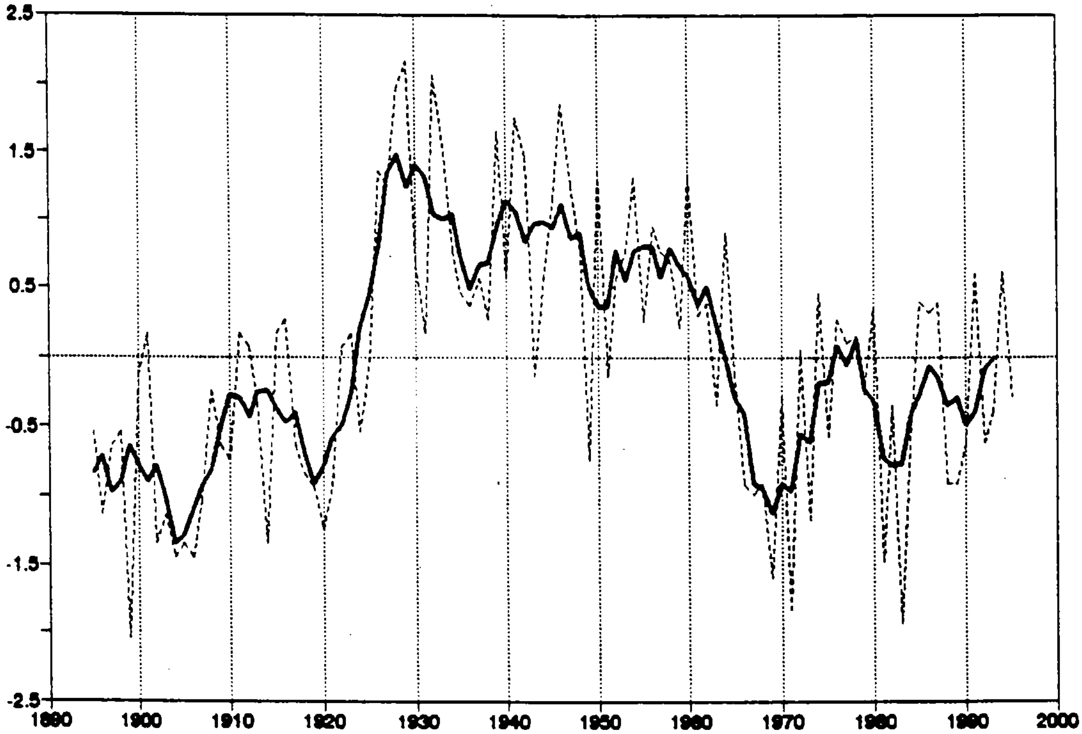

Figure 3(b) Angmagssalik.

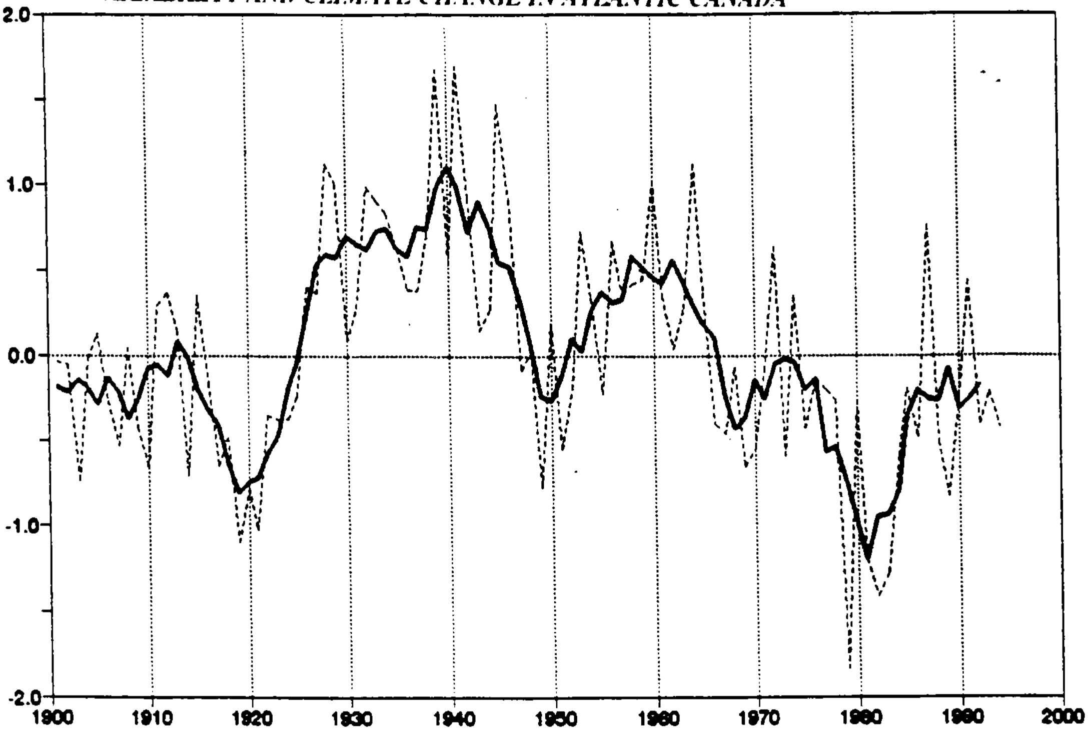

Figure 4 (a) Reykjavik

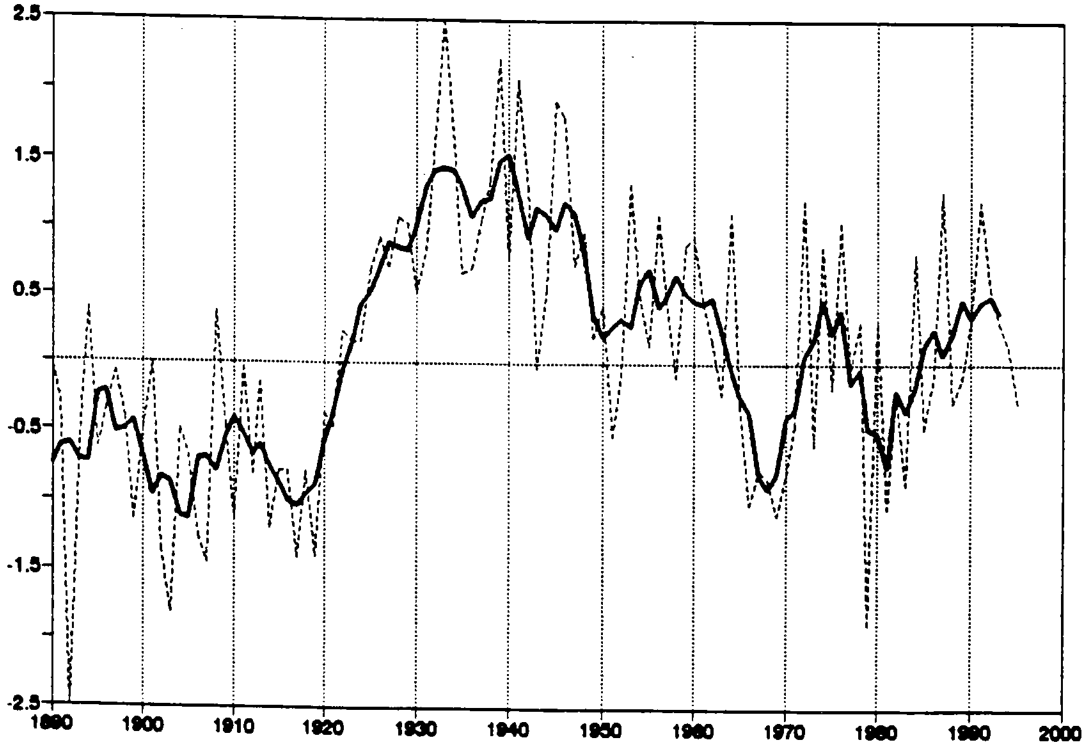

Figure 4(b) Akureyri.

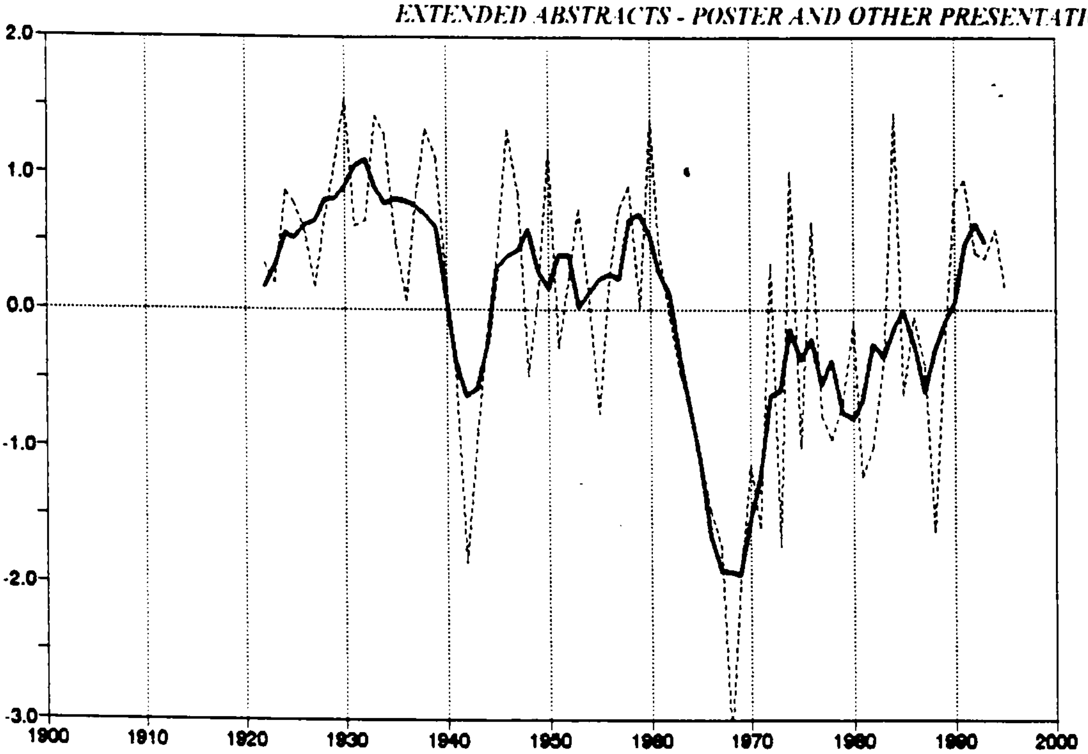

Figure 5 (a) Jan Mayen.

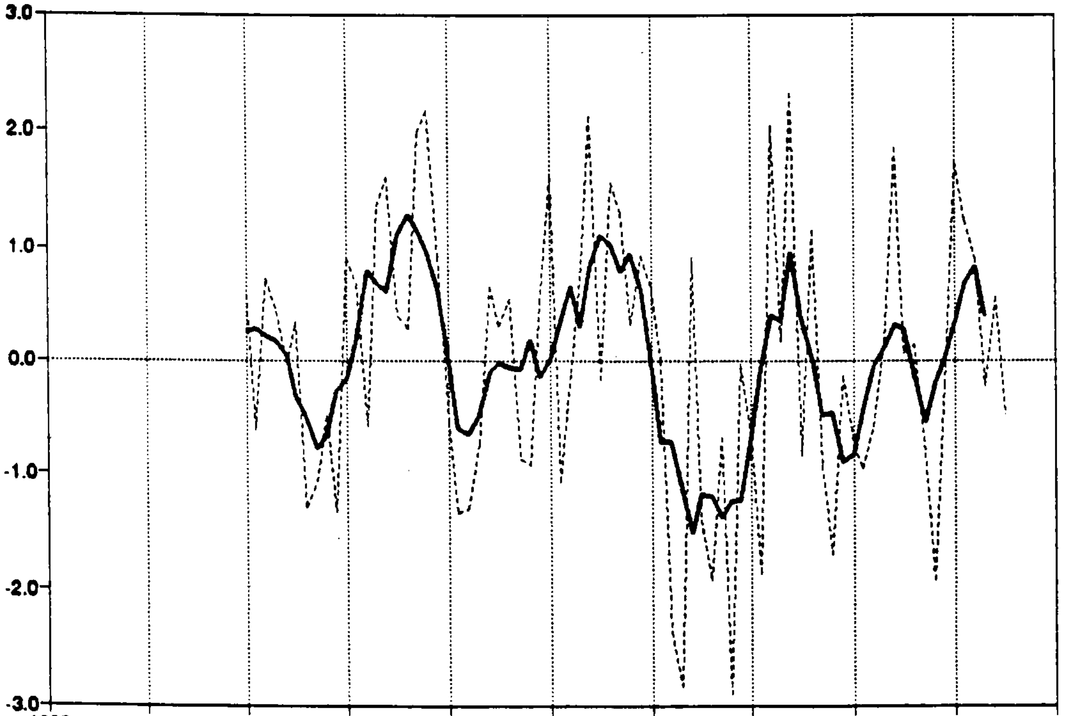

Figure 5(b) Bjornoya.

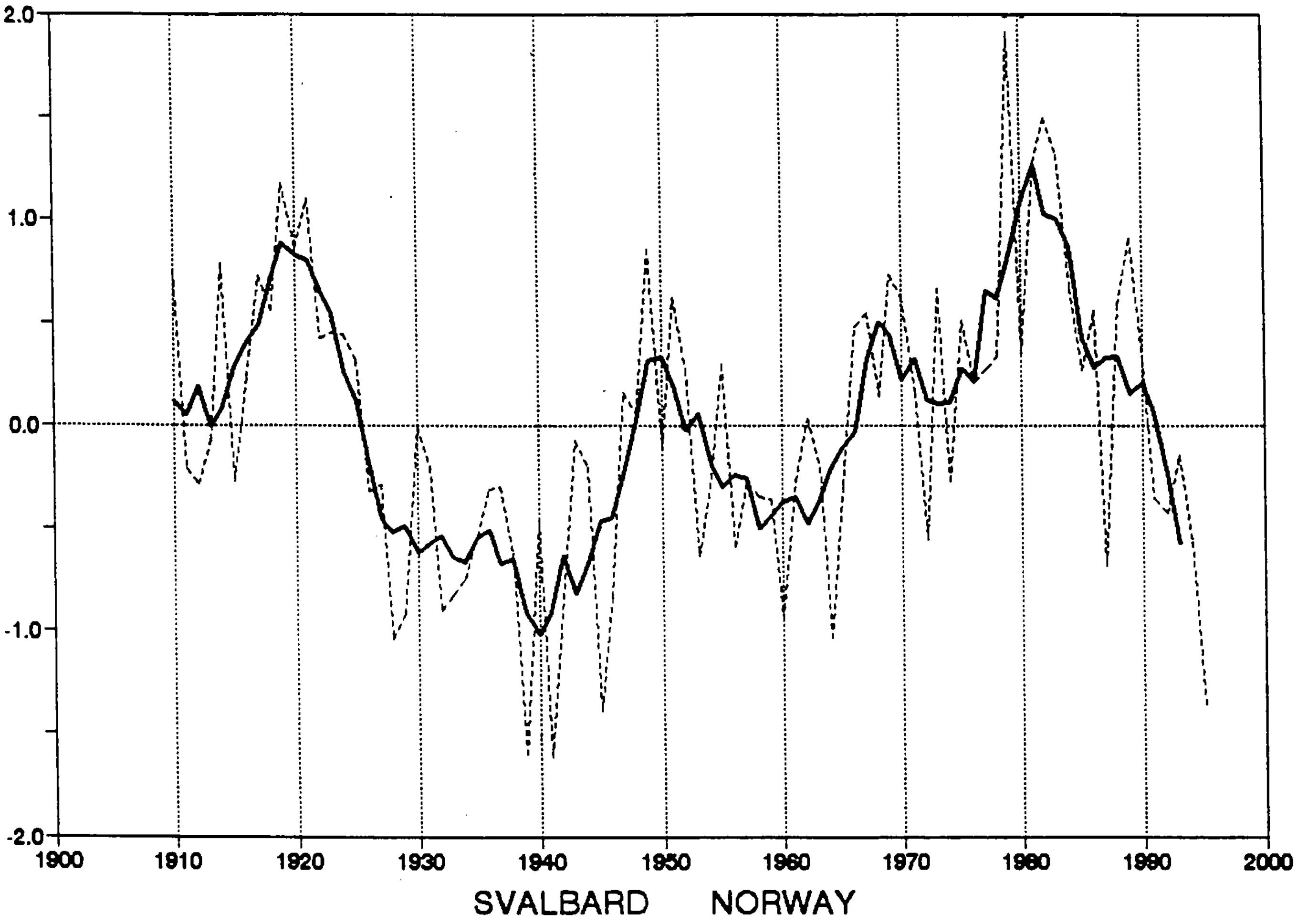

Figure 5 (c) Svalbard.

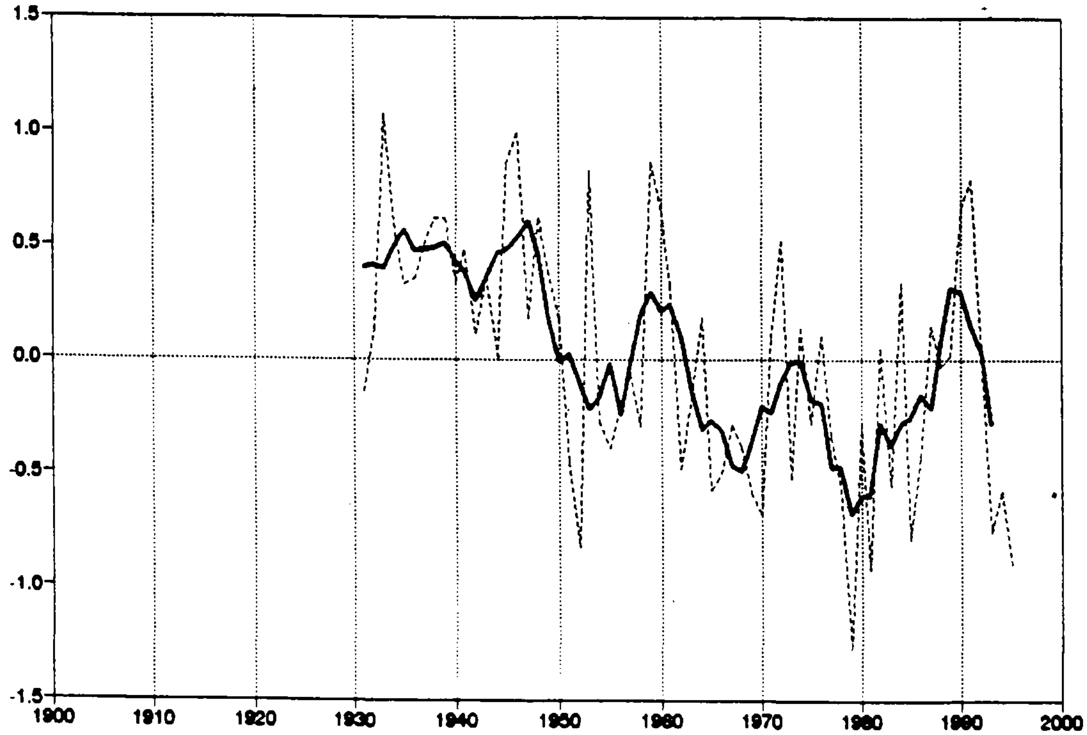

Figure 6(a) Thorshavn (Færoes).

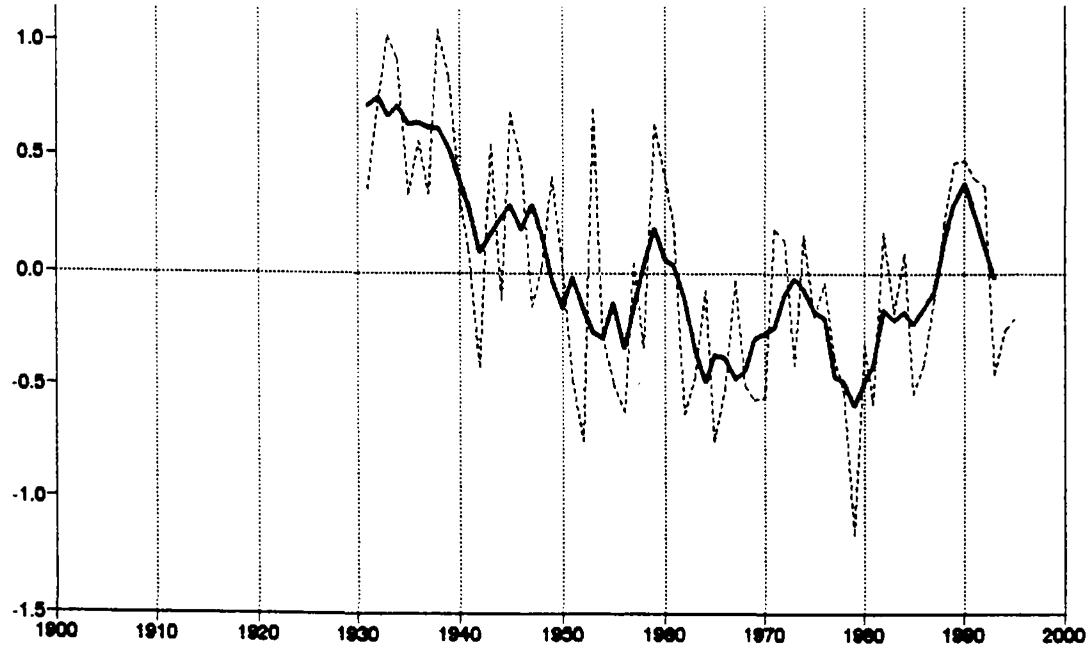

Figure 6(b) Lerwick (Shetland).

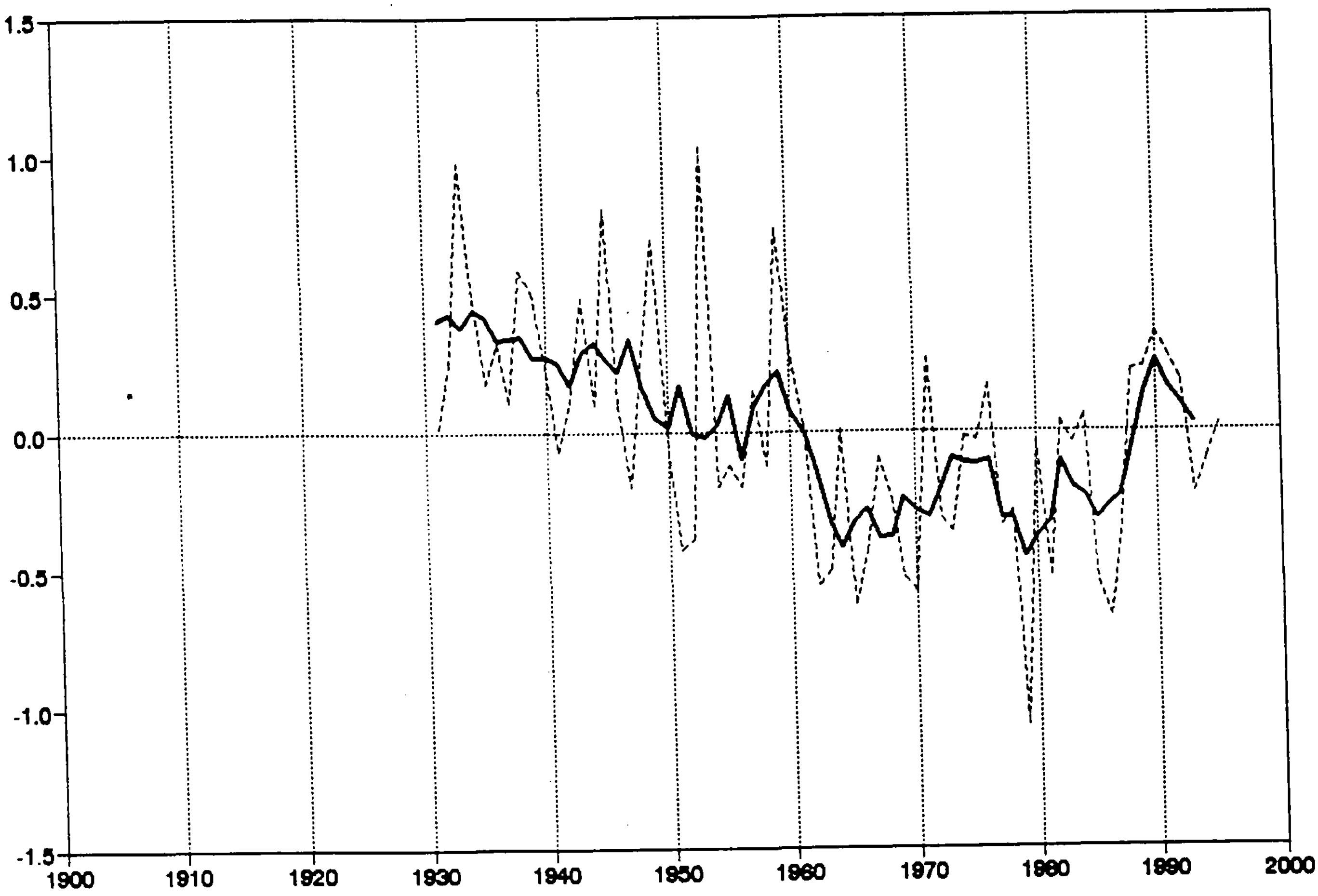

Figure 6(c) Stornoway (Hebrides).

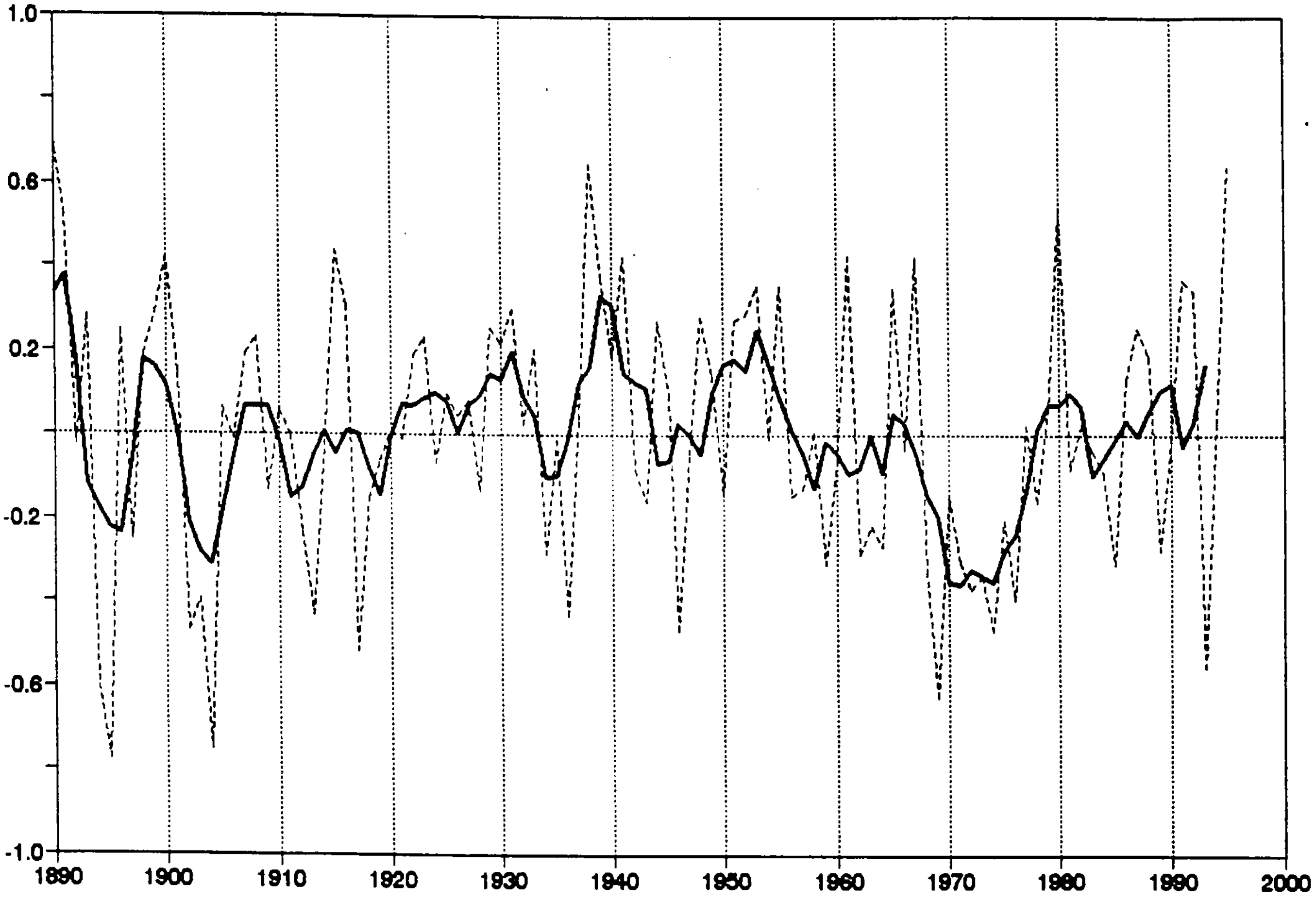

Figure 7 Ponte Delgada (Azores).

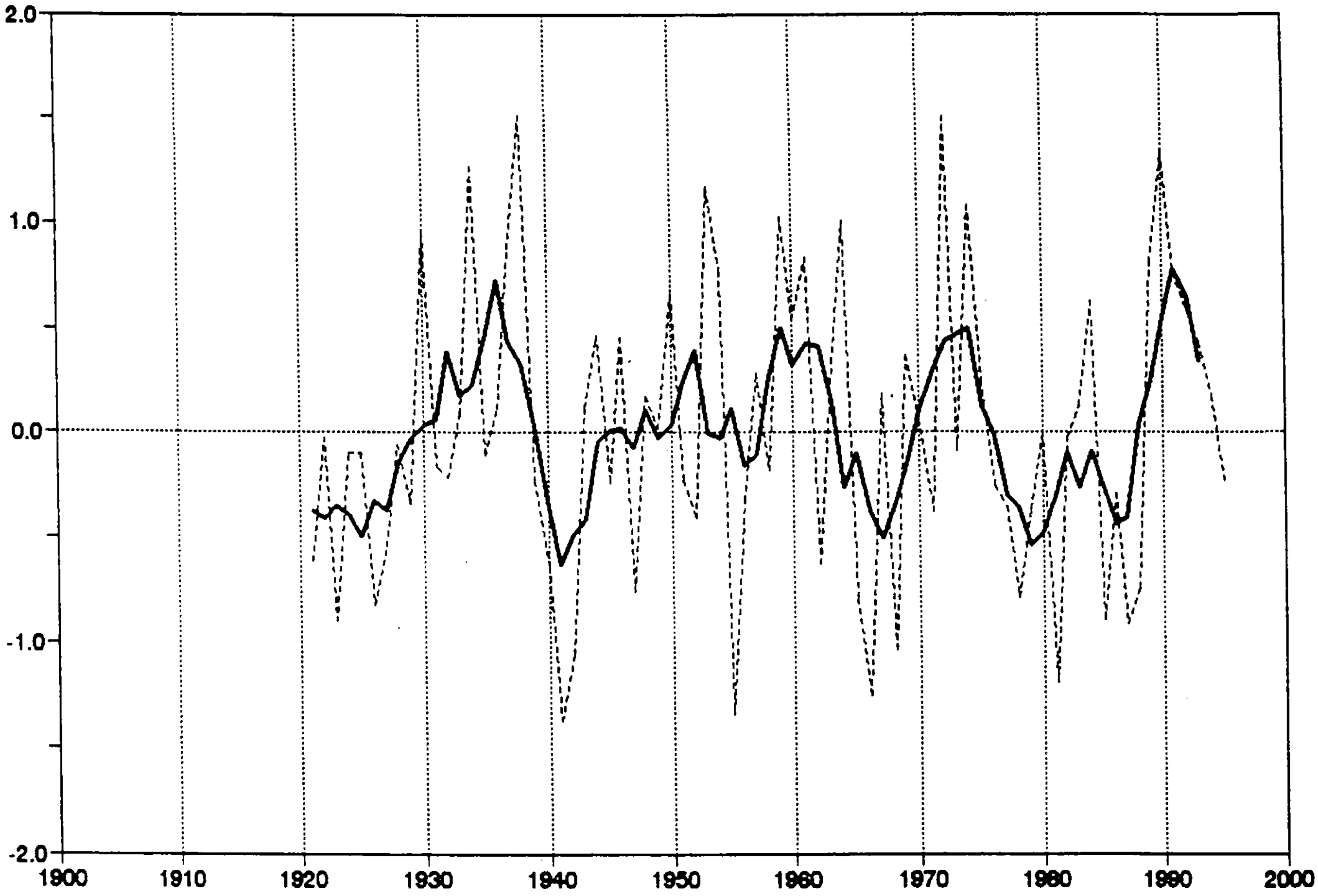

Figure 8(a) Tromso/Langnes (Norway).

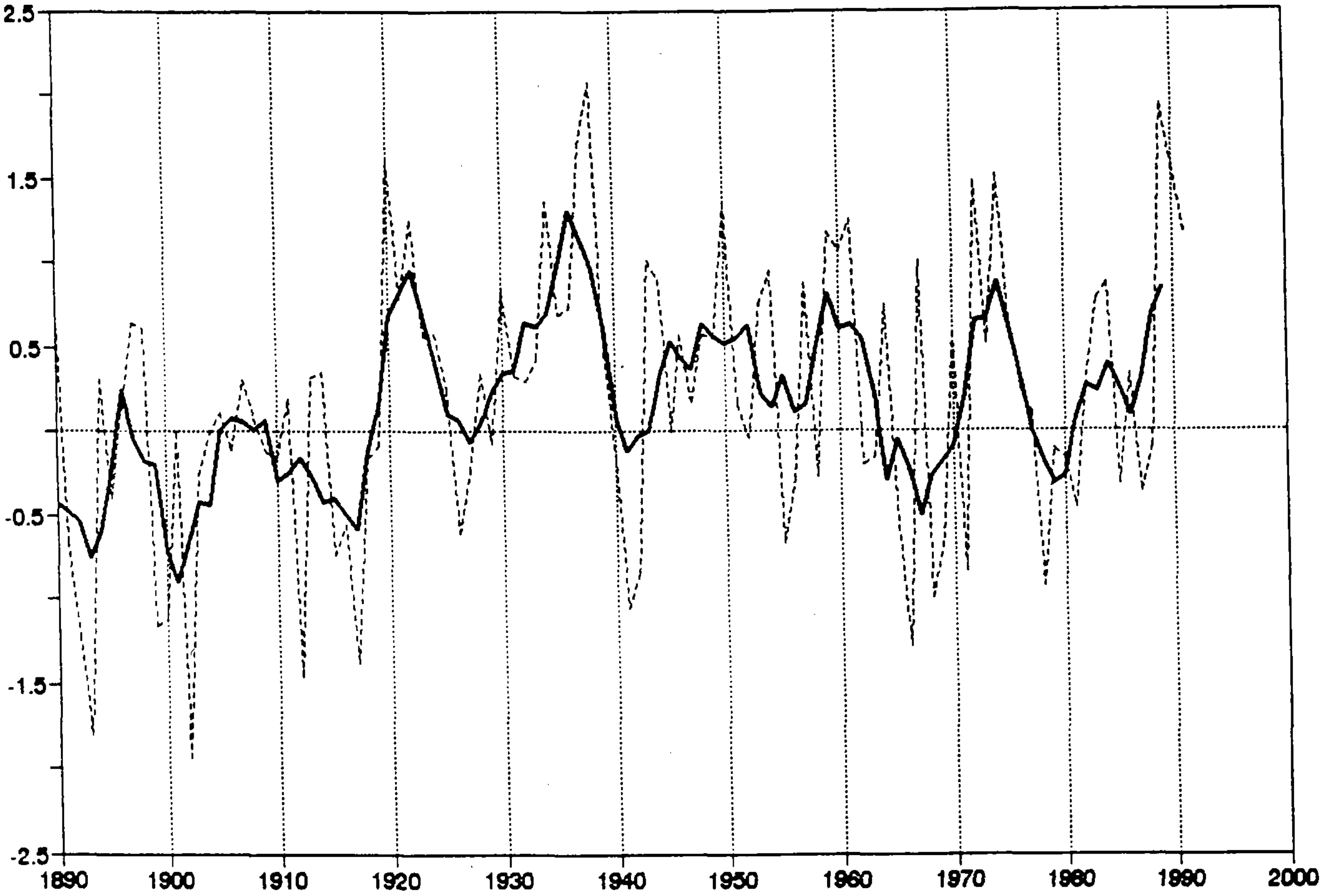

Figure 8(b) Vardo (Norway).

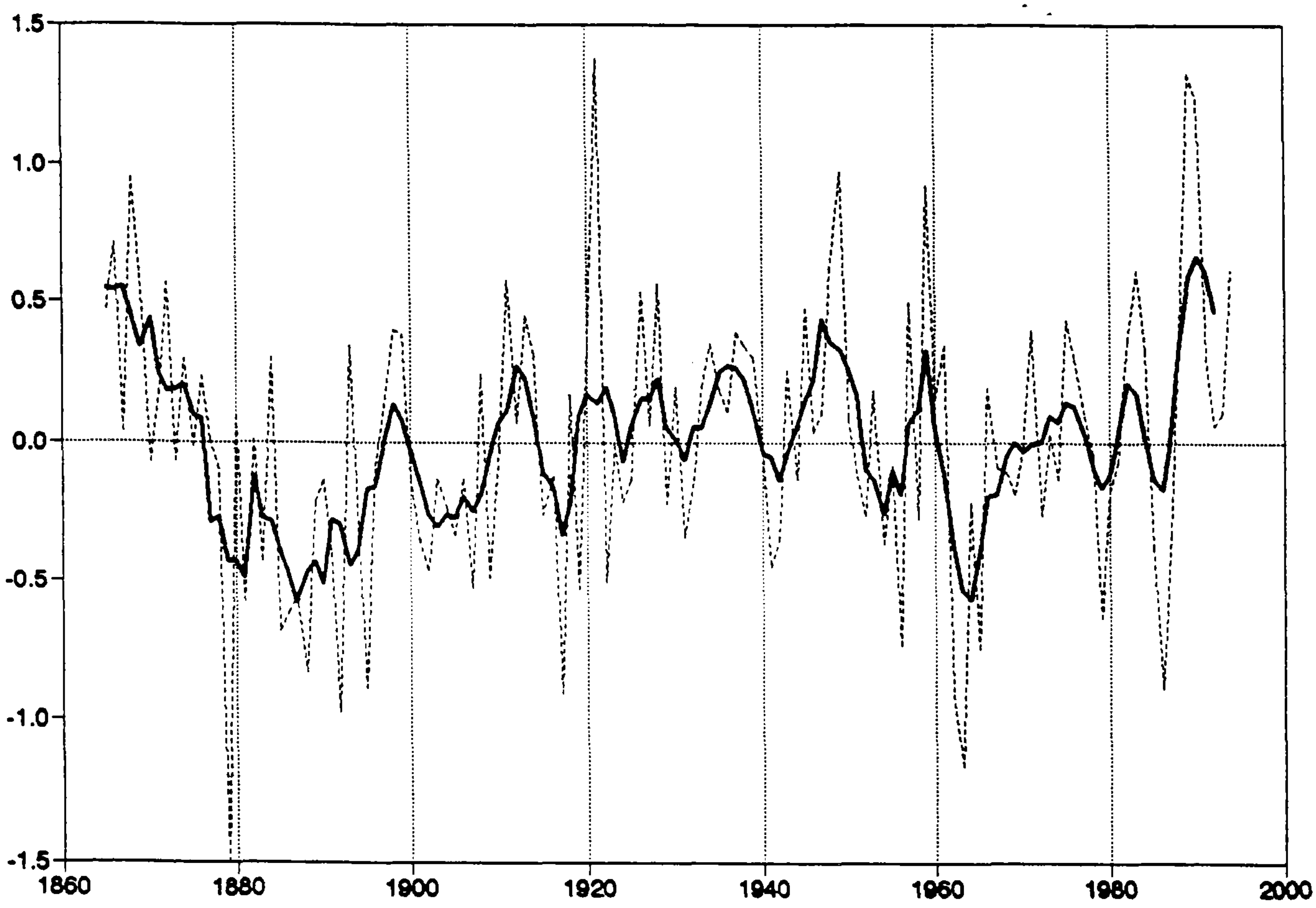

Figure 9(a) Plymouth (UK).

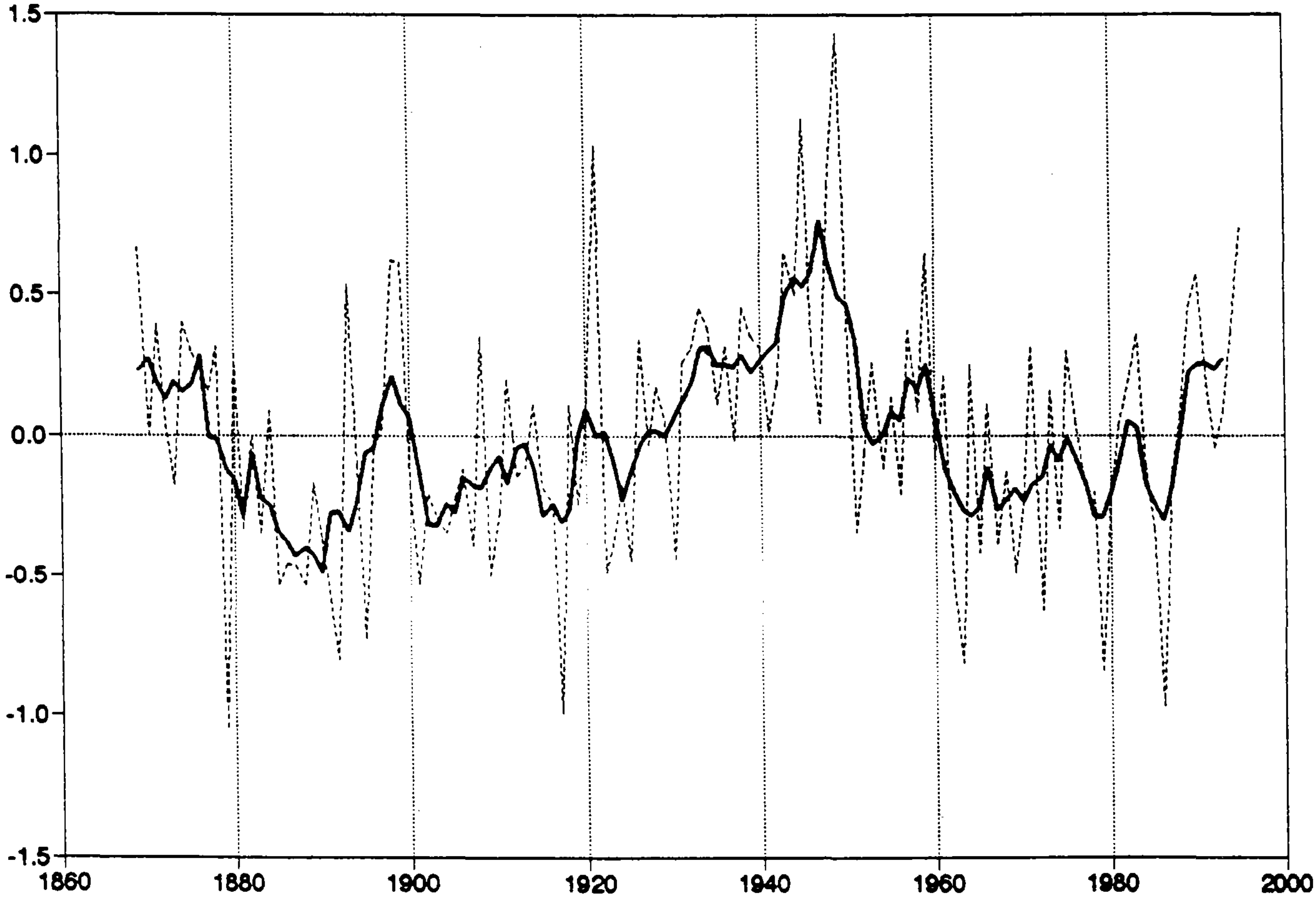

Figure 9(b) Valentia Observatory (Ireland).

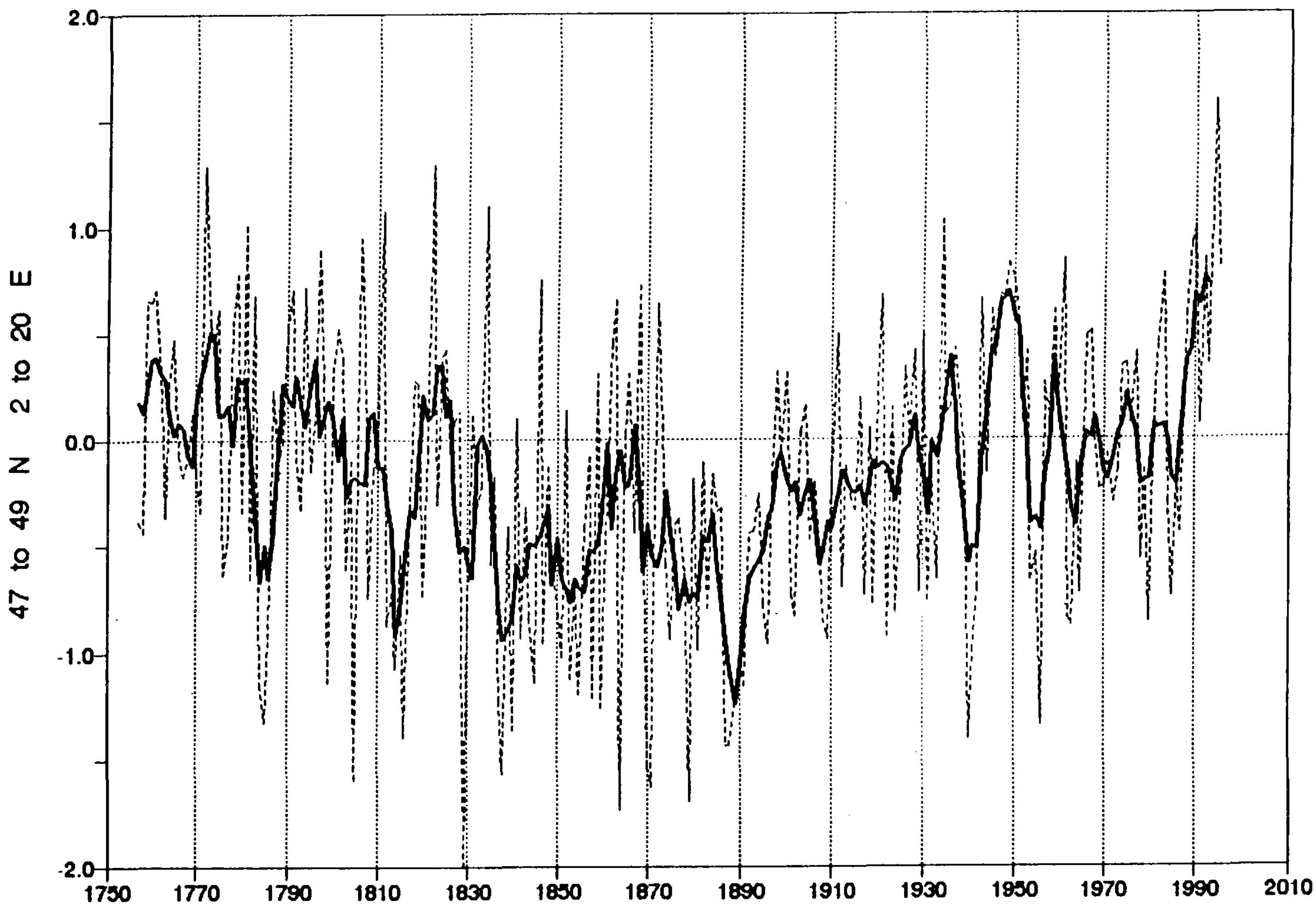

Figure 10: Section along Paris to Budapest line

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