Government of Canada
Gouvernement du Canada

# CANADA IN A CHANGING CLIMATE:

## Sector Perspectives on Impacts and Adaptation

Canada

Government of Canada Gouvernement du Canada

# CANADA IN A CHANGING CLIMATE:

## Sector Perspectives on Impacts and Adaptation

Canada

Edited by:

**F.J. Warren and D.S. Lemmen**
Climate Change Impacts and Adaptation Division
Natural Resources Canada

Recommended Citation:

Warren, F.J. and Lemmen, D.S., editors (2014): Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation; Government of Canada, Ottawa, ON, 286p.

This publication is also available at:
**adaptation.nrcan.gc.ca**

*Aussi disponible en français sous le titre :* Vivre avec les changements climatiques au Canada : perspectives des secteurs relatives aux impacts et à l'adaptation

Cat. No.: M174-2/2014E (Print)
ISBN: 978-1-100-24142-5

Cat. No.: M174-2/2014E-PDF (Online)
ISBN: 978-1-100-24143-2

This assessment is a product of Canada's Adaptation Platform, which brings together representatives from government, industry and professional organizations, to collaborate on adaptation priorities. For more information on the Adaptation Platform, and to download new products, including case studies, adaptation tools, guidance documents and reports, please visit:

nrcan.gc.ca/environment/impacts-adaptation

# ACKNOWLEDGEMENTS

**We gratefully acknowledge the following individuals for their guidance, support and input throughout the process as members of the Assessment Experts' Committee:**

Alain Bourque (Ouranos)
Paul Kovacs (Institute for Catastrophic Loss Reduction)
Jimena Eyzaguirre (ESSA Technologies Ltd.)
Linda Mortsch (Environment Canada)
Terry Robert (Fraser Basin Council)
Eric Schroff (Yukon Government)

**We also thank the following people for taking the time to provide critical, expert reviews of one or more chapters of the report:**

Zeba Ali
Shareen Amin
Faron Anslow
Michel Archambault
Kumiko Azetsu-Scott
Marie-Caroline Badjeck
Jim Barnes
Pierre Bernier
Peter Berry
Dominique Berteaux
Sébastien Biner
Danny Blair
Anne Blondlot
Marie-Eve Bonneau
Jeff Bowman
Joan Brunkard
Christopher Bryant
Sarah Burch
Brent Burton
Elizabeth Bush
Leah Carson
Norm Catto
Ginger Chew
Quentin Chiotti
James Christian
Jenna Craig
Jennifer Davis
Jackie Dawson
Ramon De Elia
Brad de Young
Claude Desjarlais
Thea Dickinson
Susan Doka
Al Douglas
Claude Duguay
Megan Duncan
Caren Dymond
Kris Ebi
Susan Evans
Jimena Eyzaguirre
Wayne Fan
Paul Fesko
Manon Fleury
Don Forbes
James Ford
Jenny Fraser
John Fyfe
Fawziah (ZuZu) Gadallah
Sylvie Gauthier
Pierre Gosselin
Stephanie Gower
Gloria Gutman
Mark Haines
Charles Hannah
Norm Henderson
Ole Hendrickson
Joseph Henton
Karen Hodges
Jane Inch
Mark Johnston
Sarah Kalff
Pam Kertland
Heather Kharouba
Paul Kovacs
François Lalonde
Van Lantz
David Lapp
Caroline Larrivée
Diane Lavoie
Wendy Leger
Chris Lemieux
George Luber
Sharon Ludlow
Jim MacLellan
Dan McKenney
Ian McLachlan
Maria Mirabelli
M. Monirul Mirza
Wendy Monk
Ana Rosa Morena
Nathalie Morin
Toni Morris-Oswald
Linda Mortsch
Marc Nelitz
Elizabeth Nelson
Marie-Eve Neron
Dirk Nyland
Sarah O'Keefe
Kenneth Olsen
Robert Page
Kathy Palko
Lynne Patenaude
Ian Perry
Eva Riccius
Jake Rice
Gregory Richardson
Dieter Riedel
John Rislahti
Susan Roberecki
Jeanne Robert
Terry Robert
Alex Rosenberg
Vincent Roy
Dave Sauchyn
Paul Schramm
Eric Schroff
Ryan Schwartz
Robert Siron
Risa Smith
Chuck Southam
Tim Takaro
Jason Thistlethwaite
Matthew Wiens
Mary-Ann Wilson
Hannah Wittman
Rebecca World
Fuyuen Yip
Terry Zdan
Xuebin Zhang

**This report could not have been completed without the help of our students. We would like to recognize the following students for their dedication to the work, attention to detail and unwavering positivity:**

Stéphanie Elias
Adam Garbo
Dong Young Lee
Laurisse Noël
Cynthia Smith

# TABLE OF CONTENTS

# SYNTHESIS

Lead Authors:

**Fiona J. Warren** and **Donald S. Lemmen** *(Natural Resources Canada)*

Recommended Citation:

Warren, F.J. and Lemmen, D.S. (2014): Synthesis; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 1-18.

# SUMMARY

Over the past 5 years, our understanding of climate change impacts and adaptation in Canada has increased both as a result of new research and through practical experience. Key conclusions arising from this update to the 2008 assessment report *'From Impacts to Adaptation: Canada in a Changing Climate'* include:

1. Canada's climate is changing, with observed changes in air temperature, precipitation, snow and ice cover and other indicators. Further changes in climate are inevitable.
2. Changes in climate are increasingly affecting Canada's natural environment, economic sectors and the health of Canadians.
3. Extreme weather events are a key concern for Canada and there is growing confidence that some types of extreme events will increase in frequency and/or intensity as the climate continues to warm.
4. Adaptation is accepted as a necessary response to climate change, complementing global measures to reduce greenhouse gas emissions. Adaptation enhances the social and economic resilience of Canadians to climate change impacts.
5. Adaptation is occurring with increasing frequency and enhanced engagement. Continued action will help to build capacity, address information needs and overcome challenges.
6. Adaptation can sometimes turn risks into opportunities, and opportunities into benefits.
7. Collaboration and adaptive management are approaches that governments and industry are increasingly pursuing to advance adaptation.

# INTRODUCTION

The climate is changing – in Canada and throughout the world. Globally, international assessments continue to identify rising air and ocean temperatures, shifting precipitation patterns, shrinking glaciers, declining snow cover and sea ice extent, rising sea level and changes in extreme events (IPCC, 2013). While rates of change vary from one indicator to another, the directions of change are consistent with climate warming, and climate models project that many of the observed trends will continue over the coming decades and beyond. Reducing greenhouse gas emissions (GHGs; mitigation) is necessary to lessen the magnitude and rate of climate change, but additional impacts are unavoidable, even with aggressive global mitigation efforts, due to inertia in the climate system. Therefore, we also need to adapt – make adjustments in our activities and decisions in order to reduce risks, moderate harm or take advantage of new opportunities. All levels of government, researchers, the private sector and non-government organizations now view adaptation as an essential complement to mitigation.

In 2008, the Government of Canada released a national-scale science assessment of climate change impacts and adaptation (*From Impacts to Adaptation: Canada in a Changing Climate*). That assessment used a regional approach to discuss current and future climate change impacts and vulnerabilities in Canada, as well as adaptation options. It built upon the findings of Canada's first national-scale assessment (*The Canada Country Study*, 1998) and drew conclusions from all available relevant literature.

This report – *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* – is an update to the 2008 assessment. It focuses on new information and knowledge, assessing advances made in understanding climate change impacts and adaptation from a sectoral perspective, based primarily on literature published up to the end of 2012. This synthesis draws from the individual chapters of the report, which include an overview of Canada's changing climate (Ch. 2), thematic chapters focused on sectors (Ch. 3 to 8) and the concluding chapter on adaptation research and practice (Ch. 9). The key findings of chapters 3 to 9 are summarized in Box 1. The rest of the synthesis is structured around high-level conclusions, supported by examples and insights from an integrative analysis across the report themes[1].

---

[1] This Synthesis does not repeat the references provided in the underlying chapters, but rather directs the reader to individual chapters of the report where specific references can be found. Occasional specific references are included when the source was not cited within another chapter or to provide additional context.

BOX 1

## KEY FINDINGS FROM THE CHAPTERS

### Natural Resources (Forestry, Energy and Mining, Chapter 3)

- Climate change will exacerbate existing climate risks related to the planning and management of natural resources. These risks relate to impacts and natural hazards associated with climate extremes (e.g. heat, cold, precipitation) and to gradual changes, such as permafrost degradation, sea level rise, and plant species migration. Climate change will also present new opportunities for the natural resource sectors, particularly in relation to northern economic development.
- Consideration of multiple stressors is critical to understanding adaptation in the natural resource sectors. Climate change itself is rarely identified as a priority concern, with industry focused on other immediate stressors, such as economic drivers. Opportunities exist to integrate consideration of climate change into current planning processes.
- Environmental assessment, risk disclosure, and sustainable forest management reporting are examples of processes that can help advance adaptation actions. These processes allow governments, investors and the public to evaluate industry understanding of changing climate risks and influence the steps taken to address those risks.
- While awareness of climate change impacts and implementation of adaptation actions is most evident in sectors where there is a clear and direct relationship between climate and resource supply, notably forestry and hydroelectricity, the application of adaptive management approaches to address climate change impacts is seen across all natural resource sectors.

### Food Production (Chapter 4)

- The impacts of climate change differ significantly between agriculture, fisheries, and non-commercial food supply, but common challenges include increased losses from invasive pests and diseases, and risks to transportation systems upon which the sectors rely.
- The net medium-term outlook is for a likely modest increase in agricultural food production. Longer and warmer growing seasons would allow higher-value warmer-weather crops to be grown further north (where soil conditions permit), lengthen outdoor feeding seasons for livestock, and allow the maple syrup industry to expand northward. However, there will likely be new pests and diseases, as well as more severe outbreaks of current ones, and challenges associated with extreme weather events and the reduced predictability of inter-annual weather variability that could negatively affect production.
- Northern and remote communities are likely to see great changes in their environment – some will ease food security concerns, while others could exacerbate already decreasing country food stocks and difficulties in delivering supplies into isolated areas.
- Canada is expected to remain a net exporter of aquatic foods at the aggregate level, with total biomass of production from wild, capture fisheries in Canada expected to increase due to climate-induced shifts in fish distributions. Regional impacts from invading species, physical habitat changes and societal responses to shifts in availability and access to aquatic food resources will gradually determine future patterns of use and overall economic implications.
- Aquaculture has a greater scope for adaptation to climate change than other fisheries, making it less vulnerable and better positioned to take advantage of opportunities than capture fisheries, and subsistence fisheries in particular.

*Box 1 continued on next page*

### Industry (Chapter 5)

- Industrial activity is sensitive to variations in weather and in extreme events, with considerable differences in the types and extent of impacts on production, operations, and revenue among and within sectors.
- Changes in industry practices have been predominantly reactive, responding to variation in the weather or extreme events, rather than proactive anticipation of future climate change. Examples of adaptation tend to be isolated rather than representative of a clear trend within the sector.
- Adaptive actions implemented by industry vary by sector, and may be under-reported for strategic reasons. Relative to other sectors, tourism and insurance show the most promise in using adaptive actions to take advantage of potential opportunities.
- There is little published research about indirect impacts of climate change on industry, such as changes associated with consumer demand, supply chains, real estate or other assets, adaptation by other sectors, legal liability or government regulation.
- Barriers towards effective adaptation include limited information on local impacts to businesses, uncertainties about the costs and benefits of different adaptive actions, and limited market demand for the implementation of adaptation.

### Biodiversity and Protected Areas (Chapter 6)

- Climate-related shifts in species distributions have already been documented for plants and animals in Canada. In many locations, differential range shifts among species are likely to result in novel ecosystems that have different species assemblages, structural attributes, and ecological functions than existing ones.
- For some species, the current and projected rates of environmental change exceed their natural ability to adapt, increasing stress and threatening biodiversity. As a result, climate change is magnifying the importance of managing ecosystems in a manner that enhances resilience and preserves biodiversity.
- Protected areas, including parks, wildlife reserves and marine protected areas will play an important role in the conservation of biodiversity by providing "refuge" or migration corridors for native species, helping to maintain genetic diversity.
- Many Canadian jurisdictions are expanding their parks and protected area systems as part of their overall management plans and climate change adaptation strategies. Associated research, monitoring, citizen science, public awareness, and visitor experience programs build understanding, engage the public and help them contribute to meaningful participatory decision-making.
- Ecological restoration can strengthen resilience to climate change. Integration of climate change adaptation strategies into restoration decision-making in Canada, as elsewhere, is complex.

### Human Health (Chapter 7)

- Stronger evidence has emerged since 2008 of the wide range of health risks to Canadians posed by a changing climate. For example, climate-sensitive diseases (e.g. Lyme disease) and vectors are moving northward into Canada and will likely continue to expand their range. In addition, new research suggests climate change will exacerbate air pollution issues in some parts of Canada, although further reductions in air contaminant emissions could offset climate-related changes to ground-level ozone and particulate matter concentrations.
- A range of climate-related natural hazards continues to impact communities, presenting increasing risks to future health. Recent flood and wildfire events have severely impacted communities through destruction of infrastructure and displacement of populations.
- Many adaptation activities are being taken from local to national levels to help Canadians prepare for the health impacts of climate change. Adaptation planning considers the underlying causes of health vulnerability, which differ across urban, rural, coastal and northern communities.

*Box 1 continued on next page*

- Provincial, territorial and local health authorities are gaining an increasing knowledge of climate change and health vulnerabilities through assessments and targeted research, and some jurisdictions have begun mainstreaming climate change considerations into existing health policies and programs. Efforts to increase public awareness about how to reduce climate-related health risks are also evident.
- Adaptation tools and measures, such as heat alert and response systems, projections of vector-borne disease expansion and greening urban environments can help protect Canadians from the effects of climate change being felt now, and those from future impacts.

### Water and Transportation Infrastructure (Chapter 8)

- Well-maintained infrastructure is more resilient to a changing climate. This is especially true with respect to gradual changes in temperature and precipitation patterns. Key vulnerabilities are associated with the impacts of extreme weather events, which can overwhelm the capacity of water infrastructure.
- Over the past five years, the work of the PIEVC (Public Infrastructure Engineering Vulnerability Committee) has been an important driver of progress on understanding how to adapt Canada's infrastructure to climate change. The broadly applicable, risk-based assessment protocol developed by the PIEVC allows engineers and planners to view and address climate change as one factor among many affecting system resiliency, and plan accordingly.
- Consideration of climate change as an element of adaptive asset management encourages consideration of climate factors as part of ongoing system monitoring, and informs decisions regarding the most cost-effective approaches for infrastructure design, operation and maintenance.
- Codes, standards and related instruments (CSRI) are recognized as a potentially important driver of infrastructure adaptation, but there are few examples of CSRIs in Canada that considered historic changes or projected future changes in climate when they were developed. Further assessment of current and future climate-related risks to infrastructure systems would help to inform appropriate adjustments to design codes and standards for addressing future climate.

### Adaptation: Linking Research and Practice (Chapter 9)

- Adaptation is being undertaken in Canada to achieve a range of goals, such as increasing capacity to adapt, improving resilience to specific climate events (especially extremes), and enhancing ability to deal with different climate conditions. Among sectors, those with a demonstrated high sensitivity and exposure to climate and weather are generally most active in taking steps to understand, assess and manage vulnerability and risk related to climate change.
- Adaptation is not solely a local issue, although examples from the municipal level still appear to dominate. There are examples of action by all levels of government, as well as community groups and industry, many of which represent collaborative initiatives.
- Understanding of the barriers and challenges to adaptation has improved, with recognition that factors beyond the basic determinants of adaptive capacity need to be addressed. As a result, understanding of how to overcome key barriers and enable adaptation has improved.
- Adaptation implementation in Canada is still in its early stages. Planning and policy exercises, and efforts to build capacity and raise awareness comprise much of the adaptation action documented, with relatively few documented examples of implementation of specific changes to reduce vulnerability to future climate change, or take advantage of potential opportunities.
- Several factors can help accelerate the transition between awareness and action, including leadership, targeted awareness-raising and supportive strategies or policies. Experiencing extreme weather events, as well as observing impacts of gradual changes (e.g. sea level rise) also stimulates adaptation.

## CANADA'S CLIMATE IS CHANGING, WITH OBSERVED CHANGES IN AIR TEMPERATURE, PRECIPITATION, SNOW AND ICE COVER AND OTHER INDICATORS. FURTHER CHANGES IN CLIMATE ARE INEVITABLE (CHAPTER 2).

Over the last six decades, Canada has become warmer, with average temperatures over land increasing by 1.5°C between 1950 and 2010 (Figure 1). This rate of warming is about double the global average reported over the same time period by Hartmann et al., (2013). Warming has been occurring even faster in many areas of northern Canada, and has been observed in all seasons, although the greatest warming has occurred in winter and spring. The annual number of extreme warm days has also risen, while the number of cold nights has declined. Table 1 provides examples of documented changes in Canada for a variety of indicators of the physical climate system.

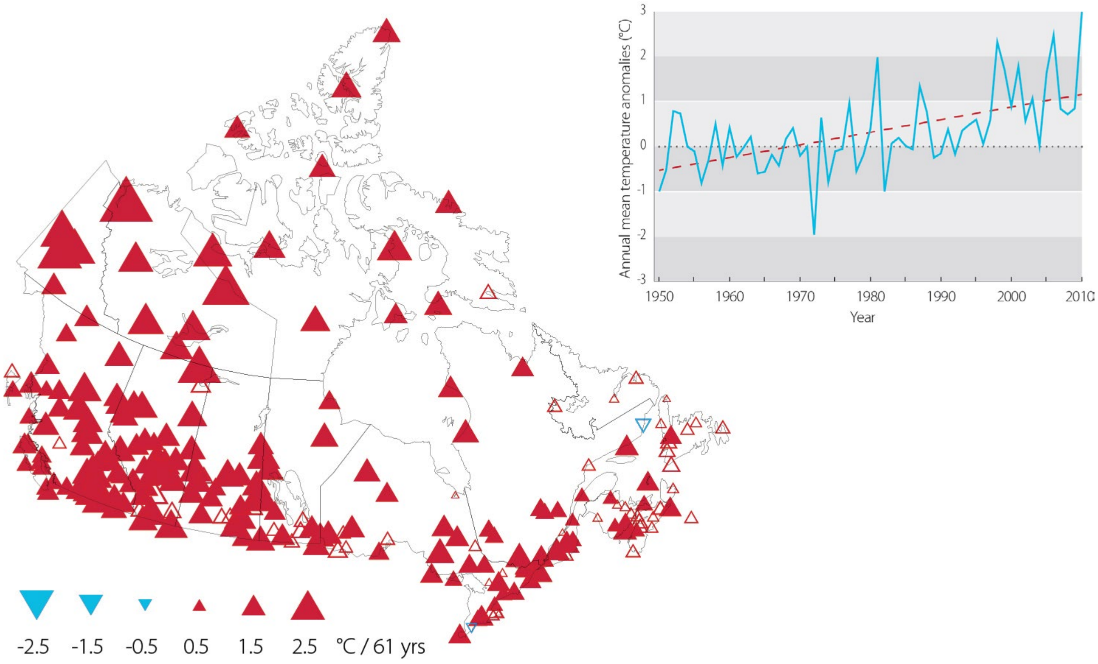


**FIGURE 1:** Patterns of change in annual mean temperature across Canada over the period1950–2010. Upward (red) and downward (blue) pointing triangles indicate positive and negative trends respectively. Filled triangles correspond to trends significant at the 5% level *(Source: Vincent et al., 2012)*. ***Inset:*** Annual mean temperature change for Canada (°C), 1950–2010, relative to the 1961–1990 average (represented by zero on the Y-axis) *(Source: Vincent et al., 2012; Environment Canada, 2011)*.

| Climate System Element | Observed Trends |
|---|---|
| **Temperature** | |
| Annual air temperature – Canada | The annual average surface air temperature over the Canadian landmass has warmed by 1.5°C over the period 1950-2010 |
| **Temperature Extremes** | |
| Hot extremes – Canada | The frequency of warm days (when the daily maximum temperature is above the daily 90th percentile) during the summer has increased nationally since 1950 |
| Cold extremes – Canada | The frequency of cold nights (when the daily minimum temperature is below the daily 10th percentile) during the winter has decreased nationally since 1950 |
| **Precipitation and other hydrological indicators** | |
| Annual precipitation – Canada | Canada has generally become wetter in recent decades, as indicated by the increasing trend in annual average precipitation |
| Snowfall/Rainfall – Southern Canada | In several regions of southern Canada, there has been a shift in precipitation type, with decreasing snowfall and increasing rainfall |
| Streamflow – Canada | Observations suggest decreasing trends in maximum and minimum river flows over the period 1970-2005 in much of southern Canada, with increases in minimum flows in western Nunavut, Northwest Territories, Yukon and northern British Columbia |
| Snowfall – Canada | Annual snowfall has declined over most of southern Canada and increased in the north over the last 6 decades |
| Snow cover – Canada | Negative trends in snow cover extent have been observed during spring over the Canadian landmass, with largest declines observed in June |
| **Permafrost** | |
| Ground temperature – Canada | Permafrost temperatures at numerous borehole sites across Canada have increased over the past two to three decades |
| **Sea Level** | |
| Sea level – Global | Global average sea level rose about 21 cm between 1880 and 2012 at an average rate of 1.6 mm/year |
| Relative sea level – Canada | Relative sea level rise of over 3 mm/year has been observed on coastlines of Atlantic Canada and the Beaufort Sea coast, with lower amounts along Pacific coastlines. Relative sea level fall of 10 mm/year has been observed around Hudson Bay where the land is rising rapidly due to post-glacial rebound |
| **Sea Ice** | |
| Seasonal ice extent – Arctic | End-of-summer minimum ice extent has declined at a rate of 13% per decade over 1979-2012, while maximum winter sea ice extent has declined at a rate of 2.6% per decade |
| Ice Type – Arctic | A shift in ice cover from one dominated by thick multi-year ice (MYI) to one increasingly dominated by thin first-year ice (FYI) has been observed |
| Eastern Canada | Declines in winter sea ice extent have been observed in the Labrador-Newfoundland and Gulf of St. Lawrence region |
| **Glaciers** | |
| Glacier mass – Yukon, British Columbia, Alberta | Western Cordilleran glaciers are losing mass and shrinking rapidly to the smallest extents in several millennia. Glaciers in British Columbia and Alberta have lost, respectively, about 11% and 25% of their surface area over the period 1985-2005, while glaciers in Yukon have lost about 22% since the 1950s |
| Glacier mass – High Arctic | Significant negative mass balances are evident from the early 1960s into the first decade of the 21st century. The rate of mass loss for glaciers throughout the High Arctic has increased sharply since 2005, in direct response to warm regional summer temperatures |
| **Lake and River Ice** | |
| Spring ice thaw – Canada | Trends towards earlier ice-free dates (lakes) and ice break-up dates (rivers) have been observed for most of the country since the mid-20th century but are particularly evident in Western Canada |
| **Ocean Climate** | |
| Canada's oceans | Long-term changes in ocean temperature (increasing), salinity (variable sign), and acidity (increasing) have been observed in all three of Canada's oceans. Long-term decreases in subsurface dissolved oxygen levels have also been observed in the Atlantic and Pacific oceans off Canada |

**TABLE 1:** Examples of observed changes in Canada (*from* Chapter 2). The length of the observational record varies with the indicator.

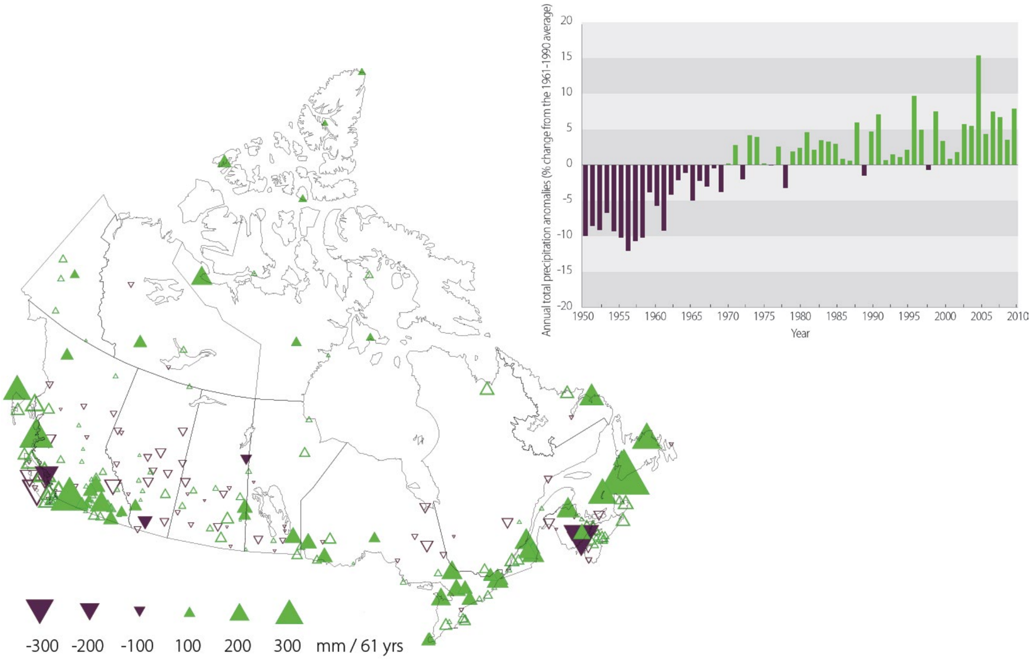


**FIGURE 2:** Patterns of change in annual total precipitation over the period 1950–2010. Upward (green) and downward (purple) pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level (*Source: Mekis and Vincent, 2011b*). ***Inset:*** Annual total precipitation anomalies (expressed in % change from the 1961–1990 average) for Canada, 1950–2010 (*Source: Mekis and Vincent, 2011a; Environment Canada, 2011)*.

Over the same time period (1950–2010), Canada as a whole has become wetter, with increasing annual average precipitation trends in many parts of the country and for the nation as a whole (Figure 2). Trends in annual precipitation have been less uniform across the Canadian landmass than those of annual air temperature. While significant changes in extreme precipitation have been observed in some areas of the country, no consistent pattern is evident for the country as a whole.

There have also been observed trends in other climate indicators in Canada (*see* Table 1). The Arctic has seen rapid declines in sea ice extent, both in summer and winter (Figure 3). In addition, snowfall has decreased across southern Canada, while snow cover is melting earlier in spring, and glaciers in western Canada and the Arctic are shrinking.

At the global scale, sea level over the past century has risen in response to warmer ocean temperatures (thermal expansion) and to the melting of glaciers, ice caps and ice sheets. Regional patterns of sea level rise along Canadian coastlines are strongly influenced by vertical land motion, with sea level rising rapidly at some sites where the land is subsiding, and falling in others where the land is rising (*see* Table 1).

Further changes in climate are inevitable. On average, warmer temperatures and more rainfall are expected for the country as a whole, with increases in extreme heat and heavy rainfall events, and declines in snow and ice cover. Sea level along many of our coastlines will continue to rise, and warmer waters and ocean acidification are expected to become increasingly evident in most Canadian ocean waters over the next century. An overview of projected changes in some key climate indicators for Canada is provided in Table 2[2].

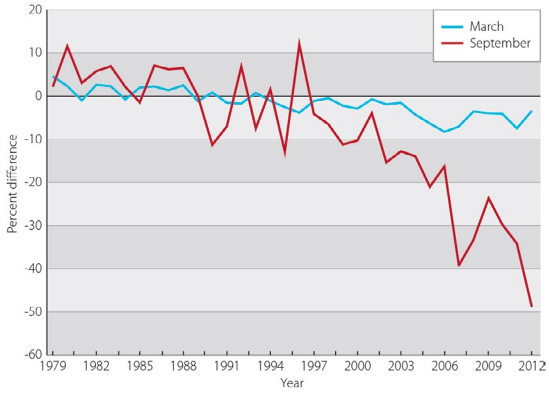


**FIGURE 3:** Trends in Arctic sea ice extent over the period 1979–2012 shown as time series of the percentage difference in ice extent in March and September relative to the mean values for the period 1979–2000. Both trends are statistically significant (*Source: Perovich et al., 2012*).

---

[2] While the changes presented in Table 2 are based on climate change projections commonly used up to 2012, they are broadly consistent with results using newer projections (such as those used in the IPCC Fifth Assessment Report).

| Temperature | Projected Changes |
|---|---|
| Seasonal temperature | Warming will be greatest in winter, and in this season, the largest increases in air temperature are projected for northern Canada. In summer, the largest increases are projected for southern Canada and the central interior. The magnitude of projected warming varies substantially with the emission scenario |
| Extremes in daily temperature | Increases in the frequency and magnitude of unusually warm days and nights and decreases for unusually cold days and nights are projected to occur throughout the 21st century |
| Long duration hot events | The length, frequency and/or intensity of warm spells, including heat waves, are projected to increase over most land areas, including Canada |
| Rare hot extremes | Rare hot extremes are currently projected to become more frequent. For example, a one-in-20-year extreme hot day is projected to become about a one-in-5 year event over most of Canada by mid-century |
| **Precipitation and other hydrological indicators** | |
| Seasonal precipitation | Increases in precipitation are projected for the majority of the country and for all seasons, with the exception of parts of southern Canada where a decline in precipitation in summer and fall is suggested |
| Heavy precipitation | More frequent heavy precipitation events are projected, with an associated increased risk of flooding |
| Rare precipitation events | Rare extreme precipitation events are currently projected to become about twice as frequent by mid-century over most of Canada |
| Streamflow | Increases in winter streamflow are projected for many regions in southern Canada. Mean annual streamflow is projected to decreases in some regions of Alberta and Saskatchewan, while projections for other regions vary across different scenarios |
| **Snow Cover** | |
| Snow cover duration | Widespread decreases in the duration of snow cover are projected across the Northern Hemisphere with the largest changes in maritime mountain regions, such as the west coast of North America |
| Snow depth | Maximum snow accumulation over northern high latitudes is projected to increase in response to projected increases in cold season precipitation |
| **Permafrost** | |
| Ground temperature | Warming of the permafrost is projected to continue at rates surpassing those observed in records to date. Low average temperatures of much of the permafrost in the Arctic mean it will take many decades to centuries for colder permafrost to completely thaw |
| **Sea Level** | |
| Global sea level rise to 2100 | Estimates of the magnitude of future changes in global sea level by the year 2100 range from a few tens of centimetres to more than a metre |
| Global sea level rise beyond 2100 | Projections of global sea-level rise beyond 2100 indicate continuing global sea-level rise over the coming centuries and millennia. Global sea-level rise may eventually amount to several metres |
| Relative sea level change | Patterns of change along Canadian coastlines will continue to be influenced by land uplift and subsidence as well as by changes in the oceans. Sea-level rise will continue to be enhanced in regions where the land is subsiding, and sea level is likely to continue to fall in regions where the land is rapidly rising. Regions where the land is slowly rising may experience a transition from sea level fall to sea level rise. |
| **Sea Ice Extent** | |
| Arctic summer sea ice | A nearly ice-free summer is considered a strong possibility for the Arctic Ocean by the middle of the century although summer sea ice may persist longer in the Canadian Arctic Archipelago region |
| **Lake Ice** | |
|  | With the continued advance of ice cover break-up dates and delays in ice-cover freeze up, ice cover duration is expected to decrease by up to a month by mid-century |

**TABLE 2:** Examples of projected changes in the climate system for Canada, derived from ensembles of global climate models driven by the SRES scenarios[3]. In general, the magnitude of the stated changes will increase under higher emission scenarios.

---

[3] New projections for Canada will be available from the Canadian Climate Change Scenarios Network (cccsn.ec.gc.ca).

## CHANGES IN CLIMATE ARE INCREASINGLY AFFECTING CANADA'S NATURAL ENVIRONMENT, ECONOMIC SECTORS AND THE HEALTH OF CANADIANS (CHAPTERS 3 TO 8).

The natural environment is inherently sensitive to climate. Shifts in the range of some species of birds, butterflies and trees in response to warming temperatures have been documented, as have changes in the timing of life-history events (such as earlier migration to breeding areas and earlier flowering of plants). Maple trees, for example, have experienced a significant northward shift since 1971 (*see* Case Study 1, Ch. 4). Northward shifts have also been observed in ecosystems of the Bering Sea, with examples of southern assemblages displacing northern aquatic populations (Ch. 4).

Declines in bird populations have also been documented, with 20 common North American bird species losing over 50% of their populations over the last 40 years (Ch. 7). Increased forest disturbance associated with insects, drought and forest fires have increased tree mortality in BC and the Prairies. Mortality rates have also risen in sockeye salmon, in response to higher water temperatures in the Fraser River (Ch. 7), while salmon production rates have declined (Ch. 4).

In addition to impacts on the natural environment, changing climate is affecting many of Canada's economic sectors as well as human health. This includes impacts on sectors with obvious climate sensitivities such as forestry, agriculture, fisheries, hydroelectricity, transportation, tourism and insurance. A prime example is the mountain pine beetle outbreak in western Canada. Warmer winter temperatures in the region are one factor that has allowed beetle populations to expand to unprecedented sizes, leading to the largest and most severe outbreak on record (*see* Case Study 1, Ch. 3). As of 2012, about 18.1 million hectares of forest were affected (Figure 4; Ch. 3). Health impacts include lengthening of the ragweed season (between 1995 and 2009, the season increased by more than 25 days in Saskatoon and Winnipeg (Ch. 7)) and spreading of Lyme disease vectors (ticks), which has resulted in the annual number of Canadian cases increasing from 30 to more than 250 in recent years (Ch. 7).

Northern Canada has experienced particularly rapid rates of warming over recent years (*see* Figure 1). Climate change impacts on livelihoods, culture, mental health and well-being have been reported by northern residents (Ch. 7). Safety concerns associated with less predictable ice conditions and marine storms are an issue, for example, as are the effects of reduced sea ice on traditional hunting activities (Ch. 4) and the impacts of permafrost thaw on infrastructure (Ch. 8). Winter roads in northern Canada have experienced reduced ice thickness and shortened operating seasons, which decreases their reliability and constrains the load volumes that can be safely transported. For example, the shortened road season in 2006 forced the

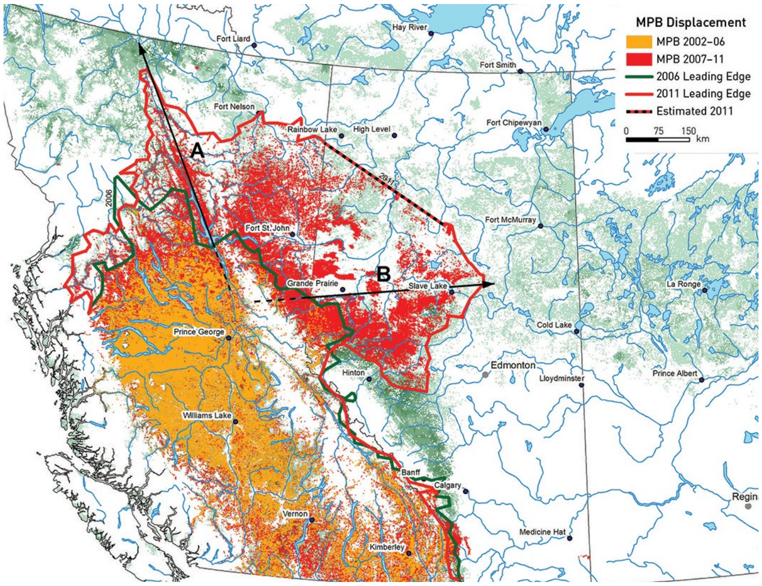


**FIGURE 4:** Map of Mountain Pine Beetle distribution, showing change for the 2002–2006 and 2007–2011 time periods and direction of change (*Source: Natural Resources Canada, 2012c*).

Diavik Diamond Mine to spend an extra $11.25 million to fly in fuel (Ch. 3). Northern communities also depend upon the winter road network for the supply of affordable food, medicines and other goods.

Together, these observed impacts illustrate that climate change is happening now, with impacts being felt across the country. While climate is one of several contributing factors in most cases, these examples provide an indication of the types of impacts that we can expect to see more of as the climate continues to change.

## EXTREME EVENTS REMAIN A KEY CONCERN FOR CANADA (CHAPTERS 3 TO 8) AND THERE IS GROWING CONFIDENCE THAT SOME TYPES OF EXTREME EVENTS WILL INCREASE IN FREQUENCY AND/OR INTENSITY AS THE CLIMATE CONTINUES TO WARM (CHAPTER 2).

Losses from severe weather have been rising across the country. Extreme events, including storms (wind, ice and snow), flooding and heat waves have had significant economic (Figure 5) and health and safety impacts on Canadians. In 2011, the Canadian insurance industry paid out a record $1.7 billion for property damage associated with weather events, such as flooding, wind and wildfires. This record will be broken in 2013, as the insured losses from flooding damage in Southern Alberta (June) and Toronto (July) are finalized (IBC, 2013a; IBC, 2013b). While factors other than climate also contributed to the rising payout trend (e.g. increased exposure of property, increasing wealth and aging infrastructure), these losses, along with the many possible health impacts (Ch. 7) demonstrate that Canadians are vulnerable to extreme weather events.

There is growing confidence that some types of extreme events will increase in frequency and/or intensity due to climate change (Ch. 2). For example, at the global scale, warm days and nights are *virtually certain*[4] to increase in frequency and magnitude and heat waves are *very likely*[4] to increase in duration, frequency and/or intensity. Heavy precipitation events and extreme sea levels are also projected to occur more frequently. In Canada, studies have suggested that droughts, especially in the southern Prairies, heavy precipitation events, with associated increased risk of flooding (Ch. 2), forest fires (Ch. 3), storms (Ch. 5) and hot days and warm nights (Figure 6; Ch. 7) would increase in frequency and/or intensity in a warmer climate.

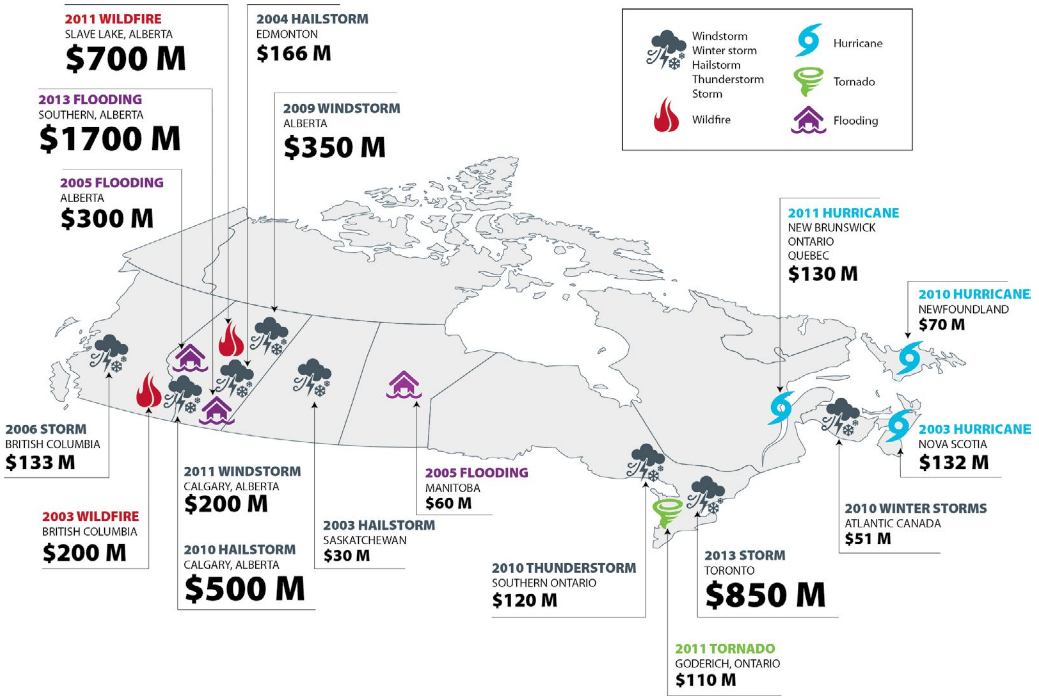


**FIGURE 5:** Examples of insured losses from extreme weather events in Canada (*Sources: IBC, 2008, 2011b, 2013a, b; McBean, 2012*).

---

[4] The IPCC denotes likelihood with the following scale: Virtually certain- 99-100% probability; Very likely- 90-100% probability; Likely- 66-100% probability; About as likely as not- 33 to 66% probability; Unlikely- 0-33% probability; Very unlikely- 0-10% probability; Exceptionally unlikely- 0-1% probability.

Extreme events were identified as key issues for all sectors discussed in this report. For example, events relating to water availability – both excesses and shortages – represent concerns for most economic sectors, as well as for biodiversity and human health. Flooding can overwhelm infrastructure, causing not only significant local impacts, but also leading to broader impacts by damaging transportation networks and compromising access and supply chains (Ch. 8). Drought is also associated with many immediate and long-term economic and social impacts (Ch. 4).

As an industry, farming relies upon the inter-annual predictability of seasonal weather as it facilitates crop selection and infrastructure investments (Ch. 4). Unpredictable conditions can cause unanticipated farm losses. For example, an unprecedented heat wave in Ontario in March 2012 caused fruit trees to blossom 5 weeks earlier than usual, and subsequent frosts in April destroyed approximately 80% of apple blossoms (Environment Canada, 2013). Total losses for tender fruits that year were estimated at $100 million (Environment Canada, 2013).

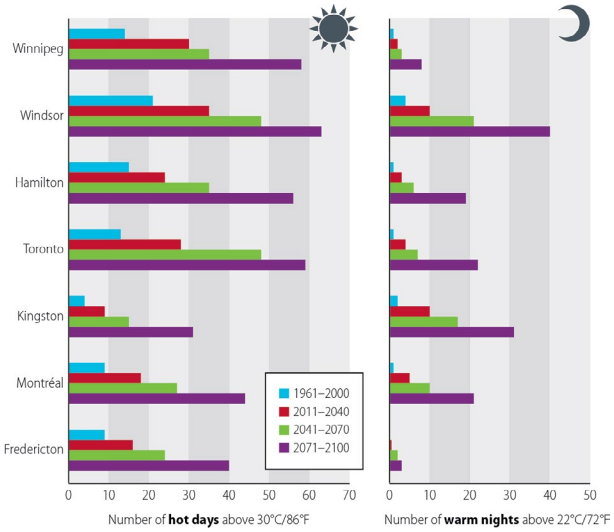


**FIGURE 6:** Historical and projected number of hot days and warm nights for selected cities in Canada (*Source: Casati and Yagouti, 2010*).

## ADAPTATION IS ACCEPTED AS A NECESSARY RESPONSE TO CLIMATE CHANGE. IT ENHANCES THE SOCIAL AND ECONOMIC RESILIENCE OF CANADIANS TO CLIMATE CHANGE IMPACTS (CHAPTERS 3 TO 9).

Across Canada, there is evidence of increasing awareness and acceptance of the need to adapt to climate change (Ch. 9). Broadened engagement in adaptation is reflected across sectors, at all levels of government, in certain industries and companies, as well as in the academic literature (Figure 7) and the media. Discussions now tend to focus on determining where adaptive action is required and improving understanding of the process of adaptation – i.e. how adaptation can be addressed and where capacity to adapt needs to be enhanced.

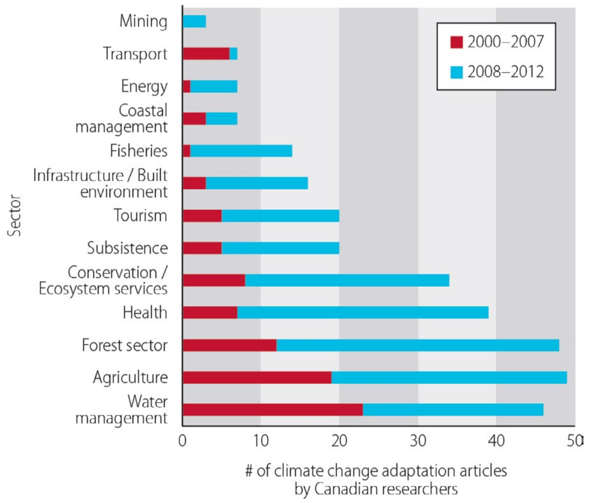


**FIGURE 7:** Number of climate change adaptation articles by Canadian researchers by sector (2000–2012).

This is especially evident for those sectors with greater exposure to weather and weather variability. Direct experience with changing conditions, such as shorter snow seasons for winter tourism (Ch. 5), shifting flow patterns for hydroelectricity generation (Ch. 3) and increasing health impacts from heat (Ch. 7), as well as extreme weather events (e.g. floods, droughts and wildfires) raises awareness of climate change and the severity of potential impacts. In the forest sector, for example, severe wildfires and pest outbreaks in British Columbia and Alberta have contributed to increased awareness of climate change adaptation, spurring industry and governments to begin to move towards adaptive management approaches that proactively address risks and opportunities, rather than depending on crisis management strategies (Ch. 3). Following the 2013 spring flood in Alberta, the provincial government introduced policies to help reduce losses from future flooding events, including new restrictions on redevelopment in floodways and flood fringes (Alberta Government, 2013).

Policies, regulations and guidelines are mechanisms that governments can use to raise awareness and encourage or require adaptive action. The City of Vancouver, for example, reviewed its flood-proofing policies and now encourages applicants with projects in identified flood hazard areas to plan for 1 metre of sea level rise (Ch. 8). For the private sector, factors that enhance awareness include reporting requirements for material risk, and the drive to stay competitive and meet trade demands. Financial disclosure of climate change risks shows promise as a tool to promote climate change adaptation within industry (Ch. 3, 5).

## ADAPTATION IS OCCURRING WITH INCREASING FREQUENCY AND ENHANCED ENGAGEMENT. CONTINUED ACTION WILL HELP TO BUILD CAPACITY, ADDRESS INFORMATION NEEDS AND OVERCOME CHALLENGES (CHAPTERS 3 TO 9).

Since publication of the 2008 assessment there has been a significant increase in the number of adaptation activities in Canada, primarily with respect to planning (including strategies, frameworks, and guidance documents) and initiatives aimed at enhancing adaptive capacity (Table 3). From the breadth and scope of these examples, it is evident that there are many different approaches to adaptation. However, adaptation actions have been mostly incremental in nature, building on existing initiatives, assuming a continuation of current climate trends, and focused on no-regrets actions that are beneficial regardless of future climate. In many cases, action on adaptation was spurred by observed impacts or experience with extreme weather events.

| Adaptation Activities | Sector |
|---|---|
| Provincial governments in BC, Alberta and Quebec are modifying seed transfer guidelines for reforestation to take shifting climate envelopes into account | Forestry (Ch. 3) |
| A hydroelectric corporation is integrating climate change considerations in demand forecasts, informing rate adjustments and procurement plans | Energy (Ch. 3) |
| The mining industry is applying techniques to protect northern infrastructure from permafrost warming (e.g. deeper pile foundations, adjustable foundations) | Mining (Ch. 3) |
| The federal government is revising taxation schemes to help producers manage weather-related risk (e.g. allowing income to be deferred) | Agriculture (Ch. 4) |
| Industry associations in BC are developing a tourism action plan to respond to mountain pine beetle damage | Tourism (Ch. 5) |
| Insurers are adjusting property insurance coverage (e.g. no longer offering sewer back up insurance in communities with recurring losses) | Insurance (Ch. 5) |
| Subsidy programs have been adopted by a number of municipalities to encourage the installation of backwater valves that can help to reduce flood damage from an increase in the frequency and intensity of rainfall events | Residential Housing (Ch. 5) |
| The Manitoba government is protecting winter habitat for the Qamanirjuaq barren-ground caribou herd in the transition zone between boreal and tundra ecosystems | Biodiversity and Protected Areas (Ch. 6) |
| The federal government is developing tools to guide public health managers on vector-borne disease surveillance and control methods | Health (Ch. 7) |
| Communities across the country are developing heat alert and response systems to protect health from extreme heat events | Health (Ch. 7) |
| A risk assessment of three coastal roads in Nova Scotia led to recommendations that include engineered shoreline protection and relocation of selected roads further inland | Infrastructure (Ch. 8) |
| Cambridge and Milton, ON are performing economic assessments of the implications of climate change for drainage infrastructure design | Infrastructure (Ch. 8) |

**TABLE 3:** Examples of adaptation activities from different sectors.

Progress on adaptation is evident, and the examples presented in this report are indicative of the type of actions that will become increasingly necessary as the climate continues to change. However, more work is needed. All chapters in this report identify information needs and knowledge and data gaps, and many discuss barriers and challenges to adaptation, including limited resources, limited motivation and issues related to governance (Ch. 9). In addition, by analyzing the examples available, it is apparent that there are relatively few examples of concrete, on-the-ground adaptation measures being implemented specifically to reduce vulnerability to projected changes in climate. This indicates that, similar to other developed countries, adaptation in Canada is still in its early stages overall. It is also recognized that the methodology of this assessment, with its focus on scientific literature, may result in an underestimation of the actual number of adaptation actions being undertaken in Canada.

Planned adaptation takes time. Adaptation often requires research, stakeholder engagement and adjustments to policies and regulations. For example, while a year-round road has been proposed to ensure access to northern mining sites to help address the declining reliability of ice-road networks (Ch. 8), this type of project cannot be undertaken without detailed planning, consultations and environmental impact studies. In the fisheries sector, fishers cannot simply adjust their harvests in response to shifting species assemblages – this requires governments to revise management plans and fishing permits (Ch. 4).

There will also be cases where maintaining current activities is not feasible and/or cost-effective, requiring discussions to extend beyond consideration of incremental, no-regrets approaches to more transformative changes. The emerging concept of transformational change refers to larger-scale, more extensive adaptations that are new to a region or resource system (Ch. 9). Transformational change may also challenge the status quo and thereby question perceptions of what is acceptable. Examples include relocating entire towns due to sea level rise; converting forest plots to parkland to reduce losses from forest fires; and designing flood-control infrastructure to fail safely (with minimal damage and losses), rather than withstand large-magnitude events. The need for transformational adaptation is likely to become more prevalent as the climate continues to change.

## ADAPTATION CAN SOMETIMES TURN RISKS INTO OPPORTUNITIES, AND OPPORTUNITIES INTO BENEFITS (CHAPTERS 3 TO 9).

While adaptation research and programming tend to focus on reducing vulnerability to negative impacts, some impacts of climate change could represent opportunities. Capturing these opportunities requires appropriate adaptation.

This may be most evident in the tourism and agriculture sectors, which both stand to potentially benefit from longer summers. With effective adaptation (e.g. strategies to deal with potential water shortages), major warm-weather tourism markets in Canada could benefit from climate change, with the golf industry, for example, profiting from increased season length and demand (Ch. 5). Similarly, with higher summer temperatures, different types of crops may be able to be grown farther north (e.g. corn and soybeans in new areas in Quebec, canola in Prince George, BC, and spring seeded small grains in western Alberta and northeastern BC; Ch. 4). Producers would need to adapt their crop selections and timing (e.g. seeding earlier in order to decrease exposure to drier late summer conditions) to take advantage of these opportunities. In all cases, risks related to increased pests, heat waves and other extreme events will also need to be addressed. In the North, changing climate and ice conditions bring potential economic opportunities related to natural resource development and tourism (Ch. 3, 5, 6). However, in addition to presenting opportunities for employment and investment, such activities also bring environmental and cultural risks.

Innovative ideas and approaches may help reduce losses associated with climate change, at least on a short-term basis. For example, faced with a surplus of blue stained wood from the Mountain Pine Beetle outbreak, the forest industry in BC began marketing the product for interior paneling and unique wood furniture, after completing studies to confirm the wood would perform to acceptable standards (Ch. 3). Also in BC, the city of Vancouver used the damage caused by the 2006 windstorm in Stanley Park as an opportunity to increase public engagement in the park and replant a more wind-resilient forest (Ch. 3). Some tourism operators and recreation sites are considering promoting "last chance tourism", where additional tourists are drawn to a park to see either changing landscapes or certain features (e.g. glaciers or certain wildlife species) before they decline or disappear (Ch. 5, 7).

## COLLABORATION AND ADAPTIVE MANAGEMENT ARE APPROACHES THAT GOVERNMENTS AND INDUSTRY ARE INCREASINGLY PURSUING TO ADVANCE ADAPTATION (CHAPTER 9).

Collaboration has emerged as an important mechanism for successful and efficient adaptation to climate change. Across sectors, there is a common challenge of needing to adapt to continuous cumulative changes with limited resources. By learning from the work of others (e.g. through assessments, communities of practice and workshops) and collaborating with organizations that share similar goals, efficiencies and synergies can be found. Numerous examples of collaborations between different levels of government, as well as industry and non-governmental groups are discussed throughout this report (Box 2) and continued collaboration will be a key driver moving adaptation forward. While roles and mandates may differ between jurisdictions and organizations, the end goals of reducing vulnerability to climate change and enhancing resilience are shared.

Many sectors are starting to use adaptive management approaches (Figure 8) to deal with changes in climate and other stressors and related uncertainties (which will always be present in adaptation decision-making). Adaptive management involves ongoing monitoring, adjusting, experimenting and re-evaluating, and requires a flexible and responsive approach to adaptation. Examples of adaptive management approaches discussed in this report include operations related to hydroelectric generation (Ch. 3), water level management on the Great Lakes (Ch. 8, 9), and forest stand management (Ch. 3).

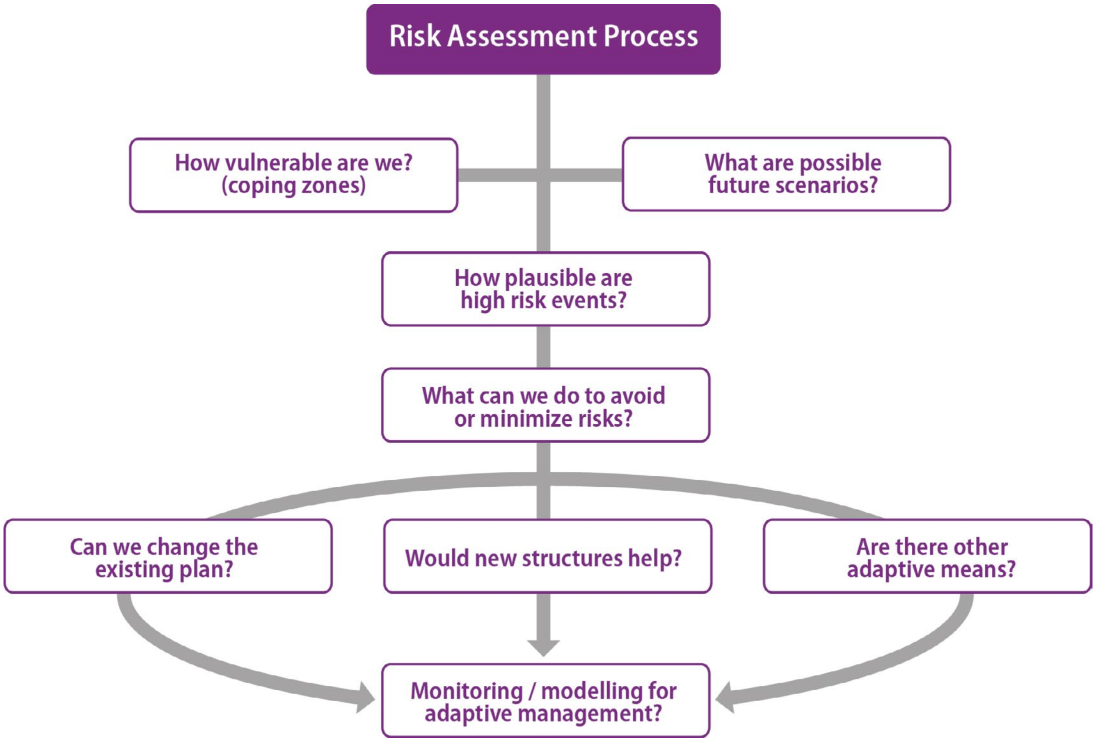


**FIGURE 8:** Adaptive management assessment process (*modified from Leger and Read, 2012, Figure 2-1, p. 8*).

BOX 2

## EXAMPLES OF CASE STUDIES HIGHLIGHTING COLLABORATION

**Collaboration to enhance adaptation decision-making (Chapter 9, Case Study 1):** Canada's federal, provincial and territorial governments have invested in collaborative programming as a cornerstone for advancing knowledge and action on adaptation, through past activities (e.g. the Canadian Climate Impacts and Adaptation Research Network [C-CIARN]) and ongoing initiatives. The most recent mechanism to enhance collaboration on adaptation across Canada is the Adaptation Platform which brings together governments, professional organizations, industry associations and financial sector representatives to address shared adaptation priorities.

**A Historical Example of Institutional Capacity for Adaptation in the Agricultural Sector – The Prairies (Chapter 4, Case Study 3):** Local communities and the farm industry worked in collaboration with academic researchers and the provincial/federal governments to establish solutions to improve resiliency to drought conditions experienced in the early 1900s. Through this collaboration, new innovative farming methods were introduced and agricultural management was made more efficient.

**The Municipal Risk Assessment Tool (Chapter 5, Case Study 2):** The Insurance Bureau of Canada brought together a team of experts including hydrologists, climate scientists, risk managers and infrastructure engineers to develop a tool (The Municipal Risk Assessment Tool – MRAT) that identifies risk zones for exposure to basement flooding at the neighbourhood level.

**Building a "Better than Building Code" Home (Chapter 5, Case Study 4):** The Institute for Catastrophic Loss Reduction and The Co-operators General Insurance Company worked together to demonstrate the benefits of enhanced construction by building a demonstration home in West Point, Prince Edward Island. Designed to be more weather resilient, the demonstration home incorporated new technologies and practices to ensure the home's ability to withstand extreme wind events.

**A landscape approach to ecological restoration (Chapter 6, Case Study 4):** Conservation partners from the public and private sectors supported efforts to plant over 4.5 million native trees and shrubs, and currently use restoration techniques to mimic features of old-growth Carolinian forests to help preserve biodiversity in the Long Point World Biosphere Reserve, which includes the Long Point National Wildlife Area along the north shore of Lake Erie (Ontario). This work is helping to create corridors and enhance ecosystem resilience and adaptive capacity throughout the Biosphere Reserve.

**Citizen-based Monitoring Programs (Chapter 6, Case Study 5):** As part of The Reef Environmental Education Foundation's (REEF) volunteer fish and invertebrate monitoring program, participants are trained to identify target species and implement a simple roving diver survey method. More than 3700 volunteer surveys have been carried out along the British Columbia coastline through this program, representing more than 2800 hours of underwater observations at more than 300 sites.

**Manitoba Flood 2011: Impetus for a Provincial Approach to Psychosocial Adaptation to Natural Hazards (Chapter 7, Case Study 3):** Many organizations, including Manitoba Health's Office of Disaster Management, Emergency Social Services, Emergency Measures Organization, Aboriginal Affairs and Northern Development Canada, Manitoba Agriculture and Food Rural Initiatives, Manitoba Family and Rural Support Services, Water Stewardship and Conservation, and Aboriginal and Northern Affairs worked in collaboration to establish the Provincial Psychosocial 2011 Flood Recovery Table in response to the 2011 flood in Manitoba.

*Box 2 continued on next page*

**City of Calgary Water Supply Infrastructure Vulnerability Assessment (Chapter 8, Case Study 1):** In 2011, the City of Calgary, together with Engineers Canada, conducted a vulnerability risk assessment of its water supply infrastructure. The team worked together to determine which climatic conditions pose the greatest risks to the design, construction, operation and management of the water supply infrastructure, in order to enhance the resiliency and quality of the system.

**British Columbia Sea Dyke Guidelines (Chapter 8, Case Study 2):** The BC provincial government, the Association of Professional Engineers and Geoscientists of British Columbia, and others worked with policymakers and planners to incorporate sea level rise into coastal floodplain mapping, sea dyke design and land use planning. Building on these outputs, a working group went on to develop a national Sea Level Rise Primer (www.env.gov.bc.ca/cas/adaptation/pdf/SLR-Primer.pdf) to help other communities identify, evaluate and compare adaptation options, and showcase different types of tools for adaptation.

**Promoting adaptation by sharing information and knowledge through a virtual community of practice (Chapter 9, Case Study 4):** The Climate Change Adaptation Community of Practice (CCACoP) is an interactive online portal that provides space for researchers, experts, policymakers and practitioners from across Canada to come together to ask questions, generate ideas, share knowledge and communicate with others working on climate change adaptation. It is a key information and knowledge-sharing network on climate change adaptation in Canada.

## CONCLUSION

Changes in the climate system and associated impacts on both natural and human systems are occurring in Canada. As a result, the need to adapt is increasingly recognized and acted upon by governments, industry and other organizations. Over the past 5 years, our understanding of the adaptation process has improved and examples of adaptation implementation have grown. We have seen broadened engagement on the issue, and changes being made to policies, plans and practices to increase resilience to climate change. Further adaptation is necessary to complement mitigation in helping to prevent and reduce future impacts, as well as to take advantage of potential opportunities. We now have the awareness and capacity to adapt in many cases; translating this to action will require continued collaborative efforts to reduce barriers, overcome challenges and enhance motivation to adapt.

## REFERENCES

Alberta Government (2013): Flood Choices for Albertans, online, <https://pabappsuat.alberta.ca/albertacode/images/Flood-Choices-for-Albertans.pdf>.

Casati, B. and Yagouti, A. (2010): Analysis of extreme temperature indices in nine Canadian communities using the Canadian Regional Climate Model projections for public health planning; Ouranos.

Environment Canada (2011): Annual 2011 Summary, Climate Trendsand Variability Report, online, <ec.gc.ca/adsc-cmda/default.asp?lang=En&n=F3D25729-1>.

Environment Canada (2013): Canada's Top Ten Weather Stories for 2012, online, <ec.gc.ca/meteo-weather/default.asp?lang=En&n=70B4A3E9-1>.

Hartmann, D.L., Klein Tank, A.G., and Rusticucci, M. (2013): Chapter 2: Observations: Atmosphere and Surface – Final Draft Underlying Scientific-Technical Assessment; in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IBC [Insurance Bureau of Canada] (2008): Facts of the General Insurance Industry in Canada; Toronto: Insurance Bureau of Canada.

IBC [Insurance Bureau of Canada] (2011b): Southern Alberta Windstorms Cost $200 Million in Insured Damage; Insurance Bureau of Canada; <http://www.ibc.ca/en/Media_Centre/News_Releases/2011/12-22-2011.asp>.

IBC [Insurance Bureau of Canada] (2013a): June Alberta Floods are Costliest Insured Natural Disaster in Canadian History – Estimate of insured losses exceed $1.7 billion; Media Release, September 23, 2013, online, <ibc.ca/en/Media_Centre/News_Releases/2013/June_Alberta_Floods_are_Costliest_Insured_Natural_Disaster_in_Canadian_History.asp>.

IBC [Insurance Bureau of Canada] (2013b): Preliminary insured losses released in the most expensive natural disaster in Ontario history – IBC expects the number to go even higher; Media Release, August 14, 2013, online, <ibc.ca/en/Media_Centre/News_Releases/2013/Preliminary_insured_losses_released_in_the_most_expensive_natural_disaster_in_Ontario_history.asp>.

IPCC (2013): Summary for Policymakers; in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, Nauels, A., Xia, Y. Bex, V., P.M. Midgley, Casati, B. and Yagouti, A. (2010): Analysis of extreme temperature indices in nine Canadian communities using the Canadian Regional Climate Model projections for public health planning; Ouranos. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Leger, W. and Read, J. (2012): Adaptive management: strategy and legacy; in Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels; Final report to the International Upper Great Lakes Study Board, Adaptive Management Technical Work Group, 167 p.

McBean, G. (2012): Telling the Weather Story; Institute for Catastrophic Loss Reduction and Insurance Bureau of Canada.

Mekis, E. and Vincent, L.A. (2011a): An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada; Atmosphere-Ocean, v. 2, p. 163-177.

Mekis, E. and Vincent, L.A. (2011b): Trends in indices related to agroclimatic conditions based on homogenized temperature and adjusted precipitation in Canada; 19th Conference on Applied Climatology, 18–20 July 2011, Asheville, NC, USA. <http://ams.confex.com/ams/19Applied/webprogram/Paper190186.html>.

Natural Resources Canada (2012c): The threat of mountain pine beetle to Canada's boreal forest; <http://www.nrcan.gc.ca/forests/insectsdiseases/13381>.

Perovich, D., Meier, W., Tschudi, M., Gerland, S., and Richter-Menge, J. (2012): Sea ice; in Arctic Report Card 2012, (ed.) M.O. Jeffries, J. A. Richter-Menge and J. E. Overland, online, <http://www.arctic.noaa.gov/report12/>.

Vincent, L. A., Wang, X. L., Milewska, E. J., Wan, H., Yang, F., and Swail, V. (2012): A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis; Journal of Geophysical Research, v. 117, D18110.

Zaturecky I. and Chiu, I. (2005): Alternative wood products from blue-stained mountain pine beetle lumber: non-structural laminated products; Mountain Pine Beetle Initiative Working Paper 2005–7, Natural Resources Canada, online, <cfs.nrcan.gc.ca/pubwarehouse/pdfs/25479.pdf>.

## CHAPTER CITATIONS

**Chapter 2**

Bush, E.J., Loder, J.W., James, T.S., Mortsch, L.D. and Cohen, S.J. (2014): An Overview of Canada's Changing Climate; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 23-64.

**Chapter 3**

Lemmen, D.S., Johnston, M., Ste-Marie, C. and Pearce, T. (2014): Natural Resources; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 65-98.

**Chapter 4**

Campbell, I.D., Durant, D.G., Hunter, K.L. and Hyatt K.D. (2014): Food Production; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 99-134.

**Chapter 5**

Kovacs, P. and Thistlethwaite, J. (2014): Industry; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 135-158.

**Chapter 6**

Nantel, P., Pellatt, M.G., Keenleyside, K. and Gray, P.A. (2014): Biodiversity and Protected Areas; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 159-190.

**Chapter 7**

Berry, P., Clarke, K., Fleury, M.D. and Parker, S. (2014): Human Health; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 191-232.

**Chapter 8**

Andrey, J., Kertland, P. and Warren, F.J. (2014): Water and Transportation Infrastructure; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 233-252.

**Chapter 9**

Eyzaguirre, J. and Warren, F.J. (2014): Adaptation: Linking Research and Practice; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, edited by F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 253-286.

# CHAPTER 1:
# INTRODUCTION

Lead Authors:

**Fiona J. Warren** and **Donald S. Lemmen** *(Natural Resources Canada)*

Recommended Citation:

Warren, F.J. and Lemmen, D.S. (2014): Introduction; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 19-22..

In 2008, Canada completed its second national science assessment on climate change impacts and adaptation – *From Impacts to Adaptation: Canada in a Changing Climate* (Lemmen et al., 2008). From a regional perspective, this assessment covered climate change risks and opportunities, and actions being taken to address them, highlighting key vulnerabilities and the potential for adaptation within human and managed systems. The current report, *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation*, is an update to the 2008 assessment. It focuses on research and knowledge developments made over the past 6 years in Canada's economic, social and environmental sectors.

Since 2008, there has been significant progress on both adaptation research and practice, in Canada and internationally. Our understanding of impacts, both observed and projected, has also improved. Increased attention is being paid to climate-related risks, particularly those associated with extreme rainfall and flooding events. At the same time, confidence relating to observed changes in the climate system and the drivers behind these changes has increased (*see* Box 1), and the associated social, economic and environmental impacts have become more apparent. Many consider climate change to be one of the most pressing challenges we are facing today.

Adaptation is now recognized as an essential response to climate change that complements efforts to reduce greenhouse gas emissions. Adaptation involves making adjustments in our decisions, activities and ways of thinking in response to observed or expected changes in climate, with the goals of (a) reducing harm and (b) taking advantage of potential opportunities. Adaptation can include behavioural changes, operational modifications, technological interventions, planning changes and revised investment practices, regulations and legislation. While adaptation in the natural environment occurs spontaneously, adaptation in human systems often benefits from careful planning that is guided by both scientific research and detailed understanding of the systems involved. Some examples of adaptation discussed in this report include: 1) the application of deeper pile foundations and adjustable foundations to protect northern mining infrastructure from damage caused by permafrost warming; and 2) the development of heat alert and response systems to protect communities from the health impacts of extreme heat events.

The volume of scientific publications focused on impacts and adaptation has risen substantially over the past 10 years, with the subject areas becoming increasingly diverse. At the same time, the focus in the research has expanded beyond

## WHAT ARE SCIENCE ASSESSMENTS?

Science assessments (Figure 1) are reports that assess, critically analyze and synthesize a growing knowledge base, drawing from published and grey literature. They are generally broad in scope, and are typically undertaken at global, regional, national and sometimes subnational scales. The Intergovernmental Panel on Climate Change (IPCC), for example, produces climate change assessments at the global scale (e.g. IPCC, 2012, 2013). As part of Canada's Adaptation Platform, the Climate Change Impacts and Adaptation Division (CCIAD) of Natural Resources Canada works with other experts in governments, universities and non-government organizations to produce science assessments on climate change impacts and adaptation that provide current, relevant and accessible sources of information to help inform the planning of programs, policies and actions. In addition to this report, CCIAD is leading or co-leading targeted assessments on climate change impacts and adaptation in Canada's a) coastal regions, b) transportation sector, and c) mining sector.

**FIGURE 1:** Examples of past assessments.

BOX 1

## THE CHANGING CLIMATE

It is evident that our climate is changing. On a global scale, average air and ocean temperatures are increasing (Figure 2), snow and ice coverage is decreasing, and sea level is rising. These trends have been clearly documented by a strong and growing body of scientific evidence (e.g. IPCC, 2013). In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change concluded that "warming of the climate system is unequivocal" (IPCC, 2007), which it expanded upon in the recently released Fifth Assessment Report, noting that recent changes are without precedent over the scale of decades to millennia (IPCC, 2013). In addition to the trends cited above, there have been observed changes in precipitation, wind patterns, and some aspects of extreme weather events (e.g. droughts, heat waves and cyclones) (IPCC, 2012, 2013).

It is also evident that changes in the global climate result from a combination of natural and anthropogenic factors. The changes observed over the 20th century have been primarily attributed to human activity, such as the burning of fossil fuels and shifts in land-use patterns. This dominant anthropogenic influence is expected to persist throughout the present century and beyond (IPCC, 2013). While reducing greenhouse gas emissions is vital to reducing the rate and magnitude of climate change, further warming of the climate system is inevitable. Due to the nature of the Earth's climate system, warming would continue even with aggressive mitigation measures (IPCC, 2013).

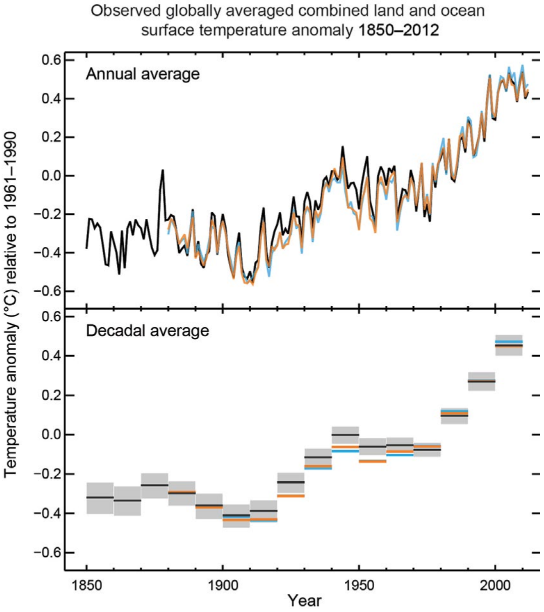


**FIGURE 2:** Observed global mean land and ocean surface temperature anomalies (from 1850-2012) from three data sets. Top panel shows annual mean values, bottom panel shows decadal mean values *(Source: IPCC, 2013).*

biophysical impacts accompanied by lists of potential adaptation options, to studies that examine the process of adaptation (the drivers and barriers) from a variety of perspectives. There are also growing examples of adaptation uptake and implementation – by governments, industry and non-governmental organizations.

This update report focuses on these recent developments in adaptation, as well as our improved understanding of the impacts of climate change. It builds upon the both the concepts and content of the 2008 assessment, and readers seeking additional information are directed to the previous report, in particular the chapter on concepts, overviews and approaches (Warren and Egginton, 2008) and the glossary. The current report assesses and synthesizes existing literature (including peer-reviewed, published and grey literature) on climate change impacts and adaptation in Canada, to discuss what we have learned since the publication of the last assessment. The sectoral/thematic approach was chosen to best present new knowledge available, and to better reach new audiences. These chapters highlight key developments in the sectors discussed, rather than presenting a comprehensive compilation of all relevant impacts and adaptation issues.

## REPORT FORMAT

This report – *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* – contains nine chapters and a synthesis. This Introduction (Chapter 1) is followed by a supporting chapter, An Overview of Canada's Changing Climate (Chapter 2), which presents observed and projected changes in climate (temperature, precipitation, extreme events) and discusses first-order impacts (including changes in sea level, sea ice, ocean climate, freshwater levels and flow, and lake ice). While some global scale results are included, Chapter 2 focuses on Canada, and provides supporting background information that will help provide context to assist readers in their interpretation of the impacts and adaptation discussions in the thematic chapters. It does not represent a comprehensive assessment of the state of knowledge on the changing climate system, but rather is intended to provide non-climate science specialists with an overview of key observed and projected changes.

Chapters 3 to 8 constitute the main body of the assessment and are structured according to the following sectors and themes: Natural Resources; Food Production; Industry;

Biodiversity and Protected Areas; Human Health; and Water and Transportation Infrastructure. These chapters address current sensitivities to climate, as well as the risks and opportunities presented by climate change. Adaptation options, approaches and planning are also discussed. Case studies are used to provide more detail on selected issues, to highlight examples of effective adaptation initiatives and to identify transferable lessons learned. Each of these chapters begins with key findings and a summary of relevant findings from the 2008 assessment report. However, in recognition of the significant differences between the sectors and the volume of new information available, they do not follow a common template.

The concluding chapter of this report, Adaptation: Linking Research and Practice (Chapter 9), examines adaptation in Canada in terms of both research and practice. It examines how research, engagement, practical adaptation action and understanding of the barriers and enablers of adaptation have progressed since the 2008 assessment report.

## REFERENCES

IPCC [Intergovernmental Panel on Climate Change] (2007): Summary for Policymakers; in Climate Change 2007: The Physical Science Basis, 18 p.

IPCC [Intergovernmental Panel on Climate Change] (2012): Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation; A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, (ed.) C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen,M. Tignor, and P.M. Midgley; Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 p.

IPCC [Intergovernmental Panel on Climate Change] (2013): Summary for Policymakers, in Climate Change 2013: The Physical Science Basis, 27 p.

Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E. (ed.) (2008): From Impacts to Adaptation: Canada in a Changing Climate; Governmentof Canada, 448p.

Warren, F.J. and Egginton, P.A. (2008): Background Information; in From Impacts to Adaptation: Canada in a Changing Climate, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, p. 27-56.

# CHAPTER 2:
# AN OVERVIEW OF CANADA'S CHANGING CLIMATE

Lead Authors:

**Elizabeth J. Bush** *(Environment Canada)*, **John W. Loder**, *(Fisheries and Oceans Canada)*, **Thomas S. James** *(Natural Resources Canada)*, **Linda D. Mortsch** and **Stewart J. Cohen** *(Environment Canada)*

Contributing Authors:

**Laura Brown**, **Ross Brown**, **Chris Derksen**; **Grace Koshida**, **Eva Mekis**, **Robin Rong** and **Lucie Vincent** *(Environment Canada),* **David Burgess**, **Mike Demuth**, **Gavin Manson** and **Sharon Smith** *(Natural Resources Canada)*, **Peter Chandler**, **Eugene Colbourne**, **Bill Crawford**, **Howard Freeland**, **Peter Galbraith**, **Denis Gilbert, Debby Ianson**, **Roger Pettipas**, **Michel Starr**, **Frank Whitney** and **Igor Yashayaev** *(Fisheries and Oceans Canada)*

Recommended Citation:

Bush, E.J., Loder, J.W., James, T.S., Mortsch, L.D. and Cohen, S.J. (2014): An Overview of Canada's Changing Climate; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 23-64.

# TABLE OF CONTENTS

# 1. INTRODUCTION

Warming of the global climate over the past century is unequivocal. It is evident in global atmospheric and oceanic temperature data, and from changes in a variety of other physical indicators, including declines in snow and ice cover. Emissions of greenhouse gases (GHGs) from human activity are the main cause of recent global warming and are expected to be the dominant cause of further warming over the coming century, the magnitude of which will be strongly influenced by whether anthropogenic emissions of GHGs continue to grow or are curtailed. These widely accepted conclusions are supported by a large body of evidence (e.g. IPCC, 2007; AMAP, 2011; NRC, 2011; IPCC, 2012, 2013) and provide the global context for examining current and projected changes in Canada's climate.

This chapter presents an overview of observed and future changes in a number of key indicators of the physical climate system (Figure 1) and provides context for the chapters that follow, highlighting significant advances in understanding since the 2008 Assessment Report ('From Impacts to Adaptation: Canada in a Changing Climate'; Lemmen et al., 2008). Focus is placed on the national scale, although regional trends and changes are described where suitable data exist. The Arctic receives particular attention due to the wealth of regional data that has been amassed for various cryospheric indicators. In addition, given the differing nature of the ocean basins bordering Canada, a regional perspective is necessary for discussion of changes in ocean climate, and in the section on freshwater resources, since available studies are primarily watershed-based.

It should be noted that this chapter does not provide climate change scenarios as a basis for the assessment in subsequent chapters. A few illustrative future climate change scenarios are presented for specific indicators and time periods. Also, this chapter makes only limited use of the results of the many new observational, modeling and analysis studies that have been appearing in the literature during the chapter's preparation, and which were synthesized in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, the first volume of which was released in 2013 (Stocker et al., 2013).

This chapter documents the evidence that shows that climate change in Canada is occurring, and discusses changes that are expected in the future, which will impact both natural and managed environments and the many economic and social activities that depend on them. This chapter provides a backdrop to what readers may experience in their own communities. It serves to illustrate the large forces at play, and how changes experienced locally will be nested within changes occurring within Canada, North America and globally.

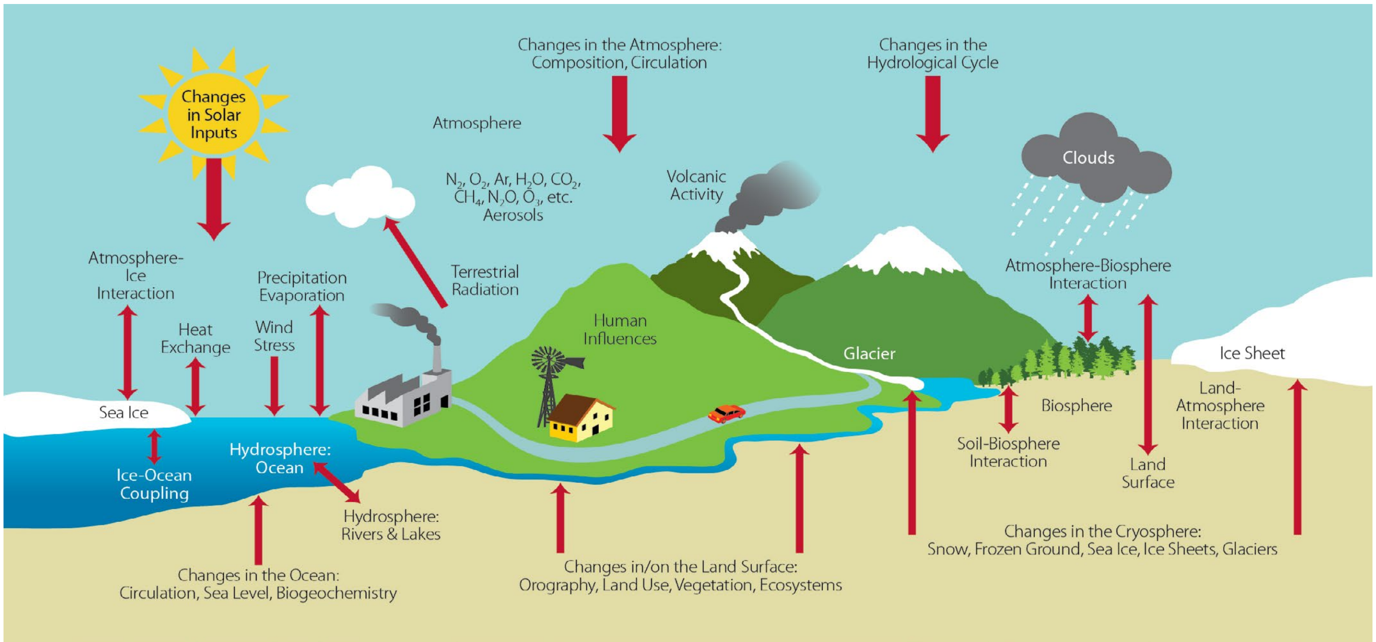


**FIGURE 1:** An illustration of the main components of the climate system (the atmosphere, hydrosphere [liquid water components], cryosphere [frozen water components], lithosphere [land surface] and biosphere [living things]) and the interactions between them. This chapter reports on four of the six changes shown in this schematic, excluding changes on the land surface and in solar outputs *(Source: Le Treut et al., 2007).*

# 2. CHANGES IN AIR TEMPERATURE AND PRECIPITATION

## 2.1 OBSERVED CHANGES IN TEMPERATURE AND PRECIPITATION

### 2.1.1 TEMPERATURE

**GLOBAL**

A 100-year warming trend[1] of 0.74°C ± 0.18 °C in global surface air temperature was observed for the period 1906-2005 (IPCC, 2007). Several reports, including the World Meteorological Organization (WMO) Statement on the Status of the Global Climate (WMO, 2013) and the American Meteorological Society (AMS) State of the Climate Report (Blunden and Arndt 2012) have identified 2010, globally, as either the warmest or second warmest year on record (ranking varies very slightly with the methods used by different agencies to estimate global mean temperature) and have confirmed the existence of a strong, long-term global warming trend (Figure 2A , WMO, 2013). In addition, the decade 2001-2010 was the warmest on record, 0.21°C warmer than the previous decade, 1991-2000, which in turn was warmer than previous decades, consistent with a long-term warming trend (Figure 2B; WMO, 2011). Surface temperatures over land have warmed faster than over the oceans, with greatest warming over high northern latitudes (Trenberth et al., 2007). The Arctic continues to warm at about twice the rate of lower latitudes (Richter-Menge and Jeffries, 2011).

Natural fluctuations in climate can induce periods of a decade or two with little change in temperature, even with increasing levels of GHGs in the atmosphere (Easterling and Wehner, 2009). Despite the apparent slowdown in the rate of observed global warming over the last decade (*see* Figure 2A), twelve of the thirteen warmest years on record have been in the 21st century, the only exception being 1998 which was influenced by the strongest El Niño of the last century (WMO, 2013). The probability is very low that such a clustering of exceptionally warm years at the end of the observational record would occur in a climate that was not undergoing long-term warming (Zorita et al., 2008). When changes in natural factors known to influence short-term climate variability (e.g. volcanic eruptions and changes in solar radiation) are accounted for, the rate of global warming since 1980 has been shown to be steady (Foster and Rahmstorf, 2011).

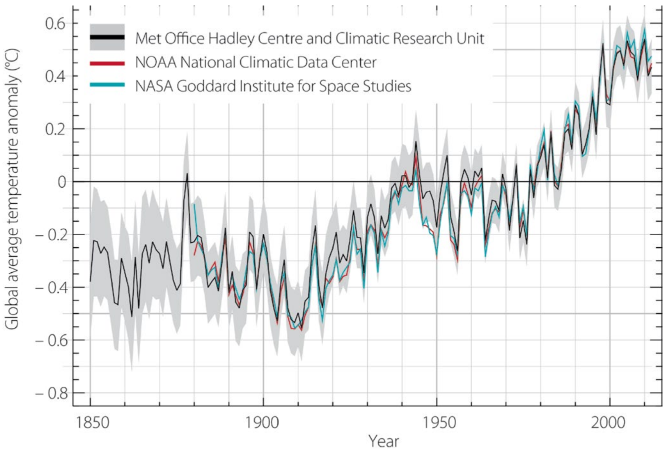


**FIGURE 2A:** Annual global average temperature anomalies (relative to 1961-1990) from 1850 to 2012 from the Hadley Centre/CRU (HadCRUT4) (black line and grey area, representing mean and 95% uncertainty range), the NOAA National Climatic Data Centre (red) and the NASA Goddard Institute for Space Studies (blue) *(Source: WMO, 2013).*

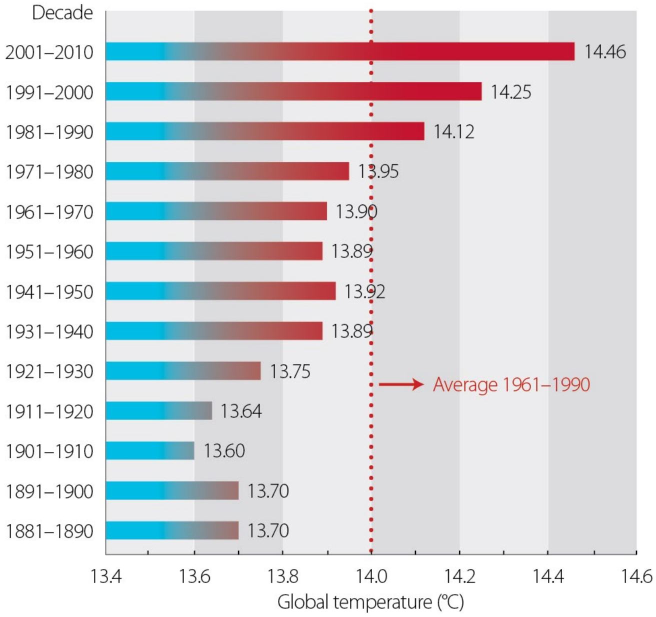


**FIGURE 2B:** Decadal global average combined land-ocean surface temperature (°C), combining three global datasets *(Source: WMO, 2011).*

---

[1] This long term trend was recently updated and is reported to be 0.85 [0.65 to 1.06°C] over the period 1880-2012 (IPCC, 2013).

Human activities affect the climate system by changing the land surface (e.g. deforestation) and altering the composition of the atmosphere. The latter involves increasing atmospheric concentrations of GHGs (that exert a warming influence) and also increasing concentrations of airborne particles (aerosols) that, for the most part, exert a climate cooling effect. Global warming since the mid-twentieth century has been attributed primarily to human emissions of GHGs (Hegerl et al., 2007). Similarly, a human influence on climate warming since the mid-twentieth century has been demonstrated for North America (Hegerl et al., 2007; Stott et al., 2010), Canada (Zhang et al., 2006) and over the entire 20th century for the Arctic (Gillet et al., 2008).

## CANADA

The annual average surface air temperature over the Canadian landmass has warmed by 1.5°C over the period 1950-2010 (Figure 3; Vincent et al., 2012, *see* Box 1). Recent analysis shows that 2011 and 2012 were 1.5°C and 1.9°C warmer than the reference period (1961-1990 average); therefore, 2010 still stands as the warmest year on record in Canada, at 3.0°C above normal (Environment Canada, 2012).

While warming has been observed consistently across most of Canada, stronger trends are found in the north and west and warming has been weak along the Atlantic coast (Figure 4; *see also* Box 2). This regional pattern of stronger warming in the west vs. the east has been observed across North America and has been linked to shifts in large-scale atmosphere-ocean circulation patterns (Trenberth et al., 2007; *see* Box 3). Daily minimum temperatures in Canada have been rising slightly faster than daily maximum temperatures over 1950-2010. Warming in Canada is generally observed in all seasons (Vincent et al. 2012), with the greatest warming since 1950 occurring in winter and spring, with strong warming particularly evident in the western half of the country in these seasons (Figure 5). Warming trends are generally much weaker in the summer and fall; spatially, the summer warming is observed across the country, whereas during the fall, the warming is pronounced in the north and east (Figure 5). The spatial pattern of temperature changes during all seasons is consistent with previously reported patterns (Zhang et al., 2000), although the previously reported cooling in the northeast of the country is no longer evident in the longer time series due to recent warming in this region.

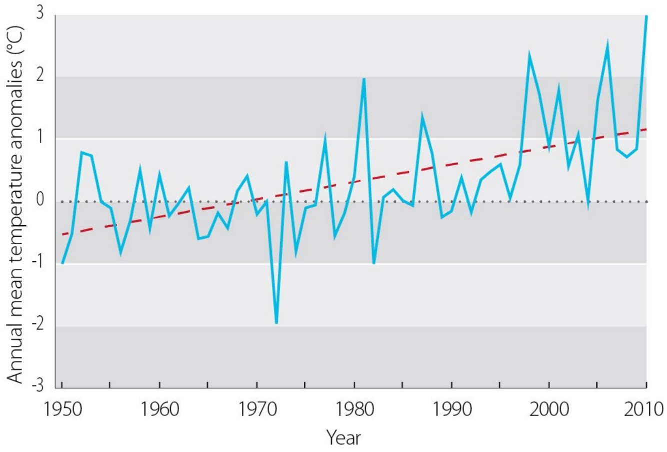


**FIGURE 3:** Annual mean temperature anomalies for Canada (°C), 1950-2010. Anomalies are calculated as departures from the 1961-1990 average (represented by zero on the Y-axis). A warming trend of 1.5°C over the period 1950-2010 is indicated by the red line *(Source: Vincent et al., 2012; Environment Canada, 2011).*

**BOX 1**

### CREATING CLIMATE DATA SETS FOR LONG TERM TREND ANALYSIS

Canada's climate varies considerably from one region to another, and is characterized by significant variability – seasonally, from year to year, and over periods of multiple years. The challenge for climate change analysis is to detect a persistent trend (in annual or seasonal temperature or precipitation, for example) over space and time that may not be readily obvious from the 'noisy' data. To do this well, long term, continuous, data sets with good spatial coverage over the country are needed.

Since most climate stations in northern Canada were only established in the late 1940s, analysis of climate trends for the country as a whole is only possible from the second half of the 20th century onwards. Even over this period, there have been changes in observing practice, including instrumentation and instrument location, and some site locations have changed. These changes can generate artificial shifts in the data – referred to as "inhomogeneities" – that can interfere with climate trend analysis. In addition, there are known systematic biases in some instruments (e.g. wind-induced undercatch of precipitation by rain gauges) for which corrections are required. Reliable trend estimates can only be calculated when appropriate adjustments have been made to the original data to account for these methodological changes. This process is called "data homogenization". Stations selected for long term climate trend analysis are located outside major urban areas so no adjustments to the data are required to account for urban heat-island effects.

BOX 2

## DEPICTING SPATIAL PATTERNS IN CLIMATE TRENDS ACROSS CANADA

Climate data are recorded at climate stations across the country and processed for long-term trend analysis (*see* Box 1). Spatial coverage of climate stations is uneven, with relatively few stations in northern Canada compared to southern Canada.

The maps of temperature and precipitation trends presented in this chapter (Figures 4, 5, and 7 to 10) provide information about the spatial coverage of the long-term stations, regional trends and the significance of those trends. Analysis and interpretation of these maps should focus on broad-scale patterns of change in and between different regions of the country, rather than on the trend values at specific sites. To illustrate future climate change, maps with continuous coverage (*see* Section 2.2) can be used because the climate models used to generate future climate simulations are grid-based and do not rely on input from observing networks. However, since variations at the scale of the computer grid and smaller are not resolved in these models, the focus of attention should still be on broad-scale patterns.

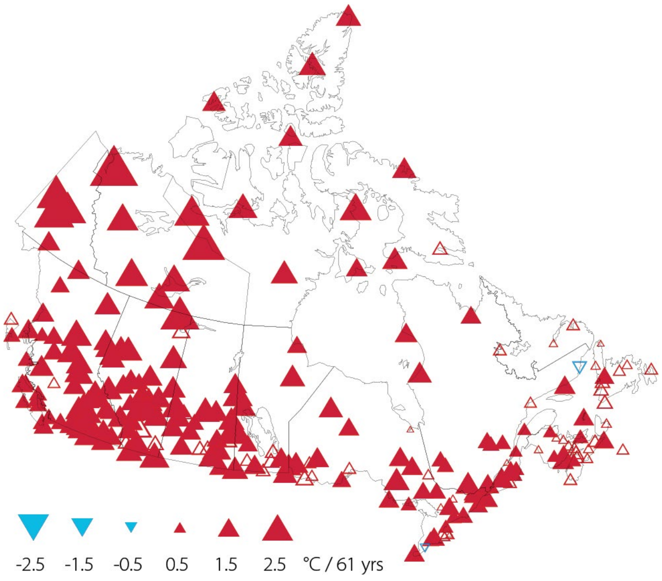
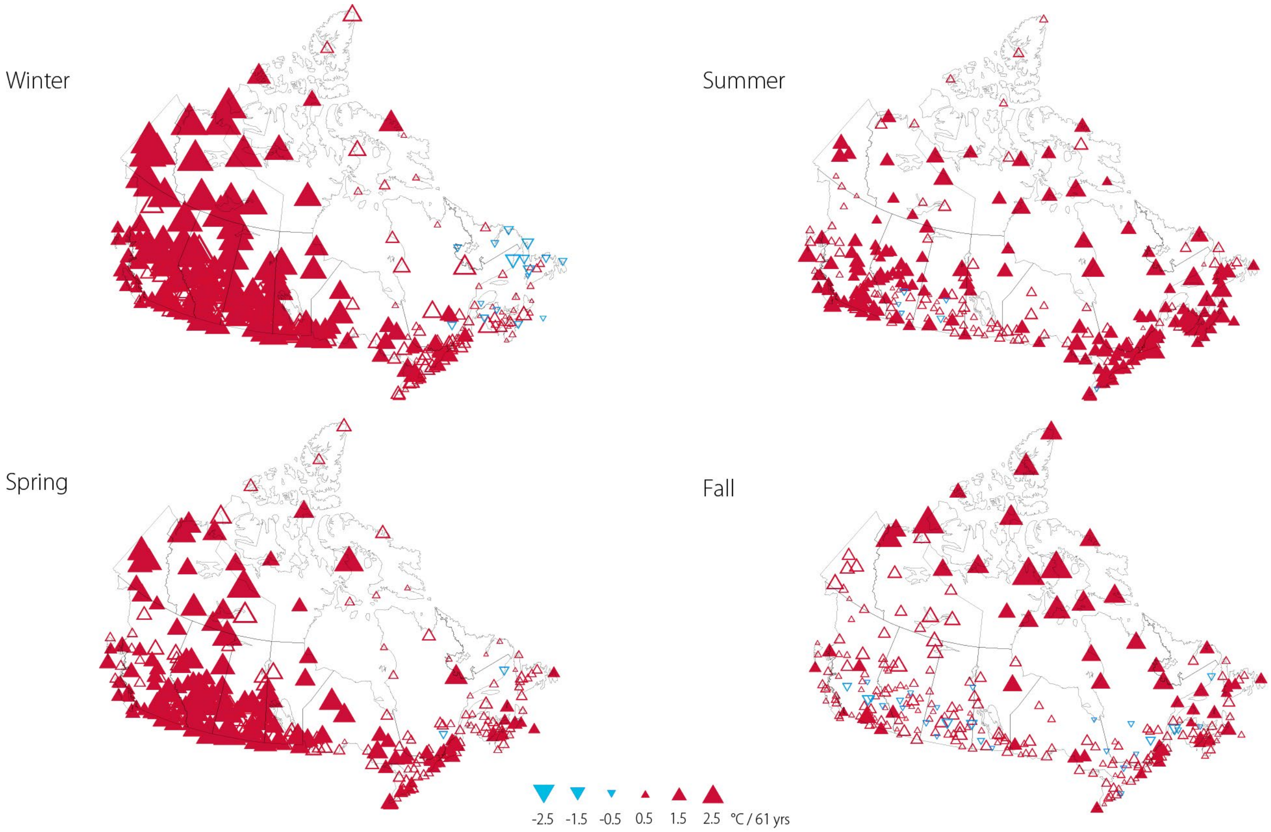


**FIGURE 4:** Trends in annual mean temperature for 1950-2010. Upward- (red) and downward- (blue) pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. The legend may not include all sizes shown in the figure *(Source: Vincent et al., 2012).*


Winter

Summer

Spring

Fall

**FIGURE 5:** Trends in seasonal mean temperature for 1950-2010. Upward- (red) and downward- (blue) pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. The legend may not include all sizes shown in the figure *(Source: Vincent et al., 2012.).*

**BOX 3**

### INTERNAL CLIMATE VARIABILITY

The atmosphere, cryosphere, ocean and land are interconnected through the exchange of heat, freshwater, energy and gases, forming a coupled climate system. Because the cryosphere and ocean contain (or can absorb) large amounts of heat and freshwater, strong feedbacks can occur within this system, resulting in natural variations or "oscillations" sometimes referred to as internal climate variability. There is increasing evidence of the occurrence of these variations in modern observations, particularly on decadal time scales and space scales of ocean basins. Prominent examples include the Arctic and North Atlantic Oscillations (AO, NAO) in atmospheric pressure patterns, the Pacific Decadal and Atlantic Multidecadal Oscillations (PDO, AMO) in ocean surface temperature, and on shorter timescales, the El Niño/La Niña (warm/cool) variations in eastern tropical Pacific Ocean temperatures.

## 2.1.2 PRECIPITATION

Warming of the Earth's surface and atmosphere results in changes in evaporation and precipitation, and in atmospheric circulation patterns that influence where rain falls. In general, warmer temperatures lead to greater potential evaporation of surface water, thereby increasing the potential for surface drying and increasing the amount of moisture in the air. As warmer air can hold more moisture, more intense precipitation events are expected (Held and Soden, 2006; Trenberth, 2011). A shift in the latitudinal distribution of Northern Hemisphere precipitation has been observed, with increases at higher latitudes and decreases in the sub-tropics (Zhang et al., 2007; Min et al., 2008).

Precipitation trends are more difficult to detect than temperature trends (e.g. Trenberth et al., 2007; Warren and Egginton, 2008). Using adjusted daily precipitation data, Mekis and Vincent (2011a) show that Canada has generally become wetter in recent decades (an increase in annual precipitation of about 16% over the period 1950-2010; Figure 6). This increase is dominated by large changes in British Columbia and Atlantic Canada (Figure 7). For the past 61 years, 21% of the stations indicate statistically significant increases in annual total precipitation, while only a few significant negative trends are found throughout the country (Mekis and Vincent, 2011b). At most stations, total precipitation has increased in spring and fall, while many sites, especially those in western Canada, show declining winter precipitation (Figure 8). The observed decrease in total winter precipitation is mainly due to the decrease in winter snowfall, while winter rainfall has changed little (Mekis and Vincent, 2011a).

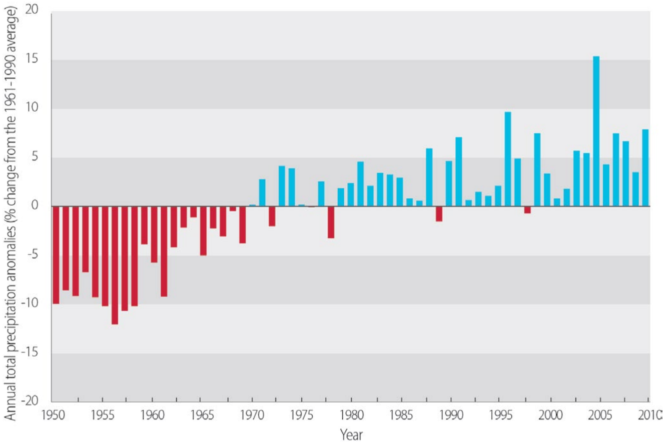


**FIGURE 6:** Annual total precipitation anomalies (expressed in % change from the 1961-1990 average) for Canada, 1950-2010 *(Source: Mekis and Vincent, 2011a; Environment Canada, 2011).*

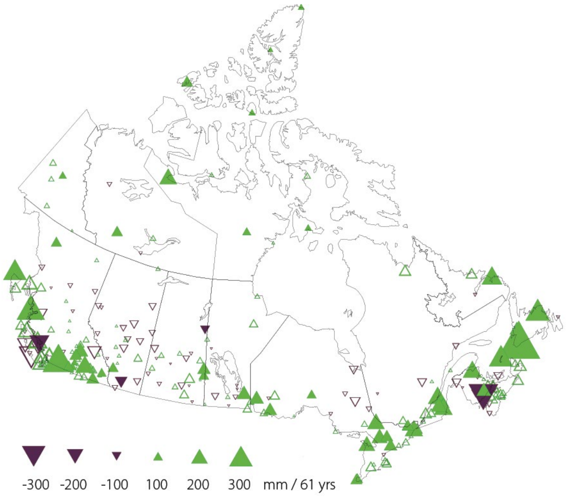


**FIGURE 7:** Annual total precipitation trends for 1950-2010. Upward- (green) and downward- (brown) pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. The legend may not include all sizes shown in the figure *(Source: Mekis and Vincent, 2011b).*

Disaggregating total precipitation into rainfall and snowfall indicates that annual rainfall in Canada has increased by ~13% over 1950-2009 (Mekis and Vincent, 2011a). Trends indicate increasing rainfall across the country, although for many locations these trends are not statistically significant (Figure 9). Seasonally, many stations show significant increasing rainfall trends in the spring and fall.

Annual snowfall for Canada as a whole has increased by about 4% over 1950-2009 (Mekis and Vincent, 2011a), although many stations in western Canada show significant decreasing trends, while increasing trends occur in the north and Atlantic regions (Figure 9). Variability in winter precipitation, particularly in Western Canada, is strongly influenced by large-scale natural climate variations (such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (*see* Box 3)), with below-normal precipitation associated with El Niño events and positive phases of the PDO, both of which have occurred more frequently since the mid-1970s (Bonsal and Shabbar, 2011). In several regions of southern Canada, there has been a shift in precipitation type, with decreasing snowfall and increasing rainfall (Figure 9), as would be expected with warming temperatures.

### 2.1.3 TEMPERATURE AND PRECIPITATION EXTREMES

In a changing climate, extreme temperatures and precipitation will also change as a result of shifts in mean conditions and/or as a result of changes in variability (Rummukainen, 2012). For example, warming is expected to be accompanied by a decrease in cold extremes and an increase in hot extremes. It is also expected that the global hydrological cycle will intensify with continued global warming, leading to an increasing intensity of both wet and dry extremes, and associated hazards such as floods and

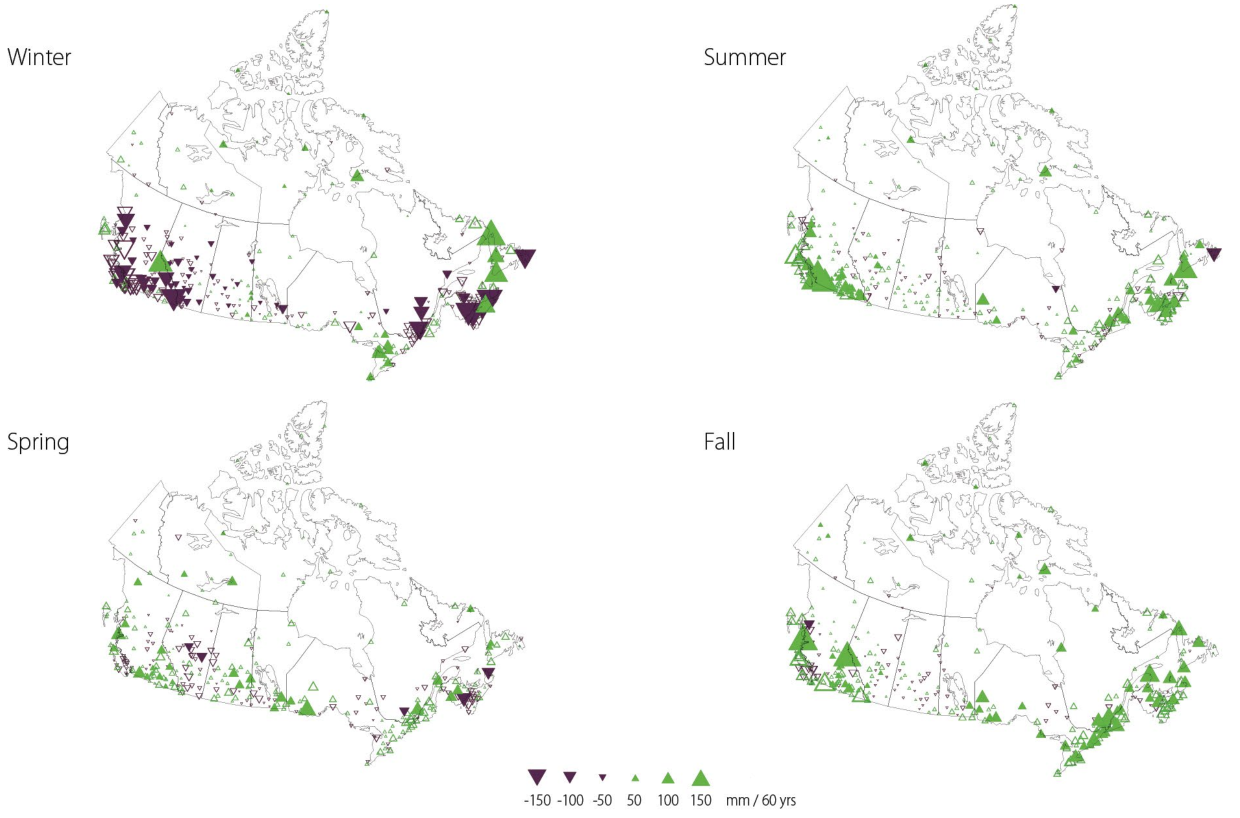


**FIGURE 8:** Seasonal total precipitation trends for 1950-2009. Upward- and downward-pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. The legend may not include all sizes shown in the figure *(Source: Mekis and Vincent, 2011a).*

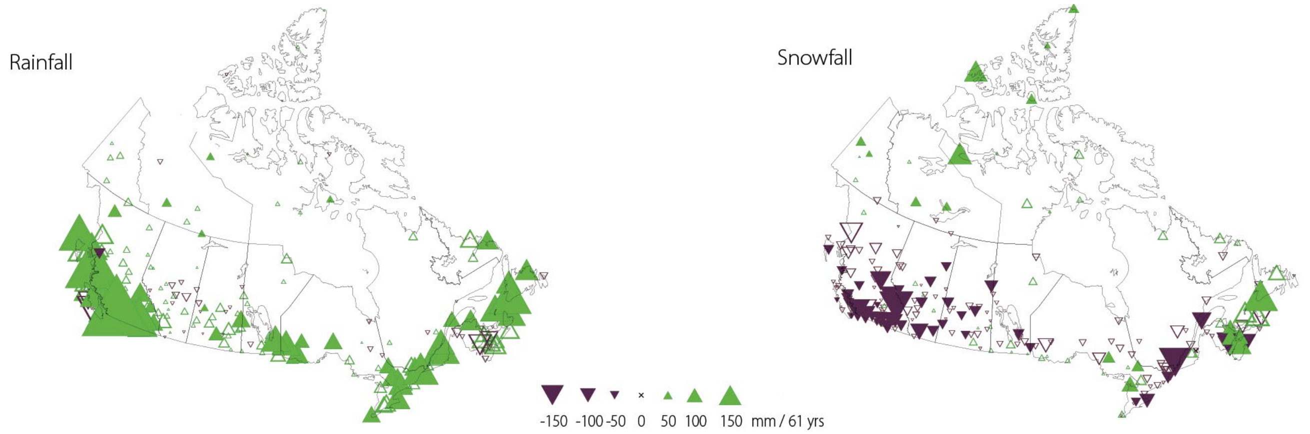


**FIGURE 9:** Annual rainfall and snowfall trends for 1950-2009. Upward- and downward-pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. The legend may not include all sizes shown in the figure *(Source: Mekis and Vincent, 2011a)*.

droughts (Trenberth, 2011; Giorgi et al., 2011). An extreme event, by definition, is rare – making analysis of changes in extreme events challenging (Zhang et al., 2011a).

At the global scale, there is abundant evidence for changes in daily temperature extremes, with an increase in the number of warm days and warm nights and a decrease in the number of cold days and cold nights over much of the global land area (Seneviratne et al., 2012). An increase in the length and/ or frequency of longer duration events (e.g. heat waves) was also found, although confidence in these results is lower than it is for changes in daily temperature extremes. There is generally less consistency and coherence in the patterns of observed changes in extreme precipitation relative to changes in extreme temperatures. Globally, however, there were more places showing an increase in the number of heavy precipitation events than a decrease, so the overall assessment was for an increase in heavy precipitation at the global scale (Seneviratne et al., 2012).

In Canada, temperature trends updated since the 2008 assessment indicate that cold events continue to decrease while warm events continue to increase. The frequency of cold nights during the winter (when the daily minimum temperature is below the daily 10th percentile) has decreased over 1950-2010 at most stations across the country; however, some small increasing trends are evident in southern Quebec and Atlantic Canada. Similarly, while the frequency of warm days during the summer (when the daily maximum temperature is above the daily 90th percentile) has increased nationally, small decreasing trends were found at several locations in the Canadian Prairies. At most stations, the annual frequency of cold nights has decreased and the annual frequency of warm days has increased, observations which are in agreement with an assessment of trends across North America (including Canada, the U.S. and Mexico; Peterson et al., 2008). Analysis to infer changes in the one-in-20 year extremes indicates that extreme minimum temperatures have warmed more than extreme high temperatures, and that the trends have been much stronger in the Canadian Arctic than in southern Canada (Wang et al., 2013). No updated Canada-wide evaluation of trends in summer heat waves or warm spells is available.

With respect to extreme precipitation in Canada, two indices, namely "very wet days" (number of days with precipitation ≥ 95th percentile value) and "heavy precipitation days" (number of days with ≥ 10 mm precipitation) have been recomputed to update the analysis presented in the 2008 Assessment to cover the period 1950-2010 (Vincent and Mekis 2006, updated; Figure 10). The results show patterns similar to earlier findings, with no consistent change in extreme precipitation for Canada as a whole. On a continental scale, while various indices of heavy precipitation have been increasing since 1950, the patterns have not been spatially uniform across

North America (Peterson et al., 2008). Increasing trends in precipitation intensity have been observed over about two-thirds of the northern hemisphere land area with sufficient data coverage for analysis (Min et al., 2011).

Drought is an extreme event with no standard definition, but in general refers to extended periods of abnormally dry weather that deplete water resources. A variety of indices are available for assessing changes in drought. Although drought occurs in most regions of Canada, much of the research has focused on the Canadian Prairies because the region is particularly susceptible to drought (Bonsal et al., 2011). Assessment of the variability of summer drought duration for the southern Prairies over different time scales indicates that 20th century droughts have been relatively benign compared to those that occurred in previous centuries (Bonsal et al., 2012). No trends in drought over the full 20th century have been discernible in any region of the country (Bonsal et al., 2011). Over the second half of the 20th century, regional trends towards more severe drought conditions were identified over southern and western Canada, as part of global analyses (Dai, 2011; Seneviratne et al., 2012).

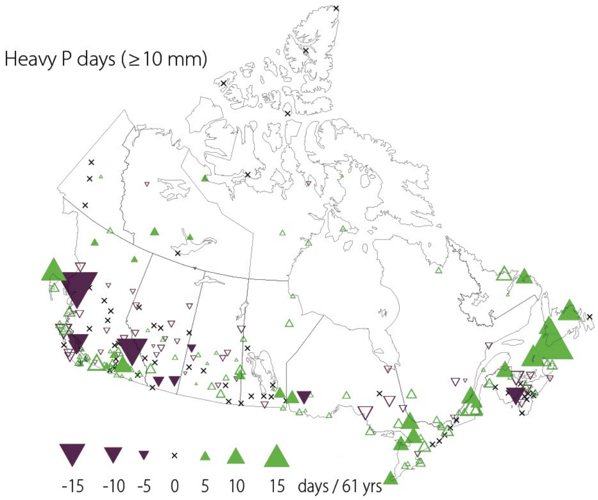


**FIGURE 10:** Trends in extreme precipitation for 1950-2010. Upward- and downward-pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. The legend may not include all sizes shown in the figure. The symbol 'x' denotes a trend near zero *(Source: Vincent and Mekis, 2006, updated).*

## 2.2 PROJECTED CHANGES IN TEMPERATURE AND PRECIPITATION

### 2.2.1 CLIMATE MODELS AND SCENARIOS

Climate change projections are provided by experiments run on supercomputers with mathematical models of the coupled atmosphere-ice-ocean-land system. These climate (or Earth) system models are based on physical laws governing the behavior of the system and interactions among its components, and can be used to simulate how the system will respond to forces of change. In such experiments, the models are driven by specified changes in 'climate forcers', including changes in GHG and aerosol emissions resulting from human activities. In general, researchers examine the results of experiments with many models using the same forcing scenario, as well as multiple forcing scenarios (*see* Box 4).

Based on SRES scenarios (Box 4), the IPCC Fourth Assessment Report provides central estimates and likely (66-100% probability) ranges of global average temperature change for the 2090-2099 period (relative to 1980-1999) of 1.8 °C (1.1 to 2.9°C) for B1, 2.8 °C (1.7 to 4.4 °C) for A1B and 3.4 °C (2.0 to 5.4 °C) for A2 (Meehl et al., 2007b). It further concluded that North America is very likely (90-100% probability) to warm this century and its annual mean warming is likely to exceed global mean warming in most areas, with strongest warming in winter and in northern regions (Christensen et al., 2007). The possibility of cooling in the northeastern part of Canada could not be ruled out because of the possible cooling in the North Atlantic associated with reduction in the Atlantic Meridional Overturning Circulation. Annual average precipitation is very likely to increase across Canada, while for southern Canada, precipitation is likely to increase in winter and spring but decrease in summer.

This chapter also presents selected climate change projections of surface air temperature change and precipitation for Canada based on the average results (computed means) from an ensemble of either 17 (B1) or 16 (A2) global climate models in CMIP3. These projections are intended to be broadly illustrative of the magnitude of potential changes across Canada over the course of this century in response to either a relatively low (B1) or relatively high (A2) forcing scenario. Recent global anthropogenic fossil fuel emissions more closely match the higher emission SRES scenarios (Peters et al., 2012). Readers are referred to Chapter 2 of the 2008 Assessment Report (Warren and Egginton, 2008) for a general discussion about climate modeling and impact assessment, and to the Canadian Climate Change Scenarios Network (cccsn.ec.gc.ca) for more technical information, including guidance on how to incorporate uncertainty in climate projections into adaptation planning.

BOX 4

## CLIMATE CHANGE SCENARIO DEVELOPMENT

Future climate change scenarios presented in the 2008 assessment report (Lemmen et al., 2008) were based on a set of coordinated experiments undertaken by a small number of global climate modeling groups for the IPCC's Third Assessment Report (IPCC, 2001). The experiments were based on a subset of the emissions scenarios described in the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000 and summarized in Warren and Egginton, 2008). A new set of internationally coordinated climate change experiments was undertaken by a much larger number of climate modeling groups to support the IPCC's Fourth Assessment (IPCC, 2007). This set of coordinated experiments – the Coupled Model Intercomparison Project Phase 3 (CMIP3) experiments (Meehl et al., 2007a) – also used the SRES scenarios developed by the IPCC, with 3 scenarios routinely modeled by most groups, representing a range of future anthropogenic radiative forcing from low (B1) to medium (A1B) to medium-high (A2). While these three scenarios capture a substantial portion of the range of projected emissions from the larger set of SRES scenarios, they do not capture the full range. Furthermore, none of the SRES scenarios included explicit consideration of climate change mitigation efforts, although they did capture future worlds with relatively low to relatively high emissions even in the absence of specific policies to address emissions.

The most recent coordinated global climate Coupled Model Intercomparison Project (CMIP5) used a new set of scenarios as the basis for projecting future climate change (Moss et al., 2010; Hibbard et al., 2011; van Vuuren et al., 2011; Taylor et al., 2012). The new scenarios, referred to as Representative Concentration Pathways (RCPs), describe trajectories of atmospheric concentration over time (for GHGs, aerosols and other air pollutants, and the resulting trajectories in net radiative forcing). Four scenarios of interest to the policy and scientific communities were chosen to represent a range of radiative forcing over the 21st century, encompassing scenarios assuming ambitious mitigation to those assuming little. Hence, RCPs differ from SRES scenarios by explicitly considering greenhouse gas mitigation efforts.

The CMIP5 experiments, based on the new RCPs, have provided a focus for discussion of future global, continental and regional-scale climate change in the Fifth Assessment Report of IPCC Working Group I. Simulations from CMIP5 were not available during the original drafting of this chapter, nor has the impacts and adaptation community had much time to conduct research using these new projections. New climate change scenarios for Canada based on these experiments will be made available to the Canadian research community and to interested Canadians through the Canadian Climate Change Scenarios Network at cccsn.ec.gc.ca.

### 2.2.2 CHANGES IN SEASONAL TEMPERATURE AND PRECIPITATION

Scenario maps of projected seasonal changes in surface air temperature (Figure 11) and precipitation (Figure 12) are presented for the middle and end of the century, relative to 1961-1990 averages, based on the CMIP3 multi-model mean results for the low (B1) and medium-high (A2) SRES emissions scenarios (*see* Box 4). These projections are generally consistent with those presented in the 2008 Assessment Report.

Seasonal variation in warming patterns are evident, with largest increases in winter occurring at high latitudes (northern Canada), while in summer the greatest warming occurs at mid-latitudes (southern Canada). Summertime warming is generally projected to be more uniform across the country, with the largest changes projected for the continental interior. Stronger latitudinal gradients are apparent in autumn, and especially so in winter. Ensemble mean results over the whole domain show that even under the low emission scenario (B1), by the middle of the century all of Canada is projected to warm by about 1.5 to 2.5°C in the season of weakest projected warming (summer). Average wintertime temperatures across most of Canada are projected to increase by ~3 to 7°C under the A2 scenario towards the end of the century, with warming of > 9°C projected in and around Hudson Bay and the High Arctic (Figure 11, panel P). This pattern of enhanced warming at high northern latitudes is a near-universal feature of climate model projections under a range of emissions scenarios, and is strongly linked to reduced snow and sea ice cover (Serreze and Barry, 2011).

Projections of precipitation change are generally less robust than those for temperature, exhibiting greater variability among models. Increases in precipitation are projected for the majority of the country and for all seasons, the exception being parts of southern Canada where a decline in precipitation in summer and fall is projected (Figure 12, panels F-L). Even in areas where summer precipitation increases, higher evaporation rates associated with warmer summers will increase the tendency towards drier conditions. An increase in aridity in southern Canada is projected, with large variations between scenarios (Sheffield and Wood, 2008; Dai, 2011).

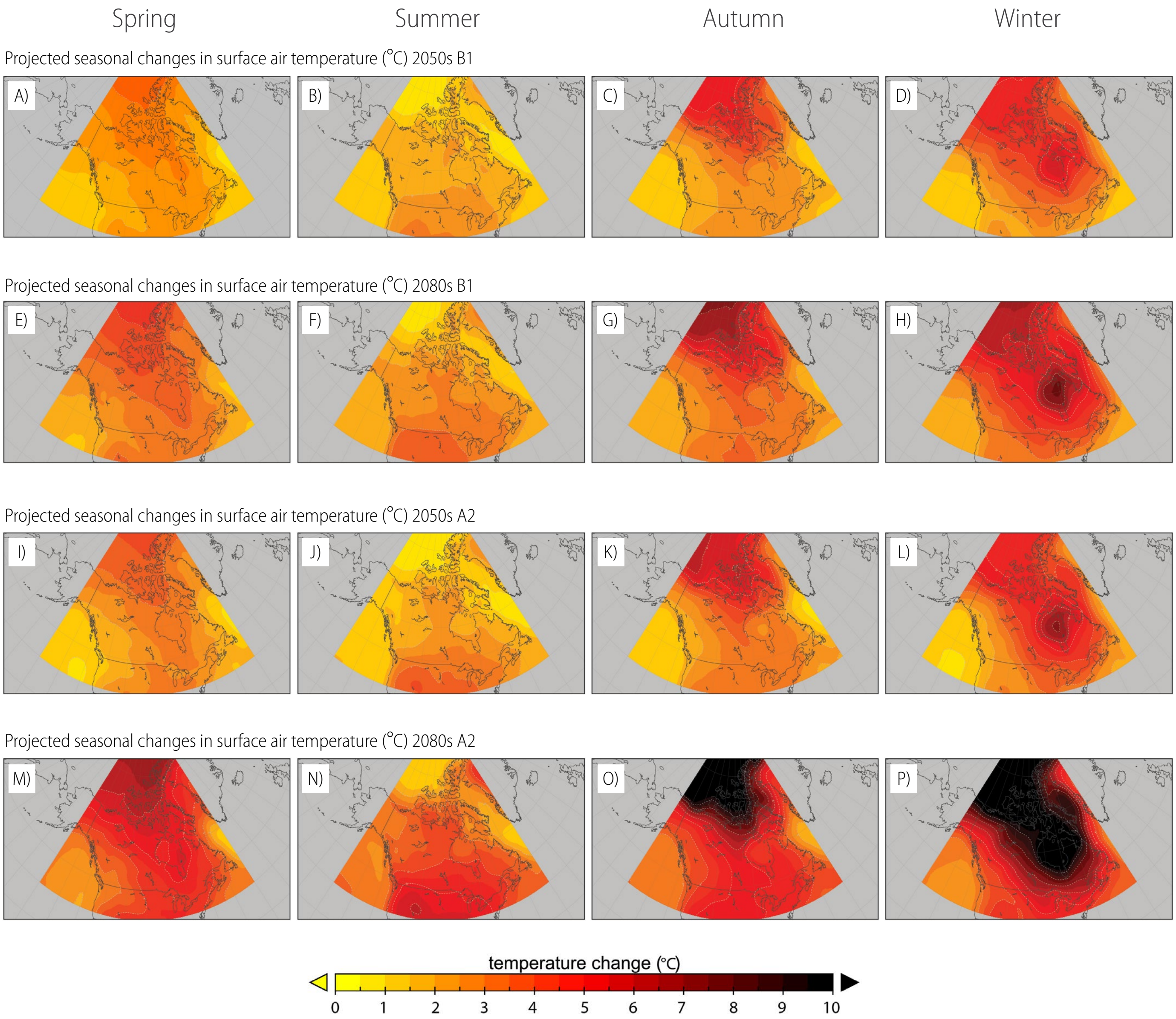


**FIGURE 11:** Projected seasonal changes in temperature across Canada for the middle and end of the 21st century under various SRES scenarios. Changes are expressed relative to average values between 1961-1990. Row 1 (A-D) is scenario B1 mid-century, row 2 (E-H) is B1 towards the end of the century, row 3 (I-L) is A2 mid-century, and row 4 (M-P) is A2 towards the end of the century. Column 1 (A, E, I, M) is Spring, Column 2 (B, F, J, N) is Summer, Column 3 (C, G, K, O) is Autumn, Column 4 (D,H, L, P) is Winter *(Source: Canadian Centre for Climate Modeling and Analysis)*.

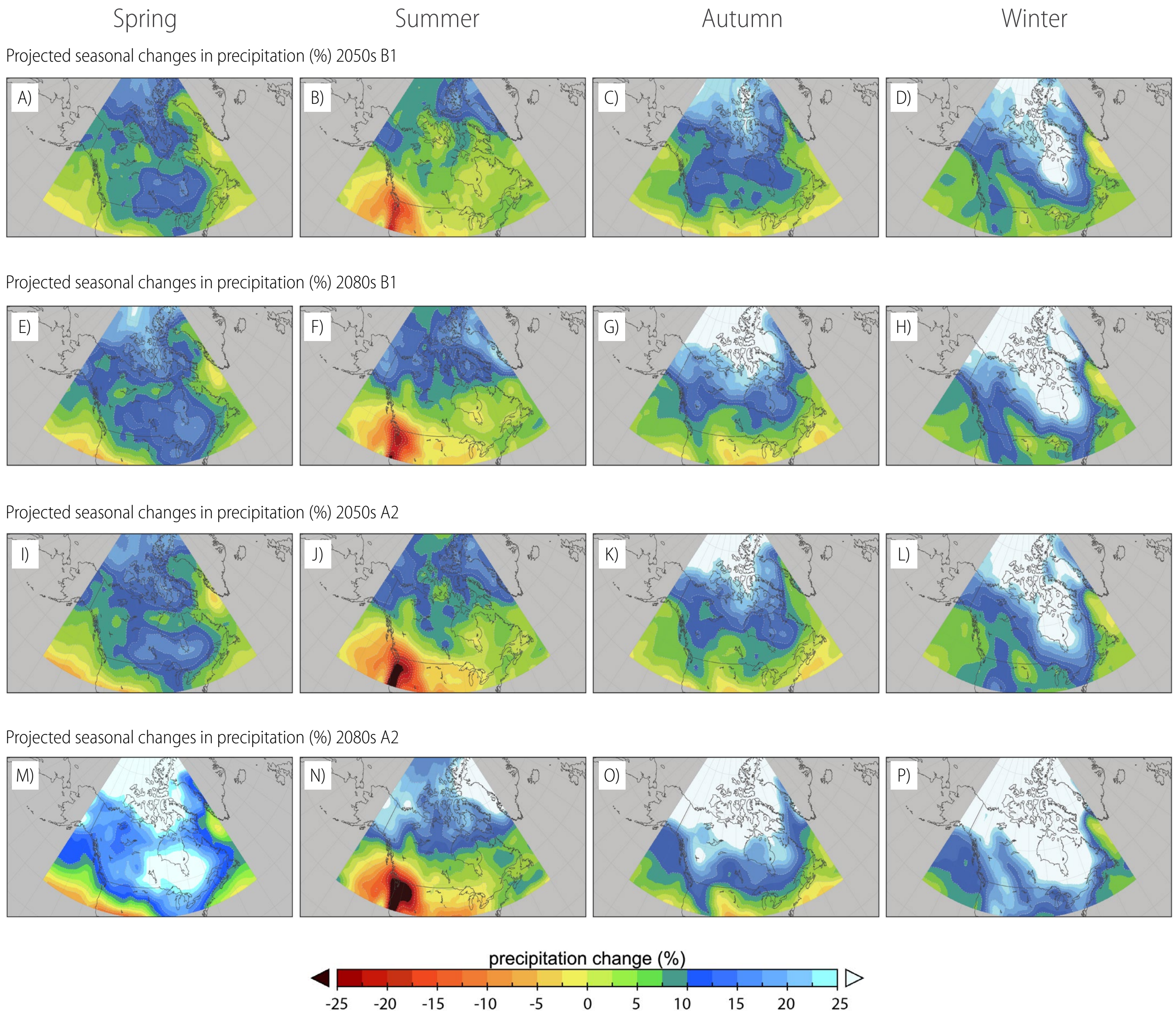


**FIGURE 12:** Projected seasonal changes in precipitation across Canada for the middle and end of the 21st century under various SRES scenarios. Changes are expressed relative to average values between 1961-1990. Row 1 (A-D) is scenario B1 mid-century, row 2 (E-H) is B1 towards the end of the century, row 3 (I-L) is A2 mid-century, and row 4 (M-P) is A2 towards the end of the century. Column 1 (A, E, I, M) is Spring, Column 2 (B, F, J, N) is Summer, Column 3 (C, G, K, O) is Autumn, Column 4 (D,H, L, P) is Winter *(Source: Canadian Centre for Climate Modeling and Analysis)*.

### 2.2.3 CHANGES IN TEMPERATURE AND PRECIPITATION EXTREMES

Changes in extreme events are of particular concern for adaptation planning. The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, SREX; 2012) provided a comprehensive assessment of projected changes in extreme weather and climate events, such as floods and droughts – at global, continental, and regional scales – using literature that for the most part was based on CMIP3 modeling experiments (Box 4) (Seneviratne et al., 2012). The report concludes that it is virtually certain (99 to 100% probability) that increases in the frequency and magnitude of warm days and nights, coupled with decreases in the frequency and magnitude for cold days and nights will occur globally during the 21st century and that the length, frequency and/or intensity of warm spells, including heat waves, are very likely to increase over most land areas (Seneviratne et al., 2012). Kharin et al. (2007) concluded that the return period for what is currently a one-in-20-year[2] extreme hot day would become a one-in-5 year event over most of Canada by mid-century. By the end of the century, such warm events are projected to become even more commonplace (Seneviratne et al., 2012; Gutowski et al., 2008).

With respect to precipitation, Kharin et al. (2007) found that return periods for one-in-20-year extreme daily precipitation events would become a one-in-10 year event by mid-century for mid to high latitude regions under moderate to high emission scenarios. The SREX concluded that the frequency of heavy precipitation is likely to increase in the 21st century over many areas of the world, but also emphasized the relatively large uncertainties associated with projections of extreme precipitation (Seneviratne et al., 2012). Regional climate models or statistical downscaling approaches can reveal important details about spatial patterns of change not evident in global studies. For example, the Canadian Regional Climate Model (CRCM) was used to explore future changes in warm-season (April-September) single and multi-day extreme precipitation events using the A2 emission scenario (Mladjic et al., 2011). In addition to finding an increase in future 20-year (and longer) return values of 1 to 7 day precipitation extremes for most parts of Canada (i.e. the 20-year events were projected to have larger precipitation totals), the study also concluded that the CRCM underestimates precipitation extremes over most of Canada, when evaluated against observed changes.

In assessing the risk of changes in drought, available studies suggest a strong tendency towards reduced aridity in winter and increased aridity in summer over large areas of the Canadian landmass. However, the lack of model agreement in the direction of projected change over many areas of Canada, including south-central Canada, indicates that these results should be interpreted cautiously (*see* Figure 3.9 in Seneviratne et al., 2012). Choice of drought index has also been shown to influence the results (Bonsal et al., 2012). The CRCM was used to evaluate potential changes in the frequency of dry days across Canada for the April–September period under the SRES A2 emission scenario, with increases in the mean number of dry days and in maximum dry spell duration (for given return periods) demonstrated for parts of southern Canada. The southern Prairies were identified in particular as having a higher likelihood of drought conditions in the future (Sushama et al., 2010, *see also* Bonsal et al., 2012).

## 3. CHANGES TO THE CRYOSPHERE

Canada is a northern country, and snow and ice are the dominant land cover for much of the country for much of the year. The presence or absence of snow and ice on and below the surface, and its seasonal variation, play important roles in climate from local to global scales. Changes to components of the cryosphere – sea ice, freshwater (lake and river) ice, snow cover, glaciers, ice caps, ice sheets and permafrost – are important indicators of a changing climate due to their climatic sensitivity and the importance of related impacts. For example, the cryosphere includes important stores of fresh water in the form of glaciers, ice caps and ice sheets. When the melt rate exceeds the accumulation rate, which is currently the case over most of Canada, the water released contributes to sea level rise. When ice is within frozen soils (permafrost), melting can lead to collapse of the soil structure, with consequences for overlying infrastructure and local hydrology. Water supply and soil moisture in many parts of the country can be affected by changes in both snow and glacier cover, with runoff from spring melt often critical to surface water supply in the high demand summer period. Loss of Arctic sea ice will have direct consequences for residents of the Arctic, for whom many aspects of community life and economic activity will be severely affected. As well, decreased sea ice will increase access to the Arctic Ocean and trans-Arctic shipping, with social, economic and environmental consequences.

---

[2] A one-in-20 year event means that such an event has, on average, a 5% chance of occurring in any given year. Similarly, a one-in 2-year event has, on average, a 50% chance of occurring in a given year.

Arctic research in Canada and other countries was substantially expanded during the third International Polar Year (IPY; 2007-2008). This work, and other recent reports on Arctic environmental change provide updated information on trends in various cryospheric indicators (AMAP, 2011; Arctic Report Card, 2012; Derksen et al., 2012). This is part of a growing body of evidence documenting widespread reductions in the spatial extent and mass of the cryosphere in response to warming air temperatures across the circumpolar north. Updated information on a few key indicators, with a focus on results for Canada, is provided here.

## 3.1 PERMAFROST

Permafrost underlies the northern half of the Canadian landmass, with a zone of relatively thin, warm, discontinuous permafrost lying south of the larger, continuous permafrost zone that extends up to the high Arctic (Smith, 2011). In the continuous permafrost zone, permafrost can extend tens to hundreds of metres below the surface. Ground temperature below the depth of seasonal variation is a good indicator of decade-to-century-scale climate variability (Romanovsky et al., 2010). Permafrost temperatures measured in boreholes at numerous sites across Canada have all increased over the past two to three decades (Smith et al., 2010; Figure 13). The magnitude of warming varies from one region to the next, reflecting differences in climate as well other factors including elevation, snow cover and the physical properties of the permafrost itself. In general, the temperature of colder permafrost has increased more rapidly than that for warmer permafrost. This difference is linked in part to the lack of vegetation and thick snow cover at high latitudes, which, south of the treeline serve to insulate the ground from air temperatures (Romanovsky et al., 2010). For permafrost at temperatures close to 0°C, energy is also being utilized to convert ice to water (phase change) rather than for temperature change.

Across northwestern Canada, warming of permafrost temperatures has been fairly continuous over the past 20 to 30 years, with evidence that warming rates have recently slowed. Across the eastern Arctic and northern Quebec, warming did not begin until 1993 and has occurred quite rapidly since then (Smith et al., 2010; *updated in* Derksen et al., 2012). Permafrost temperatures have risen about 0.2°C/decade on average in warm, discontinuous permafrost regions. There are fewer measurement sites farther north in cold tundra regions, but increases of ≥1°C/decade in permafrost temperatures have been recorded since the mid-1990s (Smith et al., 2010; *updated in* Derksen et al., 2012). These temperature trends for two representative sites, Norman Wells (warm permafrost) and CFS Alert (cold permafrost), are illustrated in Figure 13. The observed increases in permafrost temperature are largely attributable to increases in winter air temperature (Smith et al., 2012).

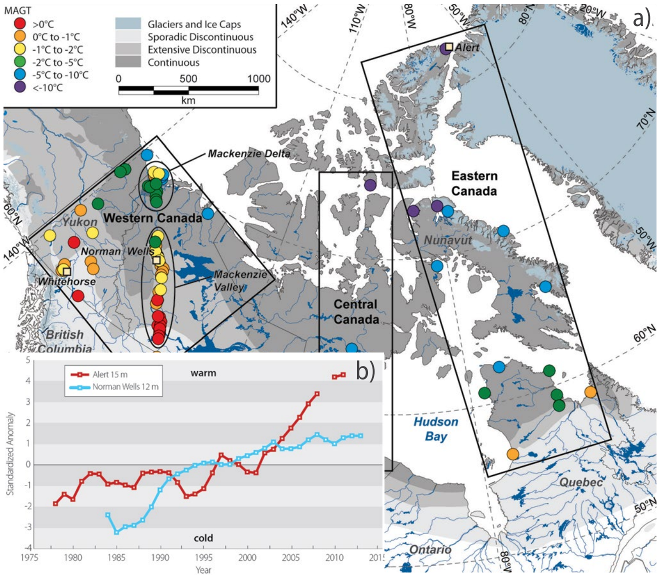


**FIGURE 13:** **a)** Mean annual ground temperature (MAGT) recorded during the IPY (2007-09) (from Smith et al., 2010). MAGT is determined at the depth of zero annual amplitude (depth to which seasonal variation penetrates) or the nearest measurement depth to it. Permafrost zones are from Heginbottom et al. (1995). **b)** Permafrost temperature standardized anomaly time series *(from Derksen et al., 2012)* relative to 1988-2007 mean for a site near Norman Wells (depth 12 m) in the central Mackenzie Valley and CFS Alert Nunavut (depth 15 m) in the high Arctic *(Credit: Sharon Smith, Natural Resources Canada)*.

With Arctic warming amplified compared to the global average, it is expected that warming of the permafrost will continue and that permafrost temperatures may increase more rapidly in the future than has been observed in records to date. However, even at the rapid warming rates seen in colder permafrost, the low average temperatures of much of the permafrost in the Arctic mean that it will take many decades to centuries for colder permafrost to completely thaw (Smith et al., 2010). Therefore, while warm, thin permafrost could eventually disappear, in colder permafrost regions climate warming will lead to a thickening of the active layer (seasonally thawed surface layer) and a decrease in permafrost thickness (Callaghan et al., 2011a).

The consequences of thawing permafrost are expected to be widespread for both natural ecosystems and human communities. Among these concerns are those related to the changing hydrology of northern ecosystems, decomposition of previously frozen soil carbon and the associated release of GHGs, and the loss of structural support from frozen ground with impacts on transportation and other infrastructure (Callaghan et al., 2011a; *see also* Chapters 3 and 8 of this report).

## 3.2 SNOW COVER

Year-to-year variability in snow cover, measured as snow cover extent (SCE) and snow cover duration (SCD), is closely linked to air temperature, particularly during the spring melt season when surface albedo feedbacks are strongest (Brown et al., 2010; Brown and Robinson, 2011). Changes in satellite-derived spring Arctic snow cover over the period 1967-2012 show statistically significant reductions over both North America and Eurasia in May and June (when snow cover is mainly located over the Arctic) (Derksen and Brown, 2011; Derksen and Brown, 2012). Successive records for the lowest June snow cover extent have been set each year for Eurasia since 2008, and in 3 of the past 5 years (2008-2012) for North America. The loss of June snow cover extent between 1979 and 2012 (-18% per decade relative to the 1979-2000 mean) is greater than the loss of September sea ice extent (-13% per decade) over the same period (*see* Section 3.5). Observed reductions in June SCE over the past decade now exceed the minimum June SCE simulated by an ensemble of climate models for this time period (Derksen and Brown, 2012).

Statistically significant negative trends have also been observed during spring over the Canadian land mass (Statistics Canada, 2012; Figure 14) with declines in snow cover of 7%, 13% and 34% in April, May and June, respectively, over the 1972-2010 period. Regionally, significant decreases in spring snow cover due to earlier melt have been observed over western and northern Canada (Figure 15, Zhang et al., 2011b), consistent with seasonal warming trends in these regions. Trends in spring snow cover extent for Canada are part of a larger-scale northern hemispheric trend of declining spring snow cover, which has become more rapid in recent decades, relative to rates of decline seen in long-term data sets covering the period 1922-2010 (Brown and Robinson, 2011).

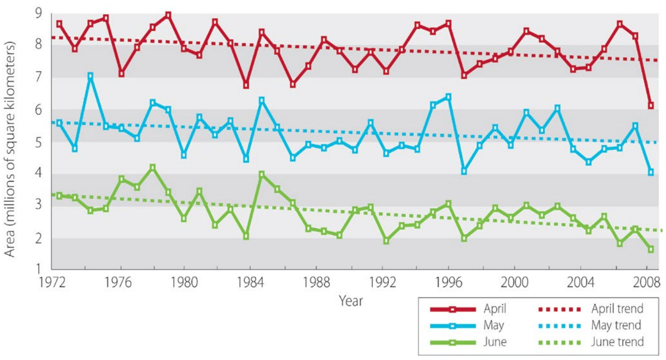


**FIGURE 14:** Changes in spring season snow cover extent over the Canadian land mass, 1972-2010, for the months of April (red lines), May (blue lines) and June (green lines) *(Source: Statistics Canada, 2012).*

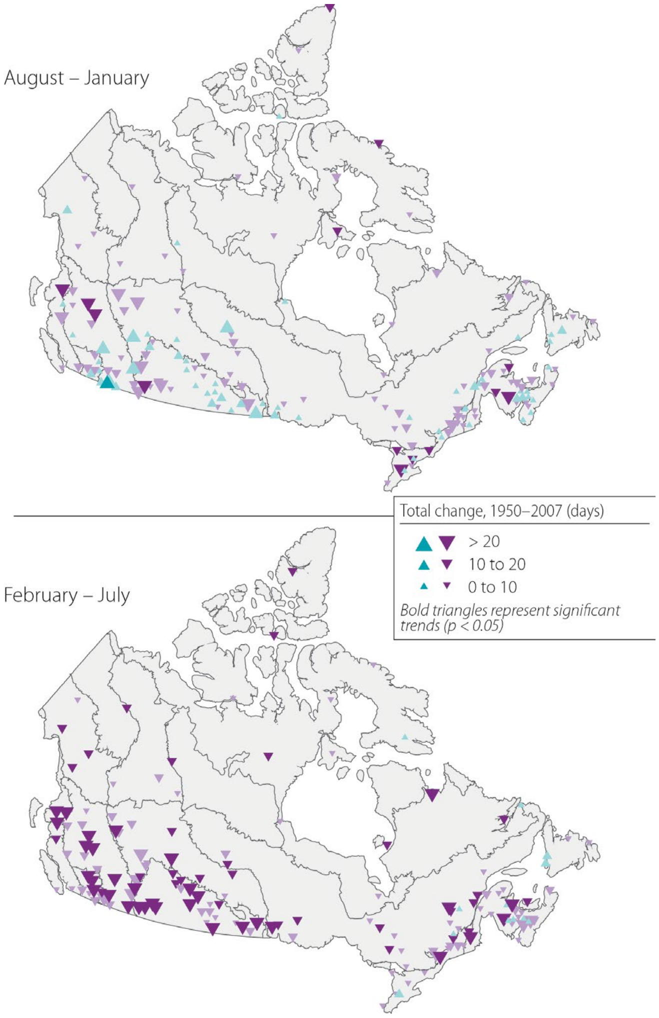


**FIGURE 15:** Change in the number of days with ≥ 2 cm of snow on the ground, 1950-2007, in a) the first half of the snow season (August to January) which indicates changes in the start date of snow cover, and b) in the second half of the snow season (February to July) which indicates changes in the end date of snow cover. Data are from daily snow depth observations. Boundaries on the map represent terrestrial ecozones *(Source: Zhang et al., 2011b)*.

In Canada, no country-wide trend in fall snow cover duration is evident in daily snow-depth observations (Figure 15), although some stations report locally significant trends toward later snow cover onset in the fall. There is, however, evidence of significant trends toward later freeze-up and snow cover onset over the Arctic since 1979 (e.g. Markus et al., 2009; Liston and Hiemstra, 2011).

Challenges in developing scenarios of future changes in snow cover using global climate models relate both to limitations of current models to capture processes important to the evolution of the snow pack, as well as limitations in observations needed for comprehensive evaluation of the models (Callaghan et al., 2011b). Widespread decreases in the duration of snow cover are projected across the Northern Hemisphere (Figure 16; Raisanen, 2008; Brown and Mote, 2009) with the largest changes in maritime mountain regions, such as the west coast of North America. This is related to the high sensitivity of winter precipitation in these regions to small changes in temperature (Brown and Mote, 2009). Climate models also project increases in maximum snow accumulation over northern high latitudes in response to projected increases in cold season precipitation.

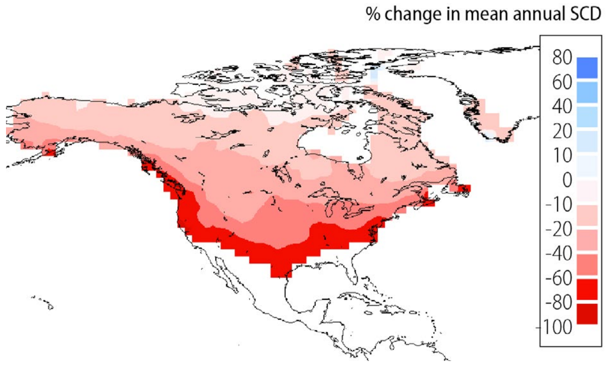


**FIGURE 16:** Projected percent changes in mean annual snow cover duration (SCD) between 1970-1999 and 2070-2099 for North America, using the IPCC SRES A2 emission scenario, for the eight global climate models used by Brown and Mote (2009, Fig. 10) *(Source: Ross Brown, Climate Research Division).*

## 3.3 GLACIERS

Many glaciers can be considered remnants from the last Ice Age that ended ca. 10 000 years ago, and as such have been in slow (and not necessarily continuous) retreat from their maximum positions for millennia. However, glaciers can also undergo quite rapid changes in response to changes in temperature and precipitation. The accelerated shrinkage of glaciers evident in many locations during the late 20th century has likely occurred in response to warming over this time period (Lemke et al., 2007). Glacier mass balance (the difference between the gain in mass from snow and ice accumulation and the loss of mass from melting and iceberg calving) is a sensitive indicator of climate change and tracks changes in glaciers over time scales of years to decades.

Glaciers in Canada are found primarily in two locations: the mountains of the western Cordillera, stretching from the Yukon to southern British Columbia and Alberta; and along the eastern margin of the Canadian Arctic Archipelago in the High Arctic. Glaciers from both regions show statistically significant declines in mass over the decades since ~1960 (Figure 17; WGMS, 2011). Multi-decadal time series show that changes have been larger for glaciers in the Western Cordillera region (Peyto, Place and Helm sites) than for those in the High Arctic (Devon NW, Meighton and White sites) (Figure 17). Cordilleran glaciers are generally exhibiting strongly negative mass balances (net losses in mass) and shrinking rapidly to the smallest extents in several millennia (Demuth et al., 2008). For example, assessment of multi-decadal changes in Yukon glaciers estimated that 22% of the surface area of these glaciers has been lost over the 50-year period since 1957-58 (Barrand and Sharp, 2010). Glaciers in British Columbia and Alberta have lost about 11% and 25% of their surface areas respectively, over the period 1985-2005 (Bolch et al., 2010).

In the High Arctic, glaciers are thicker and larger in area and thus respond more slowly to regional changes in climate. While these glaciers have exhibited more modest losses of mass compared to Cordilleran glaciers, significant negative mass balances are evident from the early 1960s into the first decade of the 21st century (Figure 17; Statistics Canada, 2010; WGMS, 2011). The rate of mass loss for glaciers throughout the High Arctic has increased sharply since 2005, in direct response to warm regional summer temperatures (Gardner et al., 2011; Sharp et al., 2011a). The mean rate of mass loss from four monitored glaciers in the Queen Elizabeth Islands between 2005-2009 was nearly 5 times greater than the ~40 year average over the period 1963-2004 (Sharp et al., 2011a). The recent series of warm summers in Arctic Canada has also been associated with major break-up events for the ice shelves that fringe northern Ellesmere Island (Copland et al., 2007; Sharp et al., 2011b; Pope et al., 2012).

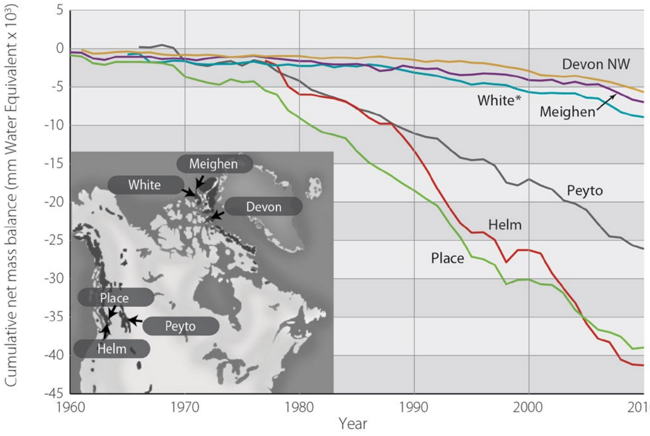


**FIGURE 17:** Cumulative net glacier mass balance patterns since observations first began over reference observing sites in the Canadian High Arctic (Devon and Meighen Ice Caps, and White Glacier*), the Canadian Rocky Mountains (Peyto Glacier) and the Cascade and Southern Coast Mountains (Place and Helm Glaciers). Values represent thickness change averaged over the glacier area (in mm water equivalent x $10^3$). Inset: The location of each site in Panel A. *White Glacier data courtesy of Trent University *(Source: Natural Resources Canada, Geological Survey of Canada).*

Changes in the mass balance of glaciers in the Canadian High Arctic are driven mainly by changes in summer melt, as there is little interannual variability in snow accumulation. The high temperature-sensitivity of High Arctic glaciers will more than counteract projected precipitation increases, such that continued wastage of glaciers with ongoing warming is expected. Arctic glaciers are projected to be significant contributors of land ice to 21st century sea level rise (Gardner et al., 2011; Radić and Hock, 2011; Lenaerts et al., 2013; *see also* Section 5.4). Ongoing reductions in glacier extent are expected to reduce run-off in the longer term and impact water availability in glacier-fed rivers with consequences for aquatic habitat and for various human activities, including hydro-electricity generation (Sharp et al., 2011a).

## 3.4 FRESHWATER ICE

Using the historical record of ice cover from 1950-2005, trends towards earlier ice-free dates have been observed for most of the country but are particularly evident in Western Canada (Figure 18) (Duguay et al., 2006; Latifovic and Pouliot, 2007). Lake ice freeze-over dates have shown few significant trends (Duguay et al., 2006). Trends towards earlier break-up in river ice have also been observed through the latter half of the 20th century, again particularly in Western Canada (Beltaos and Prowse, 2009). River ice freeze-over was found to be spatially complex, and while some locations have shown later freeze, there have been no consistent trends throughout Canada (Beltaos and Prowse, 2009).

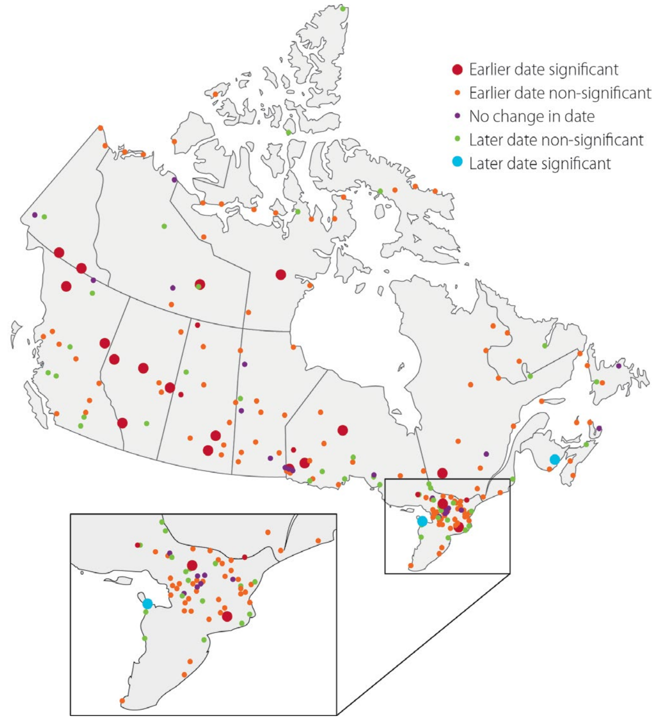


**FIGURE 18:** Changes in lake ice thaw dates across Canada, 1950-2005. Lakes with significant trends at the 90% confidence level and measurements covering at least 60% of the 1950 to 2005 time span *(Source: Icewatch, 2008).*

Large-scale internal climate variability (*see* Box 3) also influences changes in Canada's lake ice cover (e.g. Bonsal et al., 2006; Wang et al., 2012). The strongest effects are typically due to Pacific variability, although the extreme eastern parts of Canada are more affected by the North Atlantic Oscillation, and the Great Lakes region is influenced by both Pacific and Atlantic variability (Brown and Duguay, 2010).

Lake ice models driven by the CRCM (A2 scenario, *see* Box 4) provide projections of future ice cover conditions for the mid-21st century throughout Canada. Generally, ice cover break-up dates are expected to advance in the range of 1 to 3-1/2 weeks, while freeze-up dates are expected to be delayed by up to 2 weeks. The resulting ice cover duration is expected to decrease by up to a month depending on the depth of the lake, with greater reductions found for deeper lakes (Brown and Duguay, 2011; Dibike et al., 2012). River ice duration is also predicted to decrease by approximately three weeks, based on predicted changes to the 0°C isotherm (Prowse et al., 2007). Maximum lake ice thickness is predicted to decrease in the range of 10 to 30 cm, with loss exceeding 40 cm in some Arctic areas (Brown and Duguay, 2011; Dibike et al., 2012). Changes in ice thickness are also affected by snow cover, with ice thickness showing greater reductions when no snow cover is present. A severe reduction in the number of areas where occasional summer or perennial ice cover is found throughout the High Arctic is also projected (Brown and Duguay, 2011).

Predicted changes in ice cover will impact the role of lakes on energy, water and biogeochemical processes in cold regions, and result in ecosystem changes within the lakes (Prowse et al., 2011). A shorter ice season and thinner freshwater ice will have detrimental impacts on the duration and stability of winter ice roads in northern Canada (Furgal and Prowse, 2008; *see also* Chapter 8).

## 3.5 SEA ICE

Numerous studies have documented the decline in Arctic summer sea ice cover that is evident over the satellite era (1979 to present), as well as the shift toward a younger, thinner ice cover (Stroeve et al., 2012a; Derksen et al., 2012 and references therein). The results reported on below highlight trends from recent studies of particular relevance to sea ice in northern Canadian waters (including the Arctic, Hudson Bay regions and northern east coast). Key indicators for tracking changes are ice extent at the end of summer (September) when sea ice coverage reaches its annual minimum, and extent at the end of winter (March) when coverage is at a maximum.

The decreasing trend in September Arctic sea ice extent, reported in the 2008 assessment (Lemmen et al., 2008) using data up to 2005, has continued. The rate of decline in the most recent decade (1999-2010) has been more rapid than in the earlier part of the record (1979-1998) (Stroeve et al., 2012a). The lowest September sea ice extents on record were all observed in the five summers from 2007-2011 (Maslanik et al., 2011; Perovich et al., 2011; Comiso, 2012). Sea ice extent reached a new record minimum in September 2012, at 18% below the previous record minimum set in 2007 (Perovich et al., 2012). Over the satellite sea ice observation era, end-of-summer sea ice has been declining by 13% per decade (from 1979-2012). A decreasing trend in maximum winter (March) sea ice extent has also become evident over the last decade, with the trend over the satellite era reported as -2.6% per decade (from 1979-2012) (Perovich et al., 2012) (Figure 19). The observed changes in sea ice extent have been attributed to a combination of forcing from increasing atmospheric greenhouse gas levels and natural variability in air temperatures, atmosphere/ocean circulation, and ocean temperature (Min et al., 2008; Stroeve et al., 2012a).

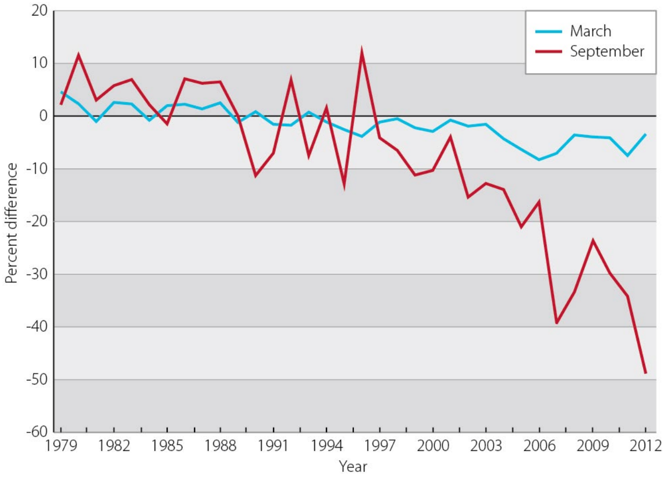


**FIGURE 19:** Trends in Arctic sea ice extent over the period 1979-2012 shown as time series of the percentage difference in ice extent in March and September relative to the mean values for the period 1979-2000. The rate of decrease for the March and September ice extents is -2.6% and -13% per decade, respectively (as determined by least squares linear regression). Both trends are statistically significant *(Source: Perovich et al., 2012).*

A number of studies have documented the shift from an ice cover formerly dominated by thick multi-year ice (MYI) to one increasingly dominated by thin first-year ice (FYI) (Derksen et al., 2012; Stroeve et al., 2012a; Comiso, 2012, Maslanik et al., 2011). Arctic Ocean (excluding the Canadian Arctic Archipelago region) MYI extent declined by 33% in March and by 50% in September between 1980-2011 (Maslanik et al., 2011). An observed increase in the variability of September sea ice cover since the early 1990s has been linked to this increasingly young ice (Stroeve et al., 2012a) as FYI can respond quickly to prevailing climate, melting rapidly during warm summers and then reforming and persisting when temperatures are sufficiently cool. Declines in Arctic sea ice extent and volume associated with ongoing climate warming are expected to continue over the coming decades. A nearly ice-free summer is now considered a strong possibility for the Arctic Ocean by the middle of the century, meaning that almost all of the ice would become FYI (although any remnant MYI would likely be found in the Canadian Archipelago region) (Meier et al., 2011; Massonnet, et al., 2012; Stroeve et al., 2012b; Wang and Overland, 2012).

A longer record of changing ice cover for Canadian sea ice regions (extending back to the 1960s) was developed using data from the historical Canadian Ice Service Digital Archive (CISDA) (Tivy et al., 2011; Howell et al., 2008a). These longer-term data sets confirm the decline of summer ice cover in northern Canadian waters, with total summer sea ice cover decreasing by 3 to 17% per decade (1968-2010), with the largest declines evident in the Hudson Strait and northern Labrador Sea (Figure 20). In almost all Canadian sea ice regions, the magnitude of the trend since 1968 is smaller than that since 1979 (Tivy et al., 2011), indicating a faster rate of decline in recent decades. The data also confirmed that substantial declines in summer MYI are evident in the southern Beaufort Sea and Foxe Basin (16% and 20% decreases per decade, respectively) (Figure 20). However, no statistically significant decline in MYI within the Canadian Arctic Archipelago (CAA) region is evident. The lack of significant declines in MYI in this area has been attributed to the inflow of MYI from the Arctic Ocean (Howell et al., 2009).

Ice conditions in the CAA are largely dependent on prevailing winds. Therefore, despite recent, consecutive, late summer 'open water' seasons in the Northwest Passage (NWP) (Perovich et al., 2011), ice conditions in the NWP, including the presence of MYI, are anticipated to remain variable and potentially hazardous for shipping for some time (Derksen et al., 2012; Howell et al., 2008a,b; Melling, 2002). Model projections of future ice conditions in the CAA support this conclusion (Sou and Flato, 2009; Stephenson et al., 2011). Projected declines in ice concentration and ice thickness within the CAA (A2 scenario) indicate that the southern route through the NWP could become consistently accessible to shipping by mid-century (using criteria for accessibility of 60% ice concentration and ice thickness less than 1.0 m). On the other hand, passage through the northern deep water route will remain limited by ice much of the time (~40%) (Sou and Flato, 2009). A similar conclusion of increased, but not consistently open accessibility of the NWP was reached by Stephenson et al. (2011).

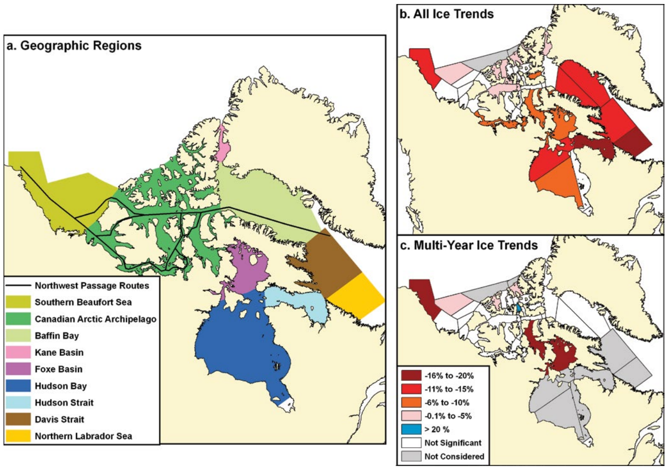


**FIGURE 20:** Trends in summer season total sea ice area (b) and multi-year sea ice area (c) for sea ice regions of Canada (a), from 1968-2010; units are % per decade. Only trends significant to the 95% confidence level are shown *(Source: Derksen et al., 2012, updated from Tivy et al., 2011).*

Observations also indicate statistically significant declines in sea ice extent in the Labrador-Newfoundland region and in the Gulf of St. Lawrence (winter only; the Gulf is ice-free in summer) (Cavalieri and Parkinson, 2012; Hutchings et al., 2012), although there has been strong decadal-scale and interannual variability in southern areas (Colbourne et al., 2012; Galbraith et al., 2012b). Both CMIP3 and CMIP5 models indicate reductions in ice extent in the Northwest Atlantic over the coming decades, but the models generally do not resolve the details of observed ice patterns in the region. Considering the recent large declines in sea ice in areas such as the Gulf of St. Lawrence and Grand Bank, together with expected continued atmospheric warming, ice-free winters may occur within a couple of decades in warm years in such areas (Hammill and Galbraith, 2012), although partial ice cover will probably continue in colder years.

# 4. CHANGES TO FRESHWATER RESOURCES

Canada is considered to have an abundance of water resources with over 8500 rivers and 2 million lakes covering almost 9% of the total land area (Monk and Baird, 2011). Yet over three quarters of the volume of river flow is to the north, where the density of people and development is sparse.

A national perspective on freshwater availability is challenging, in large part due to great regional variations in climate and watershed characteristics. Long-term measurements at gauging stations with relatively undisturbed conditions are not evenly distributed across Canada. There are gaps in the Arctic Archipelago, southern Prairies, and highly developed portions of the country. Recent research on trends and climate change impacts has tended to be regionally focused. This review focuses on streamflow/runoff and lake levels as indicators of freshwater resources, drawing on long-term observational data and published research for these indicators.

## 4.1 OBSERVED CHANGES IN FRESHWATER AVAILABILITY

As described in the preceding sections, many key climate drivers of the hydrological regime are changing across Canada. For example, in many regions, the proportion of total precipitation falling as snow is declining; the spatial coverage and duration of snow cover are decreasing, affecting the timing and amount of spring runoff; and rising air temperatures are influencing evapotranspiration and water loss to the atmosphere. These trends have implications for the water balance and are manifested as changes in the amount and timing of water availability (Bates et al., 2008).

### 4.1.1 STREAMFLOW

Many gauging stations across Canada (Box 5) are exhibiting changes in streamflow/runoff with respect to median annual flow, median flow for selected months, annual maximum and minimum flow, timing and duration of events and variability of flows (Table 1). However, the patterns are not spatially consistent (Federal, Provincial and Territorial Governments of Canada, 2010; Monk et al., 2011). The winter months – December to February – had the highest proportion of gauging sites with statistically significant increases in runoff; April median runoff also increased. These trends may be related to warming in winter and spring. Runoff for May to September decreased with the greatest reduction in flow occurring in August (28% of stations showed a significant trend; Monk et al., 2011).

Trends in annual maximum flow, usually representative of the freshet associated with spring snowmelt and/or rain events, showed a widespread decrease (Figure 21A), although only 17% of stations had a statistically significant decreasing trend (Federal, Provincial and Territorial Governments of Canada, 2010). Annual minimum flow increased in the northwest and west, while in southern Canada, low flow decreased (Figure 21B). Similar annual and monthly trends have been reported in other studies (Khaliq et al., 2008; Abdul-Aziz and Burn, 2006; Burn et al., 2008; 2010; Cunderlik and Ouarda, 2009; Monk et al., 2011; 2012). Trend analysis results can be influenced by the length of the period analysed and natural variations of a decade or longer (Khaliq et al., 2008; Chen and Grasby, 2009).

BOX 5

### STREAMFLOW ANALYSIS

Many results presented here are drawn from the Ecosystem Status and Trends (ESTR) National Assessment (Federal, Provincial and Territorial Governments of Canada, 2010; Monk and Baird, 2011) which developed a national picture of hydrologic trends for the period 1970-2005. Data from 172 streamflow gauging stations were abstracted from the Reference Hydrometric Basin Network (RHBN). These stations represent fairly "pristine" conditions where land use and land cover conditions are relatively stable and flow alterations from regulation, withdrawals or diversions are minimal (Brimley et al., 1999; Harvey et al., 1999).

### 4.1.2 LAKE LEVELS

Lake levels are highly visible indicators of changes in the water balance, human influences and availability of water in storage (Williamson et al., 2009). While there are many lakes throughout Canada, the limited number of lake observing sites precluded a national assessment of lake level trends. As such, this section discusses recent regional analyses of the Prairies and the Laurentian Great Lakes using water levels and/or net basin supply and its components as indicators.

| Variable | Trend description |
|---|---|
| Magnitude of monthly median runoff | Few trends apparent. Strong SIT in April runoff, SIT in December, January, February and March runoff, and SDT for May to August runoff |
| Magnitude of minimum runoff (1-, 3-, 7-, 30-, and 90-day) | Majority NCT especially indicators with longer duration averaging period . Approximately one quarter of sites SDT |
| Magnitude of maximum runoff (1-, 3-, 7-, 30-, and 90-day) | Majority NCT but large number of sites (especially indicators with a long duration averaging period) showing TFDT |
| Timing of annual 1-day minimum | Few sites with significant trends<br>Nearly half of sites showing TFIT towards (later) annual minimum |
| Timing of annual 1-day maximum | Few sites with significant trends. Majority of sites showing tendency towards (earlier) annual maximum |
| Frequency of extreme low flow events | Majority of sites NCT |
| Frequency of extreme high flow events | Majority of sites NCT |
| Duration of extreme events | Majority of sites NCT<br>Slight trend towards SDT in duration of low pulse events |
| Flashiness of events | A few sites with significant trends for rise rate and fall rate. Tendency towards TFIT in fall rate and TFDT in rise rate for nearly half of sites. SIT in number of reversals for one third of sites |

**TABLE 1:** Summary of national trends in streamflows based on the ESTR analysis for 1970 to 2005 and review of Canadian published literature on hydrologic trends *(Source: Monk et al. 2011; Monk and Baird, 2011)*. Note: SDT - significant declining trend ($p<0.1$); SIT - significant increasing trend ($p<0.1$); NCT - no clear trend or both increasing and decreasing trend; TFDT tendency for declining trend ($p>0.1$ i.e. not statistically significant) and TFIT tendency for increasing trend ($p>0.1$ i.e. not statistically significant).

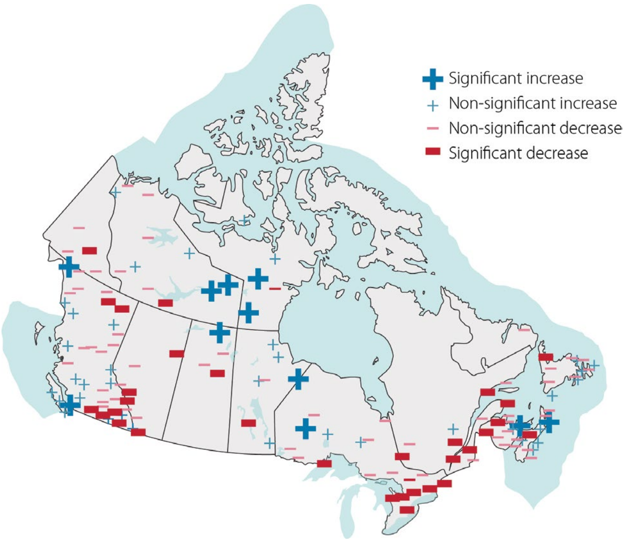


**FIGURE 21 A:** Trends in 1-day Maximum River Flow in 172 RHBN rivers (1970 to 2005) *(Source: Federal, Provincial and Territorial Governments of Canada, 2010).*

**FIGURE 21 B:** Trends in 1-day Minimum River Flow in 172 RHBN Rivers (1970 to 2005) *(Source: Federal, Provincial and Territorial Governments of Canada, 2010).*

## THE PRAIRIES

Van der Kamp et al. (2008) developed a database of measured and reconstructed water levels for sixteen closed-basin lakes in the semi-arid Canadian Prairies to assess long-term water level patterns. Observations are not continuous over the period 1910-2006, but most are concentrated in the 1960s to present. Many lakes show a tendency of water level decline but this could reflect decadal variability. The decline is likely a result of the dynamic interplay between reduced runoff and precipitation inputs and an increase in losses due to evaporation. However, from the 1960s onward in east-central Saskatchewan, some lakes had rising water levels, likely reflecting climatological changes as well as other factors such as agricultural practices and land cover/land use changes.

## LAURENTIAN GREAT LAKES

Water levels of the Laurentian Great Lakes fluctuate. Seasonally, water levels typically progress from a summer maximum to a minimum in winter/spring, with a documented earlier onset of the seasonal cycle and changes in the amplitude of water levels (Lenters, 2004; Argyilan and Forman, 2003). The lakes also exhibit interannual and inter-decadal fluctuations in water levels of less than 2.0 m (observed for the period 1918-2012), varying by lake (Wilcox et al., 2007; DFO 2013a). The most recent period of high water levels for all of the Great Lakes occurred in the 1980s. Levels subsequently declined rapidly, particularly from 1997-2000 (Assel et al., 2004). For the period 1998-2013, the upper Great Lakes – Superior, Michigan and Huron – have had a period of low water levels. Lake Michigan-Huron attained record low monthly mean levels in December 2012 and January 2013 (DFO, 2013b; Environment Canada, 2013) whereas Lake Superior set record low levels in August and September 2007 (DFO, 2007). A number of potential contributing factors have been identified, including climate change, vertical land movement and human modification of the system (e.g. dredging in the connecting channels) (International Upper Great Lakes Study – IUGLS, 2012). A similar water-level decline over this period in nearby Wisconsin seepage lakes suggests that regional climate variations may be a common driver (Stow et al., 2008). Water levels in the Great Lakes have also been correlated with large-scale atmosphere-ocean circulation patterns (e.g. Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) (Ghanbari and Bravo, 2008; Hanrahan et al., 2009; Wiles et al., 2009).

Water supply to the Great Lakes can also be represented by net basin supply (NBS) – a quantification of the factors, such as over-lake precipitation, runoff and evaporation that influence water levels. Analysis of these underlying factors and water-level trends in Lake Superior (1860-2007) and Lake Michigan-Huron (1860-2006) determined that there has been a negative linear trend in water levels – particularly since the end of the 20th century – that may have links to changes in evaporation and net precipitation (precipitation minus evaporation) (Sellinger et al., 2008; Lamon and Stow, 2010). The IUGLS (2012) undertook extensive trend and change-point analyses of water balance components for the period 1948 -2008 (Figure 22; *see also* Case Study 4 in Chapter 8). Evaporation has increased in all of the Great Lakes since 1948, but for most of the Lakes this has been offset by an increase in precipitation. This is not the case for the Lake Superior basin where evaporation has increased but precipitation has remained relatively constant, resulting in declining water supplies. Since most of the observed trends are within the range of natural variability, it is not possible to attribute these changes to climate change (Hayhoe et al., 2010).

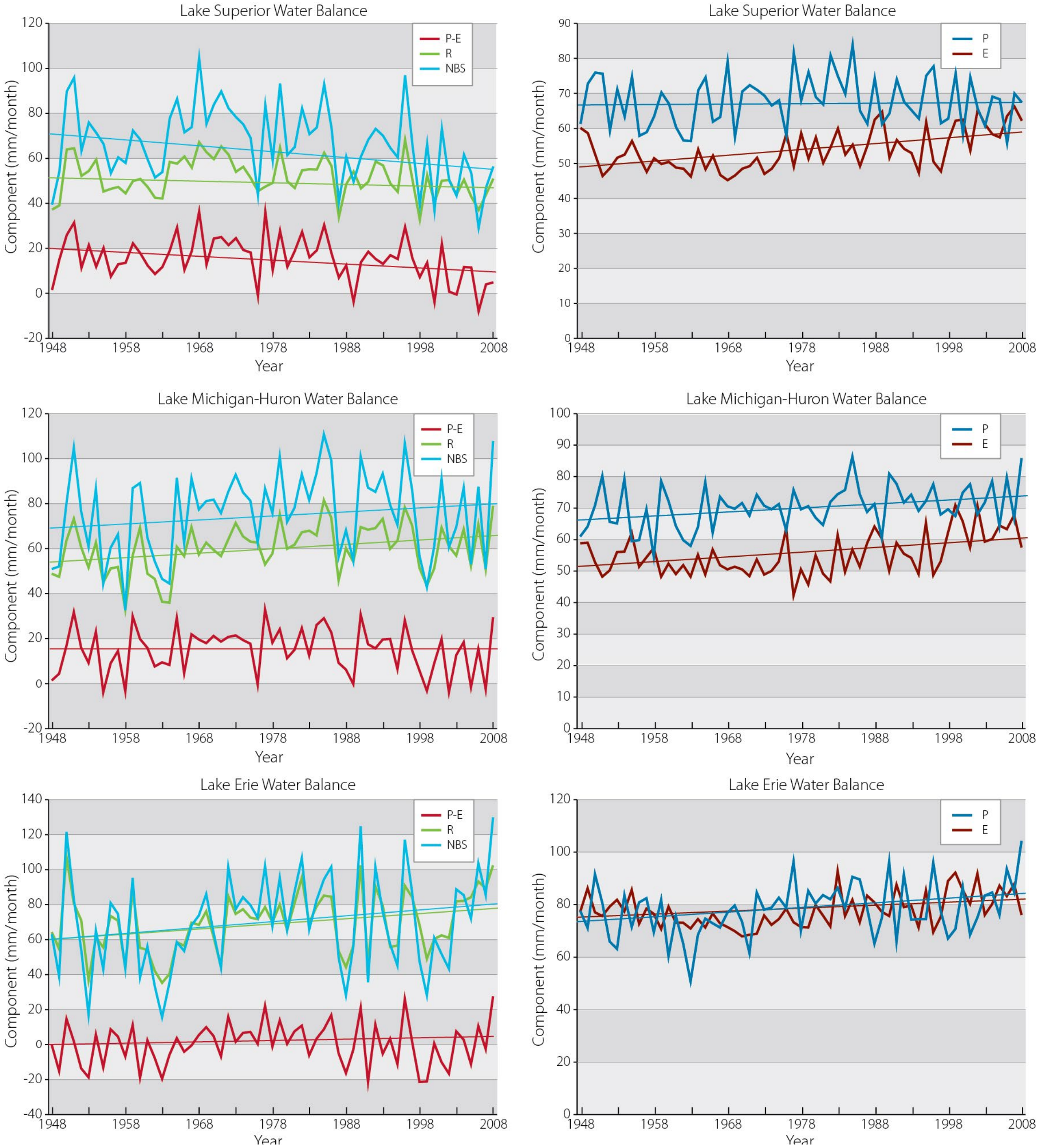


**FIGURE 22:** Trends in mean annual overlake precipitation (P), precipitation minus evaporation (P-E), runoff (R), and component net basin supply (NBS) for the upper Laurentian Great Lakes for the period 1946 to 2008. *(Source: IUGLS, 2012 derived from Fortin and Gronewold, 2012).*

## 4.2 PROJECTED CHANGES IN FRESHWATER AVAILABILITY

No national synthesis of studies investigating projected changes in surface water resources has been published since the review of studies within each regional chapter of Lemmen et al. (2008). However, several regional watershed-based studies have been published since 2008 that provide runoff projections for various climate change scenarios (Figure 23 and Table 2).

| Region | Projections | Key References |
|---|---|---|
| Baker River, BC | Most scenarios for the 2050s project increased winter runoff and decreased summer runoff, including decreased snow water equivalent | Bennett et al., 2012 |
| Campbell River, BC | Increase in 2050s winter runoff, and decrease in summer runoff; no consensus on changes in mean annual runoff | Schnorbus et al., 2011, 2012; Bennett et al., 2012 |
| Trepanier Creek, Okanagan Basin, BC | Decrease in 2050s mean annual and summer streamflow, with spring freshet occurring 2 weeks earlier, compared with 1983-1993 period | Harma et al., 2012 |
| Ingenika River, BC | Increase in 2050s winter runoff; no consensus on changes in summer runoff | Bennett et al., 2012 |
| Fraser River, BC | No consensus for 2050s mean annual flow projection for the Fraser River; flow during summer would decline in all scenarios | Shrestha et al., 2012b |
| Athabasca River, AB | Decrease in 2080s mean annual flow, and annual minimum flow | Kerkhoven and Gan, 2011; Shrestha et al., 2012b |
| Southern Prairies (tributaries of Saskatchewan River, AB, SK) | Decreases in 2050s annual runoff, except for increase in Cline River, AB due to large increase in winter runoff | Lapp et al., 2009; Shepherd et al., 2010; Forbes et al., 2011; Kienzle et al., 2012; St. Jacques et al., 2012 |
| Churchill, MB | In a hydrologic model intercomparison, 2 of 3 hydrologic model projections for a range of climate scenarios projected increases in annual runoff, while a 3rd model projected decreases | Bohrn, 2012 |
| Lake Winnipeg – Upper Assiniboine and Morris Basins, MB | Increased annual runoff projected for the Upper Assiniboine, and for most scenarios in the Morris Basin | Shrestha et al., 2012a; Stantec, 2012 |
| Spencer Creek, ON | Increase in mean annual and fall-winter streamflow, and decrease in March-April spring peak flow | Grillakis et al., 2011 |
| Credit River, ON | Mixed projections of annual streamflow | EBNFLO Environmental and AquaResource Inc., 2010 |
| Great Lakes, ON | Decrease in 2050s Net Basin Supply in Lakes Michigan-Huron and Erie; little change in Lake Superior | MacKay and Seglenieks, 2013; Chen et al., 2011 |
| Tributaries of the St. Lawrence, QC (including Richelieu, St. François, Yamachiche, St. Maurice and Batiscan Rivers) | Increases in 2050s mean winter runoff, with most scenarios projecting decreased summer runoff and increased annual runoff | Boyer et al., 2010 |
| Chaudière, QC | No consensus on projected changes in 2020s mean annual runoff | Quilbé et al., 2008 |
| Pinus River Basin (Labrador, NL) | Increase in 2050s mean annual streamflow, with spring peak occurring 2 weeks earlier compared with the 1971-2000 period | Roberts et al., 2012 |

**TABLE 2:** Summary of projected changes in freshwater. *See also* Figure 23.

Most watersheds in Canada are influenced by snow accumulation and melt patterns. Maximum snow water equivalent (SWE) is projected to decline in coastal British Columbia, the Atlantic Provinces and the Great Lakes-St. Lawrence region, while increases are projected for the Arctic coast of Nunavut (Brown and Mote, 2009).

For watersheds that contain glaciers, glacier retreat has already been observed in British Columbia and Alberta (Stahl et al., 2008; Marshall et al., 2011; Jost et al., 2012), and this is projected to continue as the climate warms. As the ice melts, this is expected to influence runoff, particularly during summer. Marshall et al. (2011) assessed glacier runoff for

2000-2007 and future scenarios to 2100 (using SRES scenarios B1 and A1B) for Rocky Mountain glaciers contributing to the Bow, Red Deer, North Saskatchewan, Athabasca and Peace Rivers. Projected changes in glacier volume range from -80% (Athabasca) to -100% (Red Deer). Projected glacier runoff changes between 2000 and 2050 for the A1B scenario are -80% for North Saskatchewan River, -100% for Bow and Red Deer Rivers, -75% for Peace River, and -60% for Athabasca River. As glacier runoff contributed around 7% to summer runoff in the Bow and North Saskatchewan Rivers in 2000-2007, projected reductions need to be accounted for in projections of streamflow during low flow periods in summer and fall. Studies are also available for drainage basins with glaciers in British Columbia (Bürger et al., 2011; Stahl et al., 2008; Jost et al., 2012).

Future lake levels in the Great Lakes basin, for three time periods in the 21st century (relative to 1970 to 1999), were evaluated recently by Angel and Kunkel (2010) using more than 500 scenarios based on Global Climate Model (GCM) runs forced by the B1, A1B, and A2 emission scenarios. While the majority of simulations project water level declines, higher water levels are also a possibility. For the 2050-2064 period, a wide range in lake levels for Lake Michigan-Huron were projected, ranging from a decline of around 1.5 m to an increase of more than 1 m. Based on the research available, including recent RCM results (e.g. MacKay and Seglenieks, 2013) the IUGLS concluded that in the short term, water level reductions may not be as extreme as projected in earlier climate change assessments, and while future lower water levels are likely, the possibility of higher levels must also be incorporated in water management and planning (IUGLS, 2012).

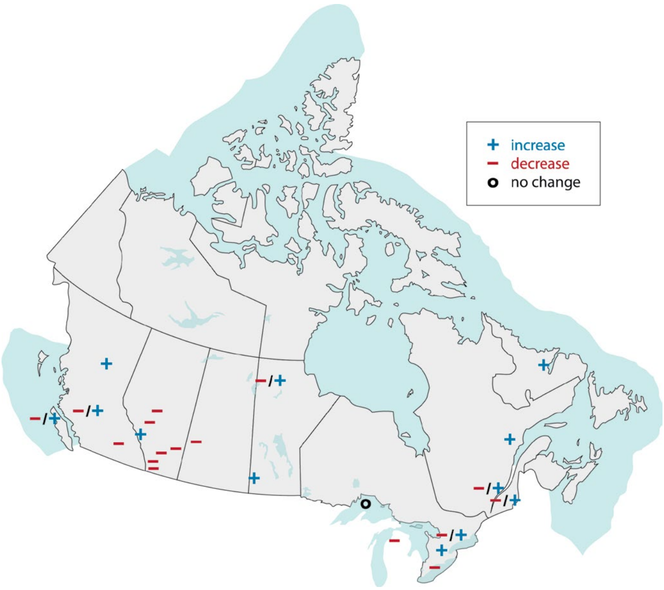


**FIGURE 23:** Projected changes in annual runoff for the 2050s period, from research published during 2008-2013. A '-/+' means that for a particular study location, scenario projections include both decreases and increases. *See* Table 2 for study references.

# 5. CHANGES IN OCEAN CLIMATE

Canada is bounded by three oceans with continental shelves, and has a long coastline with many embayments, straits, estuaries and coastal seas. Relevant ocean climate changes were discussed in the regional chapters of Lemmen et al. (2008) and are briefly discussed here as background to the thematic chapters in this updated report.

The primary observed large-scale ocean climate changes are summarized schematically in Figure 24. They include widespread warming and increasing carbon dioxide ($CO_2$) in the upper ocean (contributing to sea level rise and decreasing pH), reduced sea ice extent and freshening at high latitudes, and increasing surface salinity at low latitudes.

## 5.1 OCEAN TEMPERATURE

Influences of climate change on ocean temperature, salinity, acidity, sea level and other variables are evident from observational datasets around Canada (Hutchings et al., 2012; Christian and Foreman, 2013; Loder et al., 2013a; Steiner et al., 2013). However, it remains challenging to distinguish between anthropogenic and natural variability in the relatively short available time series for most variables. There is strong natural decadal-scale atmospheric and oceanographic variability (such as the Pacific Decadal, Arctic, North Atlantic and Atlantic Multi-decadal Oscillations) in various regions (*see* Box 3). In turn, this influences important ocean features such as El Niño in the Pacific, and the Labrador Current in the Atlantic, on regional scales.

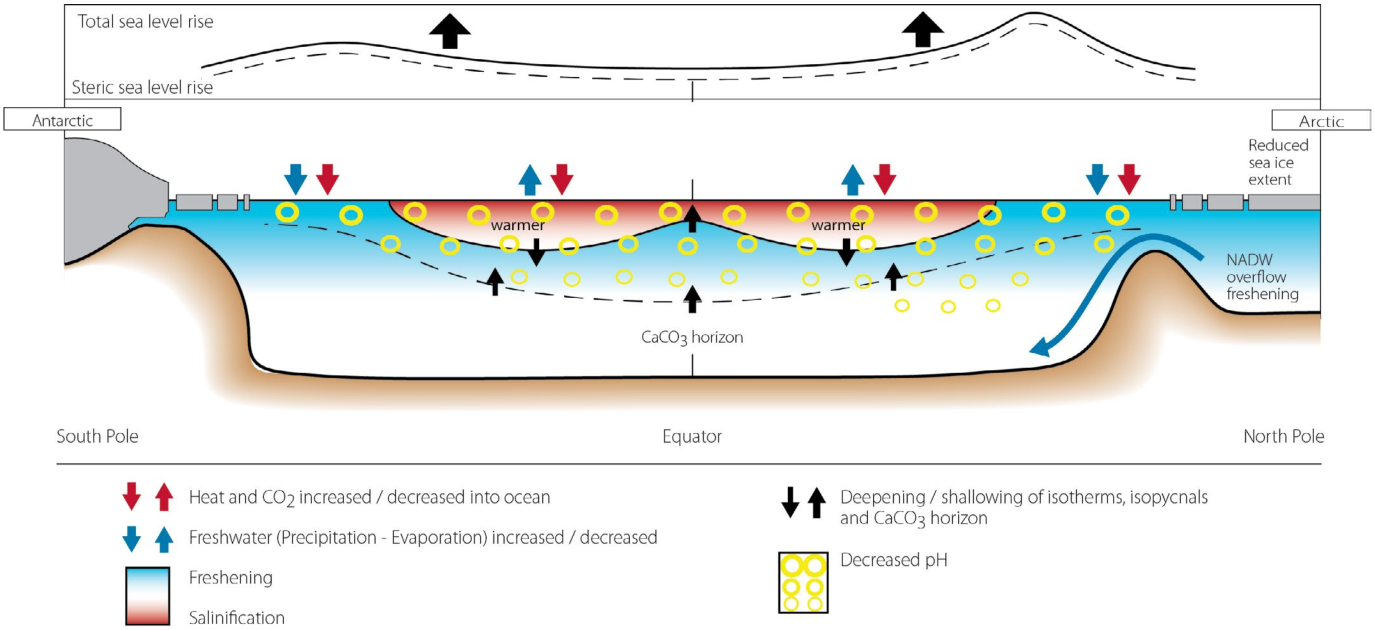


**FIGURE 24:** Schematic side view of prominent observed climate changes in the ocean. The legend identifies the direction of the changes. The "total" sea level rise is referred to as the "absolute" sea level rise, and the CaCO$_3$ (calcium carbonate) "horizon" as the "saturation depth" in the text *(Source: Bindoff et al., 2007)*.

### 5.1.1 PACIFIC COAST

Long-term warming trends of about 0.1°C per decade are present in coastal ocean temperature observations taken at British Columbia lighthouses over the past 75 years, and in offshore upper-ocean (10 to 50 m below surface) observations on Line P[3] in the Northeast Pacific over the past 55 years (Figure 25; Irvine and Crawford, 2012). Upper-ocean temperatures off British Columbia show strong natural variability associated with El Niño, La Niña and the PDO. In particular, temperatures in recent years have been cooler than in the previous two decades due to a Pacific-wide weather pattern associated with La Niña conditions in these years. Subsurface (100 to 150 m) waters on Line P show a weaker warming trend (~0.05°C per decade) and a decadal-scale variation resembling that in the upper-ocean waters. These warming trends are qualitatively consistent with global analyses of sea surface (Yasunaka and Hanawa, 2011) and subsurface (Bindoff et al., 2007) temperature datasets that indicate an overall ocean warming trend in the Northeast Pacific over the past century.

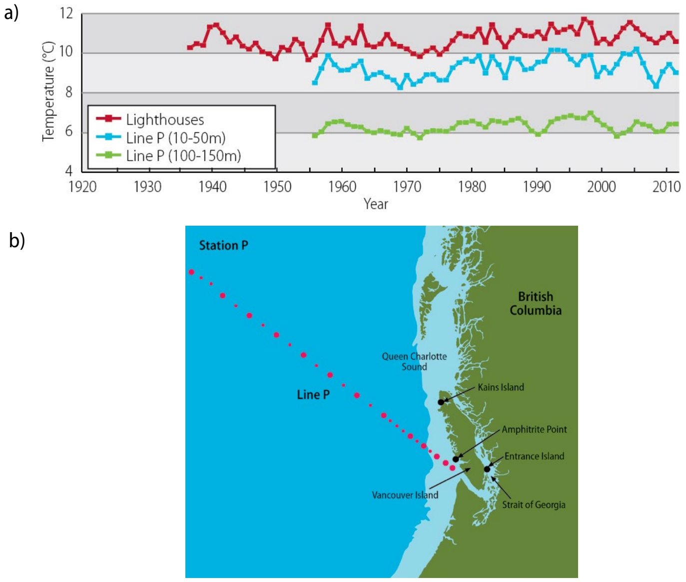


**FIGURE 25:** a) Annual-mean indices of ocean temperature in the Pacific Ocean off British Columbia, from DFO monitoring programs reported in Irvine and Crawford (2012). The Lighthouses index is the average of surface temperature measured daily at Amphitrite Point, Entrance Island and Kains Island (Chandler, 2012), while the Line P indices are based on Figure 12 of Robert et al. (2012). The trends (0.1, 0.09 and 0.05°C per decade, respectively, for the three time series), are all significantly different from zero at the 95% confidence level. b) Location map for Pacific Ocean observation sites.

---

[3] Line P is a Fisheries and Oceans Canada (DFO) monitoring line of 26 oceanographic stations extending about 1400 km offshore from the southwest coast of Vancouver Island to the former position of Ocean Weather Station (OWS) Papa in the Gulf of Alaska (Crawford et al. 2007; Figure 25b).

### 5.1.2 ATLANTIC COAST

Off Atlantic Canada, upper-ocean temperature observations over the past 60 to 80 years from mid-latitude regions to the west of the Grand Bank (such as the Bay of Fundy; Figure 26) generally show warming trends similar in magnitude to those in the Pacific. Warming trends are apparent in both the surface and near-bottom waters in the Gulf of St. Lawrence (Galbraith et al., 2012a) and Scotian Shelf (Hebert et al., 2012). The surface warming in the Gulf is consistent with increasing air temperatures (Galbraith et al., 2012b) and the higher near-bottom warming rate there is related to an increasing influence of subtropical waters from the Gulf Stream (Gilbert et al., 2005).

In contrast, there has been no significant warming trend over the past 60 to 80 years in the upper 150 m of the Labrador Sea and Newfoundland Shelf (Figure 26), where decadal-scale natural variability associated with the NAO and AMO has been dominant (Yashayaev, 2007; ICES, 2011; Loder et al., 2013b). The absence of a long-term trend in this region is consistent with the large area south of Greenland where there has been no net warming observed in surface air and water temperatures over the past century (Trenberth et al., 2007; Yasunaka and Hanawa, 2011). Over the past 2 to 3 decades there has been ocean warming in the Labrador-Newfoundland region.

### 5.1.3 ARCTIC COAST

There are no long time-series of ocean temperature in the Canadian Arctic, but the clear signals of warming in air temperature and sea ice observations, together with available ocean observations and model simulations (Galbraith and Larouche, 2011; Timmermans, 2012), point to the occurrence of upper-ocean warming in most areas.

### 5.1.4 PROJECTIONS

Projections from the CMIP3 and CMIP5 (*see* Box 4) models generally indicate widespread warming of the upper ocean around Canada during the 21st century, with substantial seasonal and spatial variability (Meehl et al., 2007b; Capotondi et al., 2012). Projected surface temperature increases from 1951-2000 to 2051-2100 from CMIP3 models for the A1B scenario are generally in the 1 to 3°C range (Capotondi et al., 2012). One exception is the northern North Atlantic south of Greenland, where most models indicate more limited warming, apparently associated with a reduction in the northward ocean transport of heat by the Atlantic Meridional Overturning Circulation (AMOC) (Drijfhout et al., 2012; Hutchings et al., 2012). However, the extent to which this projected ocean temperature anomaly will extend into the Labrador and Newfoundland coastal waters is uncertain, in view of the difficulties that global models have in resolving ice-ocean variability in the Labrador Sea (de Jong et al., 2009).

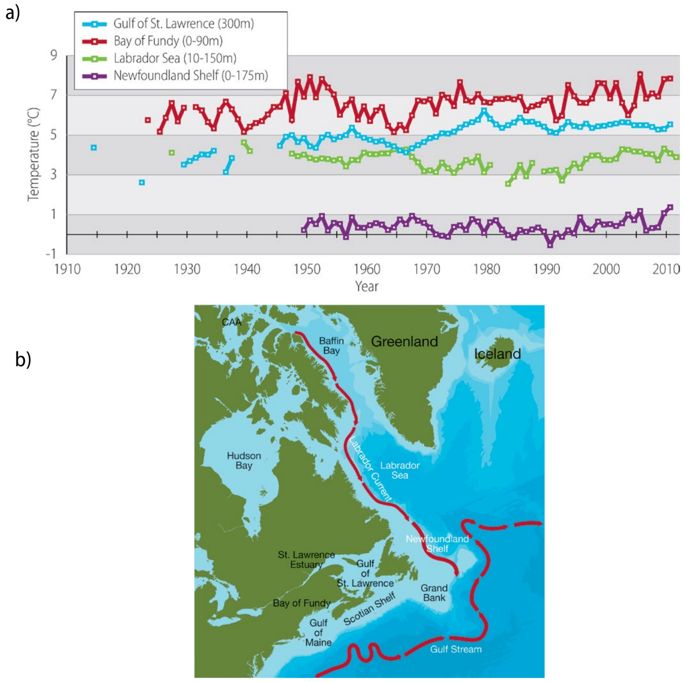


**FIGURE 26:** **a)** Annual-mean indices of ocean temperature off Atlantic Canada from DFO monitoring programs. The Bay of Fundy (BF) time series (Hebert et al. 2012) are from the Prince 5 station in Passamaquoddy Bay which has been sampled regularly since 1926, while the Newfoundland Shelf (NS) time series (Colbourne et al., 2012) are from Station 27 off St. John's which has been sampled in most months since 1950. The Gulf of St. Lawrence (GSL) time series is for near-bottom waters (Galbraith et al., 2012a) and the central Labrador Sea (LS) time series is from the vicinity of former OWS Bravo (Yashayaev and Greenan 2012), with both based on all available data. The trends for the BF and GSL time series (0.14 and 0.22°C per decade, respectively) are significant at the 95% confidence level, but those from the NS and LS series are not significant. **b)** Location map for Atlantic Ocean observation sites.

## 5.2 OCEAN SALINITY AND DENSITY STRATIFICATION

### 5.2.1 SALINITY

Ocean salinity is an important contributor to ocean climate and marine ecosystems since together with temperature and pressure (depth), it determines the density of seawater, which in turn affects ocean circulation, vertical density stratification, and vertical mixing. Changes in salinity occur in response to precipitation, evaporation, freshwater run-off from the continent, melting and freezing of sea ice, and ocean circulation and mixing, such that there is more spatial variability in salinity than temperature. Away from areas with sea ice and continental run-off, changes in ocean salinity can also be used to infer changes in precipitation-minus-evaporation (and hence the hydrological cycle) over the ocean (e.g. Helm et al., 2010).

Salinity in most locations off Pacific and Atlantic Canada over the past 60 to 80 years has been strongly influenced by decadal-scale variability similar to that observed for ocean temperature (Petrie, 2007; Yashayaev, 2007; Irvine and Crawford, 2012). Long-term trends are weak (<0.1 psu[4] per decade; Figures 27 and 28). There are also distinct local variations in some areas, apparently related to river run-off. There are indications of a long-term decrease in salinity in the near-surface waters over the Pacific shelf and offshore, but there are indications of increases in salinity in the Strait of Georgia and at the 150 m depth at Station P (Figure 27; Chandler, 2012; Freeland, 2013). The decreases in offshore surface values are consistent with the large-scale decrease observed in the Northeast Pacific (Durack and Wijffels, 2010).

On the Atlantic coast, long-term salinity changes have also been weak compared to decadal-scale variability, and have varied with location and with depth in some areas (Figure 28; ICES 2011). On the Scotian Shelf and in the Gulf of St. Lawrence and Bay of Fundy, there has been an overall tendency towards decreasing salinity in the near-surface waters but there has been increasing salinity in the deep near-bottom waters consistent with the poleward creep of subtropical waters (Gilbert et al., 2005; Hebert et al., 2012; Wu et al., 2012). Salinity variability off Labrador and Newfoundland has also been dominated by decadal-scale variability (Yashayaev, 2007; Colbourne et al., 2012), with no net change over 80 years in the Labrador Sea and a weak negative trend on the Newfoundland Shelf. More limited observations from the Arctic indicate freshening in most areas, but increased salinity in some others (e.g. Timmermans, 2012).

With the intensified hydrological cycle and land and sea ice melting expected in northern latitudes, long-term salinity decreases are generally expected in mid-to-high latitude waters such as those off Canada (Meehl et al., 2007b; Capotondi et al., 2012). Projected surface salinity decreases from 1951-2000 to 2051-2100 from CMIP3 models for the A1B scenario are generally in the range of -1 to -0.4 psu (Capotondi et al., 2012). An exception is the offshore slope and deep shelf waters between the Gulfs of St. Lawrence and Maine which are projected to have increased salinity by up to +0.4 psu because of the poleward creep of the North Atlantic's subtropical gyre and increased subtropical evaporation.

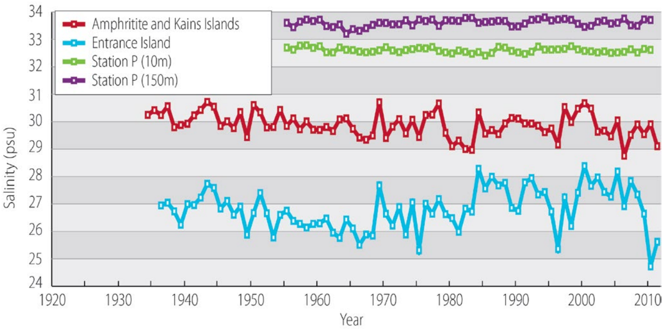


**FIGURE 27:** Annual-mean indices of ocean salinity in the Pacific Ocean off British Columbia, from DFO monitoring programs reported in Irvine and Crawford (2012). Values are in practical salinity units (psu), or parts per thousand. The Lighthouse time series (Amphitrite Point, Kains and Entrance Islands) are from Chandler (2012), while the Station P time series from the site of former OWS Papa are updates of those in Whitney et al. (2007). The trends for Station P (-0.01 and +0.02 psu per decade for 10 m and 150 m, respectively), and for Amphitrite Point and Kains Island (-0.06 psu per decade) are significant at the 95% confidence level, while the trend for Entrance Island (+0.07 per decade) is significant at the 93% confidence level. *See* Figure 25b for site locations.

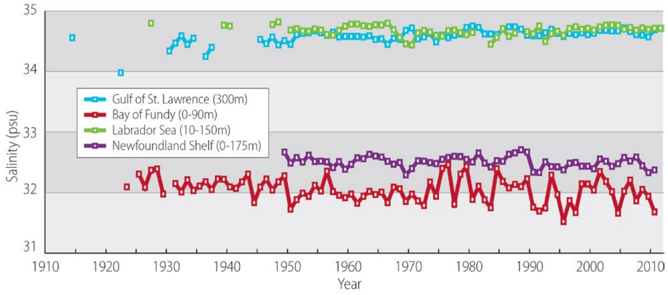


**FIGURE 28:** Annual-mean indices of ocean salinity off Atlantic Canada from DFO monitoring programs. The data sources and sites are the same as those for temperature in Figure 26. The decreasing trend for the BF (-0.02 psu per decade) and the increasing trend at depth in the GSL (+0.03 psu per decade) are significant at the 95% confidence level. The decreasing trend for the NS (-0.01 psu per decade) is significant at the 94% level, and the trend for the LS is not significant (*see* Figure 26b for site locations).

---

[4] Practical Salinity Unit, which is a unit based on the properties of sea water conductivity. It corresponds to parts per thousand (ppt) or to grams of salt per kilogram of water (g/kg).

### 5.2.2 VERTICAL DENSITY STRATIFICATION

The seasonally varying vertical stratification in upper-ocean water density is very important to ocean biogeochemistry and marine ecosystems (Box 6). Together with wind and tidal energy, it influences the vertical exchange of important dissolved and suspended materials, influencing atmospheric ventilation (e.g. $CO_2$ and oxygen) of subsurface waters, the upward supply of nutrients to the near-surface waters where phytoplankton grow, the suspension of phytoplankton, and the sinking rate of particulate material to greater depths.

**BOX 6**

#### OCEAN DENSITY STRATIFICATION

The density of seawater varies with its temperature, salinity, and depth. Ocean density stratification refers to the vertical gradient in water density whereby light, relatively warm and generally fresh near-surface water overlies cold, denser subsurface water. Important seasonal stratification develops in the upper ocean in spring and summer, as a result of the warming of near-surface water by solar radiation and atmospheric heating, and of near-surface freshening due to continental run-off. Strong stratification (large density gradients) tends to reduce vertical mixing in the ocean. Thus, the spatial and temporal variability of the stratification has important implications for mixing heat and $CO_2$ down into the ocean and for mixing nutrients (for plankton growth) up into the surface layers.

Global warming is resulting in increased upper-ocean vertical stratification in most ocean regions, due to the warming and hence lightening of surface waters. In most of the waters around Canada, this is expected to be reinforced by the freshening (and hence additional lightening) of near-surface waters (Capotondi et al., 2012). The observed long-term temperature and salinity trends off Pacific and Atlantic Canada are contributing to a long-term increase in stratification in many areas (Colbourne et al., 2012; Hebert et al., 2012; Freeland, 2013), although these changes are still dominated in some regions by decadal-scale variability (Figures 25-28). CMIP3 model projections (Capotondi et al., 2012) indicate increased upper-ocean stratification during this century around all of Canada, with both temperature and salinity contributing in most areas except in the subpolar North Atlantic where the freshening effect dominates and the subtropical North Atlantic where the warming effect dominates. This increased stratification will have important consequences for other ocean properties through reduced vertical mixing and ventilation of subsurface waters (e.g. Helm et al., 2011), and a general reduced supply of nutrients to the near-surface waters (e.g. Hutchings et al., 2012).

## 5.3 OCEAN HYPOXIA AND ACIDITY

### 5.3.1 OCEAN HYPOXIA

Observations off both Pacific and Atlantic Canada are indicating a general decline in the concentration of dissolved oxygen in subsurface (100 to 400 m) waters (Figure 29) below the more continually ventilated surface layer (Gilbert et al., 2005; Whitney et al., 2007; Hutchings et al., 2012; Crawford and Peña, 2013). This can be attributed to a combination of increasing temperatures (hence reduced solubility of oxygen) and increasing upper-ocean stratification (hence reduced ventilation), the poleward creep of subtropical waters in the Atlantic, and eutrophication from river run-off and biological productivity in some coastal areas (Gilbert et al., 2010). Concentrations in some areas are at or approaching "hypoxic" conditions (*see* Box 7), which are detrimental to marine organisms (e.g. Mucci et al., 2011; Bianucci and Denman, 2011), in part related to these climate change effects.

**BOX 7**

#### AQUATIC AND OCEAN HYPOXIA

The availability of dissolved oxygen is important to aquatic life. Ocean "hypoxia" is generally considered to occur when dissolved oxygen concentrations are lower than 60 to 80 µmole/kg. Aquatic hypoxia is best known in some lakes and coastal zones where oxidation of organic matter from runoff and plankton growth can result in local oxygen depletion and adverse conditions for aquatic life. The increasing temperature and increasing density stratification (and reduced ventilation) associated with climate change are acting to reduce dissolved oxygen levels in subsurface waters.

Low oxygen concentrations are already a serious concern for ecosystems and fisheries off Canada's Pacific coast where concentrations are naturally hypoxic at depths of 400 to 1000 m (Station P in Figure 29; Whitney et al., 2007; *see also* Chapter 4 – Food Production). This is, in part, due to these waters not having been in contact with the atmosphere for centuries during which time they have become oxygen-depleted by the oxidation of sinking organic matter. Intermittent upwelling of these waters onto the Pacific Shelf has resulted in the increasing occurrence of hypoxic bottom water conditions (Figure 29; Crawford and Peña 2013), particularly in summer, with natural decadal-scale variability clearly apparent in the observations.

Low oxygen concentrations have also become a serious issue at depth in the St. Lawrence Estuary (Figure 29), primarily due to increasing subtropical water at depth (Gilbert et al., 2005). More limited observations indicate that dissolved oxygen is also decreasing at depth on the Scotian Shelf (Petrie and Yeats, 2000) and in the Labrador Sea (Greenan et al., 2010). Past and future changes in dissolved oxygen in the Arctic are uncertain because of multiple (and in some cases offsetting) factors. For example, reduced ice cover can have different influences on stratification and ventilation, as well as on biological processes (Gilbert et al., 2010). The observed trends of reduced subsurface oxygen levels off Canada's other coasts are expected to continue with increasing $CO_2$ and heat in the atmosphere, and with increasing upper-ocean stratification in most areas (Meehl et al., 2007b; Hutchings et al., 2012). The effects of climate change are of particular concern in areas with or approaching hypoxic conditions.

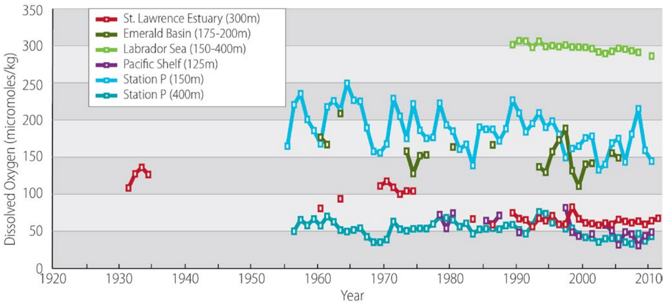


**FIGURE 29:** Annual indices of dissolved oxygen concentrations in subsurface waters off Pacific and Atlantic Canada, from DFO monitoring and other observation programs. The Pacific indices from Station P are updates of those in Whitney et al. (2007), while those for the Pacific Shelf are from Crawford and Peña (2013). The indices from the St. Lawrence Estuary, Emerald Basin (Scotian Shelf) and Labrador Sea are updates of those from Gilbert et al. (2005), Petrie and Yeats (2000) and Greenan et al. (2010). All trends are significant at the 95% confidence level: those for the first 5 sites listed are in the range of -7 to -9 µmole/kg per decade, and that at Station P (400 m) is -2 µmole/kg per decade. *See* Figures 25b and 26b for site locations.

## 5.3.2 OCEAN ACIDITY

Changes in ocean acidification (*see* Box 8) have a number of adverse implications for marine ecosystems, including a reduction in the stability of the carbonate ions used by marine organisms to build shells and skeletal structures (Doney et al. 2009; Hutchings et al., 2012).

**BOX 8**

### OCEAN ACIDIFICATION

The increasing input of anthropogenic $CO_2$ from the atmosphere to the ocean is increasing ocean acidity. $CO_2$ reacts with seawater to generate hydrogen ions and form carbonic acid, which makes seawater more acidic and lowers its pH. Ocean acidification is therefore a direct consequence of $CO_2$ emissions. The IPCC Fourth Assessment (AR4) reported that ocean pH has decreased by 0.1 units since 1750 as a result of the uptake of $CO_2$ from the atmosphere, which represents a 30% increase in acidity.

Increased acidity reduces the concentration of carbonate ions in the ocean. The carbonate ion is used by many organisms to build shells or skeletons. The so-called "saturation depths" or "horizons", below which various carbonate minerals such as aragonite and calcite dissolve more readily than they can be formed, are becoming shallower. This limits the areas of the ocean that are suitable habitats for many marine organisms.

Observations in the Arctic and Atlantic waters off Canada (Yamamoto-Kawai et al., 2009; Greenan et al., 2010) indicate decreasing pH at rates similar to those observed globally; namely, by ~0.1 pH units since pre-industrial times (Bindoff et al., 2007). Acidification is most pronounced in cold fresh Arctic waters where carbonate saturation depths are already shallow (Yamamoto-Kawai et al., 2009; Azetsu-Scott et al. 2010), and at depth in the St. Lawrence Estuary where increasing subtropical influences and biological processes have resulted in the pH decrease being a factor of 4 to 6 times larger than that in the global surface waters (Mucci et al., 2011). Widespread ocean acidification has also been detected in the North Pacific Ocean (Feely et al., 2008). In some areas off all three coasts, waters are already considered to be "corrosive" to some calcareous organisms, i.e. capable of dissolving their shells and skeletons (e.g. Feely et al., 2008; Yamamoto-Kawai et al., 2009; Mucci et al. 2011).

Projections based on the IPCC SRES scenarios (*see* Box 4) indicate further global reductions in pH of between 0.14 and 0.35 units in the 21st century (Feely et al. 2009; Hutchings et al., 2012), but larger reductions may occur in local areas. The effects will be particularly significant in the high-latitude waters around Canada where the aragonite saturation depth could shallow into the upper 50 m by 2100 (Denman et al. 2011).

## 5.4 SEA LEVEL CHANGE

### 5.4.1 PAST AND PRESENT MEAN SEA LEVEL CHANGE

Global mean sea level rose about 21 cm between 1880 and 2012 (Figure 30). The rate of rise (Box 9) increased between the 20th and early 21st centuries. In the 20th century, sea level rose 1.7 ± 0.5 mm/yr, corresponding to about 17 cm over the course of the century while from 1993 to 2003, it rose 3.1 ± 0.7 mm/yr (Bindoff et al., 2007) and it has continued at a similar rate to 2009 (Nerem et al., 2010) and in recent years (*see* Figure 30). The sources of sea-level rise include thermal expansion of the upper ocean and melt-water from glaciers, ice caps, and the Greenland and Antarctic ice sheets. Sea level rise is not uniform across the various oceans. Observed global sea-level change has exhibited substantial spatial variability, even over several decades (Meyssignac et al., 2012), mainly due to long-term spatial variability in thermal expansion and changes to salinity. Other effects, such as uneven melt-water redistribution, also contribute to spatial variability.

Much of the Canadian land mass is experiencing uplift due to glacial isostatic adjustment, which is the delayed rebounding of the land surface in response to the removal of the weight of the continental ice sheets during their retreat at the end of the last ice age (Figure 31; Peltier, 2004). The coastlines of Hudson Bay and the central Arctic Archipelago are rising rapidly and have been for thousands of years due to this adjustment, causing sea level to fall. At Churchill, Manitoba, the tide gauge shows sea-level fall of nearly 10 mm/yr since 1940 (Wolf et al., 2006), consistent with a measurement of crustal uplift slightly in excess of 10 mm/yr (Mazzotti et al., 2011).

**BOX 9**

### ABSOLUTE AND RELATIVE SEA LEVEL CHANGES

Global sea-level change is commonly discussed in terms of "absolute" sea level, meaning that it is referenced to the centre of the Earth. At coastal locations, the sea-level change that is observed or experienced relative to a fixed location on land is known as relative sea-level change. Relative sea-level change is the result of absolute sea-level change and vertical land motion, both of which can vary from one location to another. Land uplift decreases relative sea-level rise and land subsidence increases it. In determining relative sea-level changes across Canada, vertical land motion (uplift and subsidence) plays a predominant role, although regional variations in absolute sea-level change are also important.

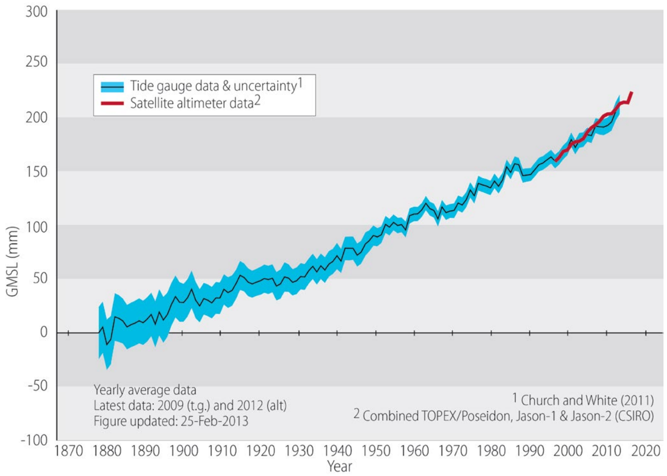


**FIGURE 30:** Observed global mean sea-level from 1880 to 2012 (*Source: Commonwealth Scientific and Industrial Research Organization [CSIRO], www.cmar.csiro.au/sealevel/ accessed June 17, 2013*). The observations are based on tide gauge data (1880 to 2009) and TOPEX/Poseidon, Jason-1, and Jason-2 satellite altimetry (1993-2012).

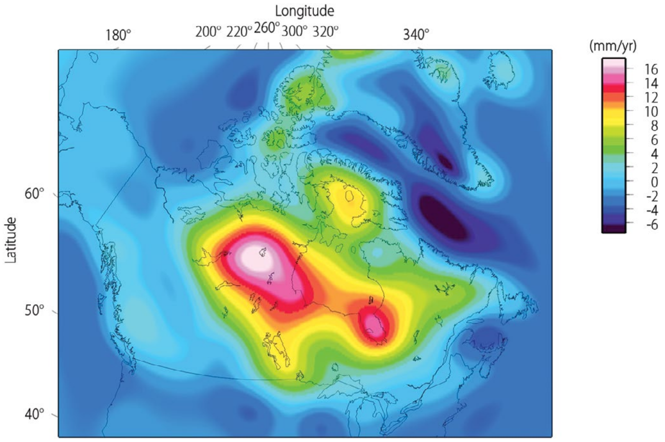


**FIGURE 31:** Present-day vertical crustal motion (in millimetres per year) predicted by the ICE-5G model of glacial isostatic adjustment (*Source: Peltier, 2004*). Relative sea level is presently falling in regions where the land is rising rapidly, such as Hudson Bay. Areas that are sinking, such as most of the Maritimes, experience relative sea-level rise that is larger than the global value. The model predictions do not include the significant vertical crustal motion in coastal British Columbia caused by active tectonics.

Outside the area of uplift, the land is sinking at lower rates. The sinking of land is due to the slow flow of rock deep in the Earth's mantle from subsiding regions towards uplifting regions. This reverses the process of flow away from regions depressed by ice sheets in the past. Most of the Maritimes, much of Newfoundland, the Yukon coast, the mainland coast of the Northwest Territories and some of its islands, and the east coast of Baffin Island in Nunavut, are subsiding. These regions have experienced relative sea-level rise over the past few thousand years. At Halifax and Charlottetown, tide-gauge records show that relative sea level has risen at about 3.2 mm/yr throughout most of the 20th century (Forbes et al., 2004, 2009), nearly double the 20th century value of global sea-level rise. At Tuktoyaktuk, on the Beaufort Coast of the Northwest Territories, relative sea-level has risen at 3.5 mm/yr in the past half-century, consistent with a combination of global sea-level rise and local land subsidence (Forbes et al., 2010).

Relative sea-level rise in British Columbia has generally been smaller than in the Maritimes, with differences along the coastline largely arising from vertical land motion due to movement of tectonic plates offshore. The effects of past and present-day mass fluctuations of mountain glaciers and a residual glacial isostatic adjustment effect from the last continental glaciation are also present. In the 20th and early 21st century (1909 to 2006), sea level rose at an average rate of 0.6 mm/yr in Vancouver and Victoria, and 1.3 mm/yr in Prince Rupert, and fell by 0.9 mm/yr in Tofino (Mazzotti et al., 2008).

Another geological factor that contributes to relative sea-level change is sediment compaction. On the Fraser Delta, ongoing subsidence due to sediment compaction has been measured at 1-2 mm/yr (Mazzotti et al., 2008, 2009). Similarly, measurements on the Mackenzie Delta in the Northwest Territories show subsidence of up to several millimetres per year relative to a nearby stable reference point. The additional subsidence of the Delta further contributes to sea-level rise on this isostatically subsiding shoreline (Forbes et al., 2010).

### 5.4.2 FUTURE CHANGES TO MEAN SEA LEVEL

Global mean sea-level will continue to rise in the 21st century (Figure 32), but there is uncertainty regarding the rate. As projected by the IPCC AR4, the increase in global sea level over the 21st century, relative to the last two decades of the 20th century, would range from 18 to 59 cm depending on the emission scenario (Meehl et al., 2007b). For all scenarios, the thermal expansion component dominated, representing 70 to 75% of the central estimates of the sea level rise by the end of the century (Meehl et al., 2007b). The report also considered that an additional sea-level rise of 10 to 20 cm from accelerated glacier discharge to the oceans could be possible. These results were obtained from process-based models incorporating physical laws and known properties of the atmosphere, oceans, glaciers and ice sheets. Updated projections following the IPCC approach (e.g. Church et al., 2011) indicate a global sea-level rise of about 20 to 80 cm by 2100.

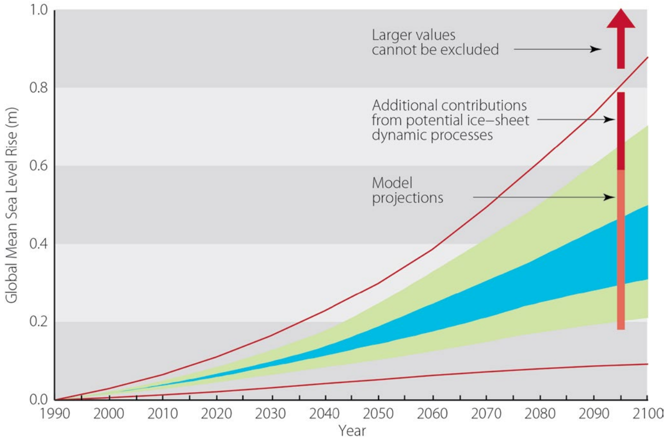


**FIGURE 32:** Projected global sea-level rise for the 21st century from the IPCC Third Assessment Report (TAR; blue and green shading and red lines; IPCC, 2001) and at the end of the century from the Fourth Assessment Report (AR4; coloured bars; IPCC, 2007). For the TAR, the blue shading shows the variation in the mean projections for a range of emissions scenarios, the green shading shows the range of all model projections, and the outer lines indicate an additional uncertainty from land ice. For AR4, the light red bar shows the range of model predictions, the dark red bar indicates a possible additional contribution from Greenland and Antarctic ice-sheet dynamics, and the dark red arrow shows that larger amounts of sea-level rise cannot be excluded[5] *(modified from Church et al., 2008)*.

Some publications, utilizing semi-empirical methods, suggest larger amounts of global mean sea-level rise by the end of the 21st century, reaching values in excess of 100 cm (e.g. 75 to 190 cm, Vermeer and Rahmstorf, 2009 and 57 to 110 cm, Jevrejeva et al., 2012). The semi-empirical projections are based on assumed relationships between global sea-level and either global temperatures or atmospheric heat balance. They do not capture the full range of physical processes responsible for changes in sea level. At present it is not known why they give higher values of sea-level rise than the process-based modeling which formed the basis of the IPCC TAR (Third Assessment Report) and AR4 (Fourth Assessment Report) results. It has been suggested that the semi-empirical projections be treated with caution owing to a number of limitations (Church et al., 2011).

An upper bound of 200 cm of global sea-level rise by 2100 was derived from glaciological modeling, to help rule out even larger values of global sea-level rise (Pfeffer et al., 2008). Based on an assessment of the probable maximum contributions from various sources of sea-level rise, and on studies using a variety of approaches, a "plausible high-end"

---

[5] The IPCC recently updated projections of future sea level rise (Stocker et al., 2013) and confirmed that higher levels of sea level rise (>1m) could not be excluded, but assessed the likely (>66% probability) upper end of the range of projected sea level rise to be about 1m relative to current levels by the end of the century.

scenario range of 55 to 115 cm of global sea-level rise by 2100 has been derived for use in flood risk planning (Katsman et al., 2011).

Included in these estimates are the contributions from melting Canadian glaciers and ice caps. The contribution to sea-level rise to 2100 from circumpolar Arctic glaciers is projected to be 5 to14 cm, with Canadian Arctic glaciers, ice fields, and ice caps projected to contribute 1 to 4 cm (AMAP, 2011). A recent update indicates a contribution of 3.5 ± 2.4 cm to global sea-level rise from the Canadian Arctic Archipelago in the 21st century (Lenaerts et al., 2013). Much smaller contributions are expected from western Canadian glaciers given their lower ice volumes (Marzeion et al., 2012).

The patterns of future relative sea-level change in Canada, like past and present-day patterns, will be influenced by land uplift and subsidence, uneven melt-water redistribution, and changes in ocean temperature, salinity and circulation (e.g. Slangen et al., 2012). Around Hudson Bay, some coastlines are rising so quickly that sea-level will continue to fall throughout the 21st century, except for the most extreme scenarios of global sea-level rise (James et al., 2011). A consequence of sea-level fall is reduced depth-under-keel of ocean-going vessels, leading to potential navigation and docking hazards. Areas that are rising more slowly may experience a transition from relative sea-level fall in the early decades of the 21st century to sea-level rise by 2100, depending on the rate of uplift and the amount of global sea-level rise. Subsiding regions will experience enhanced sea-level rise.

Melt-water redistribution in the oceans is uneven (Mitrovica et al., 2001, 2011). The shrinking mass of ice sheets and glaciers reduces their gravitational attraction to water in the oceans, leading to sea-level fall close to a source of meltwater. Near the source of meltwater, the Earth's crust responds elastically to the decreasing load, causing land uplift that also contributes to relative sea-level fall. These processes of meltwater redistribution and elastic crustal response (sometimes termed 'sea-level fingerprinting') are important in Canada because of the presence of Arctic ice caps and, in the west, mountain glaciers and ice fields. In addition, the Greenland ice sheet and Gulf of Alaska glaciers are both sources of meltwater for global sea-level rise. Due to their proximity – on a global scale – to these important sources of melt-water, large regions of Canada will experience reduced rates of relative sea-level rise. The effects of meltwater redistribution are sufficiently pronounced in parts of Arctic Canada that the range of local sea-level projections is less than half the range of global projections (James et al., 2011).

Sea levels are also affected by global ocean circulation, which accounts for greater than 2 m of current spatial variation in absolute sea level. The largest sea level gradient off the coast of Canada is located in the northwest Atlantic where the sea level change across the Gulf Stream is about 1.5m (Thompson et al., 2011). Variability in ocean currents may contribute to sea level change on all three coasts. Above-average sea-level risedue to changes in ocean circulation is projected in the Arctic and the Maritimes (e.g. Yin, 2012; Ezer et al., 2013), partly counteracting the reductions arising from melt-water redistribution. Off the west coast, long-term current-induced changes in coastal sea level may be masked by decadal-scale variations in sea level arising from changes in circulation and upper ocean temperatures associated with major El Niño and La Niña events (Thomson et al., 2008).

Projections of global sea-level rise beyond 2100 have an even larger uncertainty, but indicate continuing global sea-level rise over the coming centuries and millennia (e.g. Katsman et al., 2011; Huybrechts et al., 2011; Jevrejeva et al., 2012). Global sea-level rise may eventually amount to several metres.

### 5.4.3 EXTREME WATER LEVELS

Rising mean sea levels are an important factor with respect to extreme (high) water levels, which generally occur when storm surges coincide with high tidal levels. Contributions from harbour seiches, wind waves and interannual and seasonal variability are also important. Ocean-surface heights vary on time scales from years to hours due to atmosphere and ocean variations, such as ENSO, NAO, seasonal warming and runoff, storms, and changes to ocean circulation. In the Pacific, extreme ENSO events can result in coastal sea level changes of a few tens of centimetres. Storm surges can have amplitudes of more than a metre on all three coasts (Bernier and Thompson, 2006; Manson and Solomon, 2007; Thomson et al., 2008). This short-term, large-amplitude variability causes peak water levels to vary substantially throughout the year and from year to year. It is superimposed on the slow rise in mean sea level which causes incrementally higher water levels over time where relative sea level is rising. In the Bay of Fundy, increasing mean sea level is resulting in a small increase in the tidal range due to increased resonance of the semidiurnal tides (Greenberg et al., 2012), which will further contribute to extreme high water levels there.

Climate-related changes in the above factors will also affect extreme water levels in many regions of the globe. Possible climate changes affecting the intensity and frequency of storms, hurricanes and high wind waves are of particular concern, though they are expected to vary geographically and there is uncertainty regarding their sign and magnitude in most areas (e.g. Ulbrich et al., 2009; Harvey et al., 2012; Rummukainen, 2012; Seneviratne et al., 2012). Available analyses of observed wind speed changes at coastal locations around Canada are inconclusive regarding long-term trends (Hundecha et al., 2008; Wan et al., 2010). There are some suggestions that the strongest storms will become more intense in mid-to-high latitude areas of the North Pacific and North Atlantic (e.g. Mizuta, 2012; Woollings et al. 2012), associated with poleward shifts of the jet stream and storm tracks. However, there are differences in the details of the projected changes depending on season and location (e.g. Perrie et al. 2010; Long et al. 2009) and among models.

Changes in sea-ice cover have important implications for wind waves reaching the coast. Nearshore sea ice prevents waves from breaking directly onshore and reduces wave run-up (Forbes and Taylor, 1994; Allard et al., 1998). Ice further offshore reflects waves and reduces the amplitude of waves before they reach the shoreline (Wadhams et al., 1988; Squire, 2007), so that more open water will lead to larger waves even if the winds are unchanged. Thus, where there are projected reductions in sea ice, such as Atlantic Canada and the Arctic, there is the potential for increased extreme water levels due to run-up.

Increased extreme water levels will generally lead to increased amounts of coastal erosion. Dyked areas, coastal regions with little relief, and coastlines comprised of unconsolidated sediments are more vulnerable to erosion than high-lying, rocky coastlines. In the Arctic, increased air and water temperatures may degrade and thaw permafrost, loosening ice-bonded sediments and also contributing to erosion (Forbes, 2011). At this time, it appears that the long-term changes to the frequency and intensity of extreme coastal water levels and flooding in Canada will be primarily driven by changes in mean sea level and by sea ice changes, although tides, storm surge, and waves will continue to play prominent roles. Regions that are projected to experience an increase in mean sea-level are also likely to experience increasing extreme high water levels.

# 6. SUMMARY

Atmospheric warming has been widespread across Canada since 1950, although strongest in the north and west. It has occurred in all seasons, but has been most pronounced in winter and spring. The primary contributor to long-term warming in Canada (and the rest of the world) since the mid-20th century has been the anthropogenic emission of GHGs. Other factors can strongly influence short-term climate variability imposed on the long-term trend.

A range of indicators provides a coherent picture of the response of the atmosphere-ice-ocean system to this climate warming. An increase in hot extremes and a decrease in cold extremes of air temperature have been observed across the country. Canada as a whole has become wetter, although with notable spatial and seasonal variability. In most of southern Canada there has been a decrease in snowfall and an increase in rainfall consistent with warmer temperatures. A reduction in the spatial extent and mass of the Canadian cryosphere is evident in observations of rapidly declining snow and sea ice cover, shorter seasons of ice cover on many lakes and rivers, widespread warming of permafrost and shrinkage of glaciers in both western Canada and the High Arctic. Indicators of surface freshwater availability, such as streamflow, provide integrated responses to climate and cryospheric change, but spatially consistent patterns across the country are difficult to discern.

Natural climate fluctuations such as El Niño and the North Atlantic Oscillation contribute to regional climate variability on short (decadal) time scales. The warming projected to occur throughout this century will be associated with a continuation and potential acceleration of many of the trends observed over the past half century. Some patterns of change may prevail for Canada as a whole (a warmer, wetter Canada with less snow and ice), but regional and seasonal variability will continue. In particular, amplified warming and related impacts in the Arctic are expected. Precipitation changes are particularly uncertain, but potential declines in southern Canada, combined with warmer summers and increased evaporation, could increase seasonal aridity and reduce freshwater availability in some areas.

Long-term changes in ocean climate – temperature, salinity, oxygen levels and acidity – consistent with increasing atmospheric $CO_2$ and anthropogenic climate warming have been observed in all three of Canada's oceans. However, natural variability on decadal to multi-decadal time scales has also contributed to the observed changes in some areas (e.g. the Northwest Atlantic) off Canada. Nevertheless, warmer waters, reduced sea ice, reduced upper ocean salinities, and increased vertical density stratification are expected in most Canadian waters over the next century. The observed global trends of ocean acidification and reduced sub-surface oxygen levels are expected to continue and to be evident in Canadian waters as well.

Sea level change along Canadian coastlines has been, and will continue to be, affected by both global and local factors. Expansion of warming waters and increased meltwater from land ice are both contributing to rising global sea levels. Estimates of the magnitude of future changes in global sea level by the year 2100 range from a few tens of centimetres to more than a metre. Vertical land movement strongly influences relative sea level changes at the local scale. Where the land is currently subsiding, such as most of the Maritimes, relative sea level is rising at rates larger than the global average, and will continue to rise. Where the land is rising rapidly (e.g. around Hudson Bay), sea level will continue to fall except under extreme scenarios of sea level rise. Areas where land is rising more slowly may see a transition from relative sea level fall to relative sea level rise over the 21st century. Extreme sea levels are likely to be experienced more frequently in the coming century where relative sea level is rising and where sea ice is projected to decrease in the Arctic and in Atlantic Canada.

## ACKNOWLEDGEMENTS

The authors would like to thank the following colleagues who reviewed and offered constructive comments on chapter drafts: John Fyfe and Xuebin Zhang of Environment Canada, Kumiko Azetsu-Scott, Diane Lavoie, Charles Hannah and Rick Thomson, of Fisheries and Oceans Canada, and Don Forbes and Joseph Henton of Natural Resources Canada. We would also like to express our gratitude to the anonymous external reviewers for their time and efforts.

# REFERENCES

Abdul-Aziz, A.O. I. and Burn, D.H. (2006): Trends and variability in the hydrological regime of the Mackenzie River Basin; Journal of Hydrology, v. 319, no. 1-4, p. 282-294.

Allard, M., Michaud, Y., Ruz, M.-H. and Héquette, A., (1998): Ice foot, freeze-thaw of sediments, and platform erosion in a subarctic microtidal environment, Manitounuk Strait, northern Quebec, Canada; Canadian Journal of Earth Sciences, v. 35, p. 965-979.

Allen, M.R. and. Ingram, W.J (2002): Constraints on the future changes in climate and the hydrological cycle; Nature, v. 419, p. 224-226.

AMAP [Arctic Monitoring and Assessment Programme] (2011): Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere; Oslo, Norway. xii + 538 p.

Angel, J. R. and Kunkel, K. E. (2010): The response of Great Lakes water levels to future climate scenarios with an emphasis on Lake Michigan-Huron; Journal of Great Lakes Research, v. 36, p. 51-58.

Arctic Report Card (2012): (ed) J. Richter-Menge, M.O. Jeffries and J.E. Overland, online, <http://www.arctic.noaa.gov/report12/>.

Argyilan, E.P. and Forman, S.L. (2003): Lake level response to seasonal climatic variability in the Lake Michigan-Huron system from 1920 to 1995; Journal of Great Lakes Research, v. 29, no. 3, p. 488-500.

Assel, R.A., Quinn, F.H., and Sellinger, C.E. (2004): Hydroclimatic factors of the recent record drop in Laurentian Great Lakes water levels; Bulletin of the American Meteorological Society, v. 85, p. 1143–1151.

Azetsu-Scott, K., Clarke, A., Falkner, K., Hamilton, J., Jones, E.P., Lee, C., Petrie, B., Prinsenberg, S., Starr, M. and Yeats, P. (2010): Calcium carbonate saturation states in the waters of the Canadian Arctic Archipelago and the Labrador Sea; Journal of Geophysical Research, v. 115, C11021.

Barrand, N.E. and Sharp, M.J. (2010): Sustained rapid shrinkage of Yukon glaciers since the 1957-1958 International Geophysical Year; Geophysical Research Letters, v. 37, L07501.

Bates, B. C., Kundzewicz, Z. W, Wu, S. and Palutikof, J. P. (ed.) (2008): Climate Change and Water; Technical Paper of the Intergovernmental Panel on Climate Change (IPCC); IPCC Secretariat, Geneva. 210 p.

Beltaos, S., and Prowse, T. (2009): River-ice hydrology in a shrinking cryosphere; Hydrological Processes, v. 23, p. 122-144.

Bennett, K.E., Werner, A.T., and Schnorbus, M. (2012): Uncertainties in Hydrologic and Climate Change Impact Analyses in Headwater Basins of British Columbia; Journal of Climate, v. 25, no. 17, p. 5711-5730.

Bernier, N.B. and Thompson, K.R. (2006): Predicting the frequency of storm surges and extreme sea levels in the northwest Atlantic; Journal of Geophysical Research, v. 111, C10009.

Bianucci, L. and Denman, K.L. (2011): Carbon and oxygen cycles: Sensitivity to changes in environmental forcing in a coastal upwelling system; Journal of Geophysical Research, v. 117, G01020.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D. and Unnikrishnan, A. 2007. Observations: oceanic climate change and sea level; in: Climate Change 2007: The Physical Science Basis; (Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change); (ed.) S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller; Cambridge University Press, Cambridge, United Kingdom. p. 385–432. Blunden, J. and Arndt, D. S. (ed.) (2012): State of the Climate in 2011; Bulletin of the American Meteorological Society, v. 93, no. 7, S1–S264.

Bohrn, S. K. (2012): Climate Change Impacts Assessment and Uncertainty Analysis at the Hydrology of a Northern, Data-Sparse Catchment Using Multiple Hydrological Models; Civil Engineering, University of Manitoba, Winnipeg; online, <http://mspace.lib.umanitoba.ca//handle/1993/13692> .

Bolch, T., Menounos, B., and Wheate, R. (2010): Landsat-Based Inventory of Glaciers in Western Canada, 1985-2005; Remote sensing of Environment v. 114, p. 127-137.

Bonsal, B.R., Prowse, T.D., Duguay, C.R., and Lacroix, M.P. (2006): Impacts of large-scale teleconnections on freshwater-ice duration over Canada; Journal of Hydrology, v. 330, p. 340-353.

Bonsal, B.R. and Shabbar, A. (2011): Large-scale climate oscillations influencing Canada, 1900-2008; Canadian Biodiversity: Ecosystem Status and Trends, 2010. Technical Thematic Report No. 4, Canadian Councils of Resource Ministers, Ottawa, ON. iii + 15 p.

Bonsal, B.R., Wheaton, E. E., Chipanshi, A.C., Lin, C., Sauchyn, D. J., and Wen, L. (2011): Drought research in Canada: A Review. Atmosphere-Ocean v. 49, no. 4, p. 303-319.

Bonsal, B.R., Aider, R., Gachon, P. and Lapp, S. (2012): An assessment of Canadian prairies drought: past, present and future; Climate Dynamics, v. 41, no. 2 p. 501-516.

Boyer, C., Chaumont, D., Chartier, I., and Roy, A. G. (2010): Impact of climate change on the hydrology of St. Lawrence tributaries; Journal of Hydrology, v. 384, p. 65-83.

Brimley, B., Cantin, J-F., Harvey, D., Kowalchuk, M., Marsh, P., Ouarda, T., Phinney, B., Pilon, P., Renouf, M., Tassone, B. Wedel, R. and Yuzyk. T. (1999): Establishment of the Reference Hydrometric Basin Network (RHBN) for Canada; Environment Canada, 44 p.

Brown, L.C. and Duguay, C.R. (2010): The response and role of ice cover in lake-climate interactions; Progress in Physical Geography v. 34, no. 5, p. 671-704.

Brown, L.C. and Duguay, C.R. (2011): The fate of lake ice in the North American Arctic; The Cryosphere, v. 5, p. 869-892.

Brown, R., Derkesen, C. and Wang, L. (2010): A multi-data set analysis of variability and change in Arctic spring snow cover extent, 1967-2008; Journal of Geophysical Research, v. 115, D16111.

Brown, R.D., and Mote, P.W. (2009): The response of the Northern Hemisphere snow cover to a changing climate; Journal of Climate, v. 22, p. 2124-2145.

Brown, R.D. and Robinson, D. A. (2011): Northern Hemisphere spring snow cover variability and change over 1922-2010 including an assessment of uncertainty; The Cryosphere v. 5, p. 219-229.

Bürger, G., Schulla, J., and Werner, A. T. (2011): Estimates of future flow, including extremes, of the Columbia River headwaters; Water Resources Research, v. 47, p. 10.

Burn, D. H., Buttle, J. M., Caissie, D., MacCulloch, G., Spence, C., and Stahl, K. (2008): The processes, patterns, and impacts of low flows across Canada; Canadian Water Resources Journal, v. 33, no. 2, p. 107-124.

Burn, D. H., Sharif, M., and Zhang, K. (2010): Detection of trends in hydrological extremes for Canadian watersheds; Hydrological Processes, v. 24, no. 13, p.1781-1790.

Callaghan, T.V., Johansson, M., Asinimov, O., Christiansen, H.H., Instanes, A., Romanovsky, V., and Smith, S. (2011a) Changing Permafrost and its Impacts; in AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii + 538 p.

Callaghan, T.V., Johansson, M., Brown, R.D., Groisman, P.Y., Labba, N., Radionov, V., Barry, R.G., Bulygina, O.N., Essery, R.L.H., Frolov, D.M., Golubev, V.N., Grenfell, T.C., Petrushina, M.N., Razuvaev, V.N., Robinson, D.A., Romanov, P., Shindell, D., Shmakin, A.B., Sokratov, S.A., Warren, S. and Yang, D. (2011b): The changing face of arctic snow cover: a synthesis of observed and projected changes. AMBIO v. 40, p. 17-31.

Capotondi, A., Alexander, M.A., Bond, N.A. Curchitser, E.N., and Scott, J.D. (2012): Enhanced upper ocean stratification with climate change in the CMIP3 models; Journal of Geophysical Research, v. 117, C04031.

Cavalieri, D.J., and Parkinson, C.L. (2012): Arctic sea ice variability and trends, 1979-2010; The Cryosphere, v. 6, p. 881-889.

Chandler, P. (2012): Sea surface temperature and salinity trends observed at lighthouses; in State of the physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2011, p. 35-37; (ed.) J.R. Irvine and W.R. Crawford; Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document 2012/072, vi + 141p.

Chen, J., Brissette, F. P., Poulin, A., and Leconte, R. (2011): Overall uncertainty study of the hydrological impacts of climate change for a Canadian watershed; Water Resources Research, v. 47, W12509.

Chen, Z., and Grasby, S. E. (2009): Impact of decadal and century-scale oscillations on hydroclimate trend analyses; Journal of Hydrology, v. 365, p. 122-133.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Xuejie, G., Held, I., Jones, R., Koli, R.K., Kwon, W., Laprise, R., Rueda, V.M., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A. and Whetton, P. (2007): Regional Climate Projections; in Climate Change 2007: The Physical Science Basis; Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; (ed.) S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. Cambridge University Press.

Christian, J.R. and Foreman, M.G.G. (2013): Climate trends and projections for the Pacific Large Aquatic Basin; Canadian Technical Report of Fisheries and Aquatic Sciences, 3023: xi + 112 p.

Church, J.A., White, N.J., Aarup, T., Wilson, W.S., Woodworth, P.L., Domingues, C.M., Hunter, J.R., and Lambeck, K. (2008): Understanding global sea levels: past, present and future; Sustainable Science, v. 3, no. 1, p. 9-22.

Church, J.A., Aarup, T., Woodworth, P.L., Wilson, W. S., Nicholls, R.J., Rayner, R., Lambeck, K., Mitchum, G.T., Steffen, K., Cazenave, A., Blewitt, G., Mitrovica, J.X. and Lowe, J.A. (2010): Sea-level Rise and Variability: Synthesis and Outlook for the Future; in Understanding Sea-level Rise and Variability, (ed.) J.A. Church, P.L. Woodworth, T. Aarup, and W.S. Wilson, Wiley & Sons, New Jersey, 428 p.

Church, J.A., Gregory, J.M., White, N.J., Platten, S.M., and Mitrovica, J.X. (2011): Understanding and projecting sea level change; Oceanography, v. 24, no. 2, p. 130-141.

Church, J. A. and White, N.J. (2011): Sea-Level Rise from the Late 19th to the Early 21st Century; Surveys in Geophysics, v. 32, no. 4-5, p. 585-602.

Colbourne, E., Craig, J., Fitzpatrick, C., Senciall, D., Stead, P., and Bailey, W. (2012): An assessment of the physical oceanographic environment on the Newfoundland and Labrador Shelf during 2011. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document 2012/044, iv + 32 p.

Comiso, J.C. (2012): Large Decadal Decline of the Arctic Multi-year Ice Cover; Journal of Climate, v. 25, p. 1176-1193.

Copland L., Mueller, D.R., and Weir, L. (2007): Rapid loss of the Ayles Ice Shelf, Ellesmere Island, Canada; Geophysical Research Letters, v. 34, L21501.

Crawford, W.R. and Peña, A. (2013): Declining oxygen on the British Columbia continental shelf; Atmosphere-Ocean, v. 51, p. 88-103.

Crawford, W.R., Galbraith, J., and Bolingbroke, N. (2007): Line P ocean temperature and salinity, 1956-2005; Progress in Oceanography, v. 75, p. 161-178.

Cunderlik, J. M., and Ouarda, T.B. (2009): Trends in the timing and magnitude of floods in Canada; Journal of Hydrology, v. 375, p. 3-4, p. 471-480.

Dai, A. (2011): Drought under global warming: a review; Wiley Interdisciplinary Reviews: Climate Change, v. 2, no. 1, p. 45-65.

de Jong, M.F., Drijfhout, S.S., Hazeleger, W., van Aken, H.M. and Severijns, C.A. (2009): Simulations of hydrographic properties in the northwestern North Atlantic Ocean in coupled climate models; Journal of Climate, v. 22, p. 1767-1786.

Demuth, M.N., Pinard, V., Pietroniro, A., Luckman, B.H., Hopkinson, C., Dornes, P., and Comeau, L. (2008): Recent and past-century variations in the glacier resources of the Canadian Rocky Mountains: Nelson River System; in Terra Glacialis Special Issue – Mountain glaciers and climate changes of the last century, (ed.) L. Bonardi; p. 27-52.

Denman, K., Christian, J.R., Steiner, N., Portner, H.-O., and Nojiri, Y. (2011): Potential impacts of future ocean acidification on marine ecosystems and fisheries: current knowledge and recommendations for future research; ICES Journal of Marine Science, v. 68, no. 6, p. 1019–1029.

DFO (Fisheries and Oceans Canada) - Canadian Hydrographic Service (2007): Water Levels, Great Lakes and Montreal Harbour; Monthly Water Level Bulletin, online, <http://www.waterlevels.gc.ca/C&A/bulletin_e.html>.

DFO (Fisheries and Oceans Canada) - Canadian Hydrographic Service (2013a): Central and Arctic Region Historical Water Level Data, online, <http://www.waterlevels.gc.ca/C&A/network_means.html>.

DFO (Fisheries and Oceans Canada) - Canadian Hydrographic Service (2013b): Water Levels, Great Lakes and Montreal Harbour; Monthly Water Level Bulletin, online, <http://www.waterlevels.gc.ca/C&A/bulletin_e.html>.

Derksen, C. and Brown, R.D. (2011): Terrestrial snow (Arctic); in State of the Climate in 2010, Bulletin of the American Meteorological Society, (ed.) J. Blunden, D.S. Arndt, M.O. Baringer. v. 92, no. 6, p. S1-S266.

Derksen, C. and Brown, R. (2012): Spring snow cover extent reductions in the 2008-2012 period exceeding climate model projections; Geophysical Research Letters, v. 39, L19504.

Derksen, C., Smith, S.L., Sharp, M., Howell, S., Brown, L., Fletcher, C., D. Mueller, L. Copland, Y. Gauthier, M. Bernier, R. Brown, C.R. Burn, C. Duguay, A. Langlois, A. Walker, A.G. Lewkowicz, and Bourgeois, J. (2012): Variability and Change in the Canadian Cryosphere; Climatic Change, v. 115, no. 1, p. 59-88.

Dibike, Y., Prowse, T., Bonsal, B., de Rham, L., and Saloranta, T. (2012): Simulation of North American lake-ice cover characteristics under contemporary and future climate conditions. International Journal of Climatology Online, first published February 9, 2011.

Doney, S.C., Fabry, V.J., Feely, R.A. and Kleypas, J.A.( 2009): Ocean acidification: the other CO2 problem; Annual Review of Marine Science, v. 1, p. 169–192.

Drijfhout, S., van Oldenborgh, G.J., and Cimatoribus, A. (2012): Is a decline of AMOC causing the warming hole above the North Atlantic in observed and modeled warming patterns?; Journal of Climate, v. 25, p. 8373-8379.

Duguay, C.R., Prowse, T.D., Bonsal, B.R., Brown, R.D., Lacroix, M.P. and Ménard, P. (2006): Recent trends in Canadian lake ice cover; Hydrological Processes, v. 20, p. 781-801.

Durack, P. J., and Wijffels, S.E. (2010): Fifty-year trends in global ocean salinities and their relationship to broad-scale warming; Journal of Climate, v. 23, p. 4342-4362.

Easterling, D.R., and Wehner, M.F. (2009): Is the climate warming or cooling? Geophysical Research Letters, v. 36, L08706.

EBNFLO Environmental and AquaResource Inc. (2010): Guide for assessment of hydrologic effects of climate change in Ontario; prepared for the Ontario Ministry of Natural Resources and Ministry of the Environment in partnership with Credit Valley Conservation.

Environment Canada (2011): Annual 2011 Summary, Climate Trends and Variability Report, online, <ec.gc.ca/adsc-cmda/default.asp?lang=En&n=F3D25729-1>.

Environment Canada (2012): Annual 2011 Summary, Climate Trends and Variability Report, <http://ec.gc.ca/adsc-cmda/default.asp?lang=En&n=4A21B114-1>.

Environment Canada (2013): LEVELnews: Great Lakes – St. Lawrence River Water Levels – Michigan-Huron Sets Two New Recorded Lows in January 2013; v. 21, no. 2 , online, <http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=7AD8D7A7>.

Ezer, T., Atkinson, L.P., Corlett, W.B., and Blanco, J.L. (2013): Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast; Journal of Geophysical Research, v. 118, p. 685–697.

Federal, Provincial and Territorial Governments of Canada (2010): Canadian Biodiversity: Ecosystem Status and Trends 2010; Canadian Councils of Resource Ministers, Ottawa, ON, vi + 142 p., online, <www.biodivcanada.ca/ecosystems>.

Feely, R.A., Doney, S.C., and Cooley, S.R. (2009): Ocean acidification: Present conditions and future changes in a high-CO2 world; Oceanography, v. 22, no. 4, p. 36-47.

Feely, R.A., Sabine, C.L., Hernandez-Ayon, J.M., Ianson, D., and Hales, B. (2008): Evidence for upwelling of corrosive "acidified" water onto the continental shelf; Science, v. 320, p. 1490-1492.

Forbes, D.L., Craymer, M.R., James, T.S., Solomon, S.M., Marsh, P., Manson, G.K., Whalen, D., Hopkinson, C. (2010): Sea-level rise, subsidence and potential inundation on the outer Mackenzie Delta; Program of IPY Oslo Science Conference, Polar Science - Global Impact, Oslo, 8-12 June 2010, online, <http://elsevier.conference-services.net/resources/247/1976/pdf/Oslo2010_1904.pdf>.

Forbes, D.L., Manson, G.K., Charles, J., Thompson, K.R., and Taylor, R.B. (2009): Halifax Harbour extreme water levels in the context of climate change: scenarios for a 100-year planning horizon; Geological Survey of Canada, Open File 6346, 21 p.

Forbes, D.L., Parkes, G.S., Manson, G.K., and Ketch, L.A. (2004): Storms and shoreline retreat in the southern Gulf of St. Lawrence; Marine Geology, v. 210, p. 169-204.

Forbes, D.L. and Taylor, R.B., (1994): Ice in the shore zone and the geomorphology of cold coasts; Progress in Physical Geography, v. 18, p. 59-89.

Forbes, D.L. (editor) (2011): State of the Arctic Coast 2010 – Scientific Review and Outlook; International Arctic Science Committee, Land-Ocean Interactions in the Coastal Zone, Arctic Monitoring and Assessment Programme, International Permafrost Association. Helmholtz-Zentrum, Geesthacht, Germany, 178 p. <http://arcticcoasts.org>.

Forbes, K. A., Kienzle, S.W., Coburn, C.A., Byrne, J.M. and Rasmussen, J. (2011): Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada; Climatic Change, v. 105, no. 3-4, p. 555-576.

Fortin, V. and Gronewold, A. (2012): Water balance of the Laurentian Great Lakes; Encyclopedia of Lakes and Reservoirs, Encyclopedia of Earth Sciences Series, (ed.) L. Bengtsson, R.W. Fairbridge and R.W. Herschy.

Foster, G. and Rahmstorf, S. (2011): Global temperature evolution 1979-2010; Environmental Research Letters, v. 6, p. 044022.

Freeland, H. J. (2013): Evidence of change in the winter mixed layer in the Northeast Pacific Ocean: A problem revisited; Atmosphere-Ocean, v. 51, p. 126-133.

Furgal, C. and Prowse, T.D. (2008): Northern Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, ON, p. 57-118.

Galbraith, P.S. and Larouche, P. (2011): Sea surface temperature in Hudson Bay and Hudson Strait in relation to air temperature and ice cover breakup, 1985-2009. Journal of Marine Systems, v. 87, p. 66-78.

Galbraith, P.S., Chassé, J., Gilbert, D., Larouche, P., Brickman, D., Pettigrew, B., Devine, L., Gosselin, A., Pettipas, R.G. and Lafleur, C. (2012a): Physical oceanographic conditions in the Gulf of St. Lawrence in 2011; Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document 2012/023, iii + 85 p.

Galbraith, P.S., Larouche, P., Chassé, J. and Petrie, B. (2012b): Sea-surface temperature in relation to air temperature in the Gulf of St. Lawrence: interdecadal variability and long term trends; Deep Sea Research Part II, online, <http://dx.doi.org/10.1016/j.dsr2.2012.04.001>.

Gardner, A.S., Moholdt, G., Wouters, B., Wolken, G.J., Burgess, G.J., Sharp, M.J., Cogley, J.G., Braun, C. and Labine, C. (2011): Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago; Nature, v. 473, p. 357-360.

Ghanbari, R. N. and Bravo, H. R. (2008): Coherence between atmospheric teleconnections, Great Lakes water levels, and regional climate; Advances in Water Resources, v. 31, p. 1284-1298.

Gilbert, D., Rabalais, N.N., Diaz, R.J. and Zhang, J. (2010): Evidence for greater oxygen decline rates in the coastal ocean than in the open ocean; Biogeosciences, v. 7, p. 2283-2296.

Gilbert, D., Sundby, B., Gobeil, C., Mucci, A., and Tremblay, G. H. (2005): A seventy-year record of diminishing deep-water oxygen levels in the St. Lawrence estuary: the northwest Atlantic connection; Limnology and Oceanography, v. 50, p. 1654–1666.

Gillet, N.P., Stone, D. A., Stott, P.A., Nozawa, T., Karpechko, A.Y., Hegerl, G.C., Wehner, M.F. and Jones, P.D. (2008): Attribution of polar warming to human influence; Nature Geoscience, v. 1, p. 750-754.

Giorgi, F., Im, E.-S, Coppola, E., Diffenbaugh, N.S., Gao, X.J., Mariotti, L., and Shi, Y. (2011): Higher hydroclimatic intensity with global warming; Journal of Climate, v. 24, p. 5309-5324.

Greenan, B., Harrison,G., Yashayaev, I., Azetsu-Scott, K., Head, E., Li, W., and Loder, J. (2010): Physical, chemical and biological conditions in the Labrador Sea in 2009; Atlantic Zone Monitoring Bulletin, Fisheries and Oceans Canada, v. 9, p. 11-19, online, <http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/docs/bulletin_9_03.pdf>.

Greenberg, D.A., Blanchard, W., Smith, B., and Barrow, E. (2012): Climate change, mean sea level and high tides in the Bay of Fundy; Atmosphere-Ocean, v. 30, no. 3, p. 261-276.

Grillakis, M. G., Koutroulis, A. G., and Tsanis, I. K. (2011): Climate change impact on the hydrology of Spencer Creek watershed in Southern Ontario, Canada; Journal of Hydrology, v. 409, no. 1-2, p. 1-19.

Gutowski, W.J., Hegerl, G.C., Holland, G.J., Knutson, T.R., Mearns, L.O, Stouffer, R.J., Webster, P.J., Wehner, M.F., Berkeley, L. and Zwiers, F.W. (2008): Causes of observed changes in extremes and projections of future change; in U.S. Climate Change Science Program, Synthesisand Assessment Product 3.3, Weather and Climate Extremes in a Changing Climate.

Hammill, M.O. and Galbraith, P.S. (2012): Changes in seasonal sea-ice cover and its effect on marine mammals; in State-of-the-Ocean Report for the Gulf of St. Lawrence Integrated Management (GOSLIM) Area, (ed.) H. P. Benoît, J. A. Gagné, C. Savenkoff, P. Ouellet and M.-N. Bourassa, Canadian Manuscript Report of Fisheries and Aquatic Sciences, v. 2986, viii + 73 p.

Hanrahan, J. L., Kravtsov, S.V., and Roebber, P. J. (2009): Quasi-periodic decadal cycles in levels of lakes Michigan and Huron; Journal of Great Lakes Research, v. 35, p. 30-35.

Harma, K. J., Johnson, M.S., and Cohen, S.J. (2012): Future Water Supply and Demand in the Okanagan Basin, British Columbia: A Scenario-Based Analysis of Multiple, Interacting Stressors; Water Resources Management, v. 26, no. 3, p. 667-689.

Harvey, B.J., Shaffrey, L.C., Woollings, T.J., Zappa, G., and Hodges, K.I. (2012): How large are projected 21st century storm track changes? Geophysical Research Letters, v. 39, no. 18, L18707.

Harvey, K.D., Pilon, P.J., and Yuzyk, T.R. (1999): Canada's Reference Hydrometric Basin Network (RHBN); in Partnerships in water resource management: Proceedings of the CWRA 52nd Annual Conference, Canadian Water Resources Association, Nova Scotia, p. 5-70.

Hayhoe, K., VanDorn, J., Croley, T., Schlegal, N., and Wuebbles, D. (2010): Regional climate change projections for Chicago and the US Great Lakes; Journal of Great Lakes Research, v. 36, p. 7–21.

Hebert, D., Pettipas, R., Petrie, B., and Brickman, D. (2012): Meteorological, sea ice and physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine during 2011; Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document 2012/055, vi + 43 p.

Heginbottom J.A., Dubreuil, M.A., and Harker, P.A. (comp.) (1995): Canada – Permafrost; The National Atlas of Canada (5th edition), Plate 2.1, (MCR 4177), Geomatics Canada and Terrain Sciences Division, National Atlas Information Service and Geological Survey of Canada, Ottawa, ON.

Hegerl, G.C., Zwiers, F.W., Braconnot, P., Gillet, N.P., Luo, Y., Marengo Orsini, J.A., Nicholls, N., Penner, J.E. and Stott, P.A. (2007): Understanding and Attributing Climate Change; in Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon, S., Quin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (ed.), Cambridge University Press.

Held, I.M. and Soden, B.J. (2006): Robust responses of the hydrological cycle to global warming; Journal of Climate, v. 19, p. 5686-5699.

Helm, K.P., Bindoff, N.L. and Church, J.A. (2010): Changes in the global hydrological cycle inferred from ocean salinity; Geophysical Research Letters, v. 37, L18701.

Helm, K.P., Bindoff, N.L., and Church, J.A. (2011): Observed decreases in oxygen content of the global ocean; Geophysical Research Letters, v. 38, L23602.

Hibbard, K.A., van Vuuren, D.P., and Edmonds, J. (2011): A primer on the Representative Concentration Pathways (RCPs) and the coordination between climate and integrated assessment modeling communities; in CLIVAR Exchanges, v.16, no. 2 (Special Issue on WCRP CMIP5), p. 12-15.

Howell, S.E.L., Tivy, A., Yackel, J.J., and McCourt, S. (2008a): Multi-year sea-ice conditions in the Western Canadian Arctic Archipelago region of the Northwest Passage: 1968-2006; Atmosphere-Ocean, v. 46, no. 2, p. 229-242.

Howell, S.E.L., Tivy,A., Yackel, J.J., Else, B.G.T., and Duguay, C.R. (2008b): Changing sea ice melt parameters in the Canadian Arctic Archipelago: implications for the future presence of multiyear ice; Journal Of Geophysical Research: Oceans, v. 113, C09030.

Howell, S.E.L., Duguay, C.R., and Markus, T. (2009): Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979-2008; Geophysical Research Letters, v. 36, L10502.

Hundecha, Y., St.-Hilaire, A., Ouarda, T.B., and El Adlouni, S. (2008): A nonstationary extreme value analysis for the assessment of changes in extreme annual wind speed over the Gulf of St. Lawrence, Canada; Journal of Applied Meteorology and Climatology, v. 47, p. 2745-2759.

Hutchings, J.A., Côté, I.M., Dodson, J.J, Fleming, I.A., Jennings, S., Mantua, N.J., Peterman, R.M., Riddell, B.E., Weaver, A.J. and VanderZwaag, D.L. (2012): Sustaining Canadian marine biodiversity: responding to the challenges posed by climate change, fisheries and aquaculture; Expert panel report prepared for the Royal Society of Canada. <https://rsc-src.ca/sites/default/files/pdf/RSCMarineBiodiversity2012_ENFINAL.pdf>.

Huybrechts, P., Goelzer, H., Janssens, I., Driesschaert, E., Fichefet, T., Goosse, H., and Loutre, M.-F. (2011): Response of the Greenland and Antarctic ice sheets to multi-millennial greenhouse warming in the Earth system model of intermediate complexity; LOVECLIM, Surveys in Geophysics, v. 32, p. 397-416.

ICES [International Council for the Exploration of the Sea] (2011): ICES status report on climate change in the North Atlantic; ICES Cooperative Research Report 310, International Council for the Exploration of the Sea, 262 p., online, <http://info.ices.dk/pubs/crr/crr310/CRR%20310%20Climate%20Change.pdf>.

Icewatch (2008): Changes in lake ice signal a changing climate; Environment Canada, Ottawa, ON, 8p., Catalogue No. EN84-65/2008E-PDF. ISBN 978-1-100-11308-1.

International Upper Great Lakes Study [IUGLS] (2012): Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels, Final Report to the International Joint Commission, March 2012; 215 p.

IPCC (2001): Climate Change 2001: The Scientific Basis; Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson, Cambridge University Press, Cambridge, U.K. 881 p.

IPCC (2007): Climate Change 2007: Synthesis Report; Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) R.K. Pachauri and A. Reisinger, Geneva, Switzerland, 104 p.

IPCC (2012): Special Report on Managing the risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX); A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, (ed.) C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. and P.M. Midgley, Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC (2013): Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker,T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Irvine, J.R. and Crawford, W.R. (2012): State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2011; Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document 2012/072, vi+ 141p.

James, T.S., Simon, K.M., Forbes, D.L., Dyke, A.S., and Mate, D.J. (2011): Sea-level Projections for Five Pilot Communities of the Nunavut Climate Change Partnership; Geological Survey of Canada, Open File 6715, 23 p.

Jevrejeva, S., Moore, J.C., and Grinsted, A. (2012): Sea level projections to AD2500 with a new generation of climate change scenarios; Global and Planetary Change, v. 80-81, p. 14-20.

Jost, G., Moore, R. D., Menounos, B. and Wheate, R. (2012): Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada; Hydrology and Earth System Sciences, v. 16, no. 3, p. 849-860.

Katsman, C.A., Sterl, A., Beersma, J. J., van den Brink, H. W., Church, J. A., Hazeleger, W., Kopp, R.E., Kroon, D., Kwadijk, J., Lammersen, R., Lowe, J., Oppenheimer, M., Plag, H.-P., Ridley, J., von Storch, H., Vaughan, D.G., Vellinga, P., Vermeersen, L.L.A., van de Wal, R.S.W. and Weisse, R. (2011): Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta—the Netherlands as an example; Climatic Change, v. 109, p. 617–645.

Kerkhoven, E. and Gan, T.Y. (2011): Differences and sensitivities in potential hydrologic impact of climate change to regional-scale Athabasca and Fraser River basins of the leeward and windward sides of the Canadian Rocky Mountains respectively; Climatic Change, v. 106, no. 4, p. 583-607.

Khaliq, M. N., Ouarda, T. B., Gachon, P., and Sushama, L. (2008): Temporal evolution of low-flow regimes in Canadian rivers; Water Resources Research, v. 44, W08436.

Kharin, S. Kharin, V. V., Zwiers, F. W., Zhang, X., and Hegerl, G. C. (2007): Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations; Journal of Climate, v. 30, p. 1419-1444.

Kienzle, S. W., Nemeth, M. W., Byrne, J. M., and MacDonald, R. J. (2012): Simulating the hydrological impacts of climate change in the upper North Saskatchewan River basin, Alberta, Canada; Journal of Hydrology, v. 412-413, p. 76-89.

Lamon, E. C. and Stow, C. A. (2010): Lake Superior water level fluctuation and climatic factors: A dynamic linear model analysis; Journal of Great Lakes Research, v. 36, p. 172–178.

Lapp, S., Sauchyn, D. J., and Toth, B. (2009): Constructing scenarios of future climate and water supply for the SSRB: use and limitations for vulnerability assessment; Prairie Forum, v. 34, no. 1, p. 153-180.

Latifovic, R., and Pouliot, D. (2007): Analysis of climate change impacts on lake ice phenology in Canada using the historical satellite data record; Remote Sensing of Environment, v. 106, p. 492-507.

Le Treut, H. Sommerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., and Prather, M. (2007): Historical overview of climate change; in IPCC, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lemke, P., Ren, J., Alley, R.B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R.H. and Zhang, T. (2007): Observations: Changes in Snow, Ice and Frozen Ground; in IPCC, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E., (ed.) (2008): From Impacts to Adaptation: Canada in a Changing Climate 2007; Government of Canada, Ottawa, ON, 448 p.

Lenaerts, J.T.M., van Angelen, J.H., van den Broeke, M.R., Gardner, A.S., Wouters, B., and van Meijgaard, E. (2013): Irreversible mass loss of Canadian Arctic Archipelago glaciers; Geophysical Research Letters, v. 40, p. 870-874.

Lenters, J. D. (2004): Trends in the Lake Superior Water Budget Since 1948: A Weakening Seasonal Cycle; Journal of Great Lakes Research, v. 30, p. 20–40.

Liston, G.E. and Hiemstra, C.A. (2011): The Changing Cryosphere: Pan-Arctic Snow Trends (1979–2009); Journal of Climate, v. 24, p. 5691-5712.

Loder, J.W., Han, G., Galbraith, P.S., Chassé, J. and van der Baaren, A. (Eds.). (2013a): Aspects of climate change in the Northwest Atlantic off Canada. Canadian Technical Report of Fisheries and Aquatic Sciences 3045: x +190 p.

Loder, J.W., Wang, Z., van der Baaren, A., and Pettipas, R. (2013b): Trends and variability of sea surface temperature in the North Atlantic from the HadISST, ERSST and COBE datasets. Canadian Technical Report of Hydrography and Ocean Sciences. 292: viii + 36 p.

Long, Z., Perrie, W., Gyakum, J., Laprise, R. and Caya, D. (2009): Scenario changes in the climatology of winter midlatitude cyclone activity over eastern North America and the Northwest Atlantic; Journal of Geophysical Research, v. 114, D12111.

MacKay, M., and Seglenieks, F. (2013): On the simulation of Laurentian Great Lakes water levels under projections of global climate change; Climatic Change, v. 117, p. 55-67.

Manson, G.K., and Solomon, S.M. (2007): Past and Future Forcing of Beaufort Sea Coastal Change; Atmosphere-Ocean, v. 45, p. 107-122.

Markus, T., Stroeve, J.C., and Miller, J. (2009): Recent changes in Arctic sea ice melt onset, freezeup, and melt season length; Journal of Geophysical Research: Oceans, v. 114, C12024, p. 1-14.

Marshall, S., White, E., Demuth, M., Bolch, T., Wheate, R., Menounos, B., Beedle, M., and Shea, J. (2011): Glacier Water Resources on the Eastern Slopes of the Canadian Rocky Mountains; Canadian Water Resources Journal, v. 36, no. 2, p. 109-134.

Marzeion, B., Jarosch, A.H., and Hofer, M. (2012): Past and future sea-level change from the surface mass balance of glaciers; The Cryosphere, v. 6, p. 1295-1322.

Maslanik, J., Stroeve, J., Fowler, C., and Emery, W. (2011): Distribution and trends in Arctic sea ice age through spring 2011; Geophysical Research Letters, v. 38, L13502.

Massonnet, F., Fichefet, T., Goose, H., Bitz, C.M., Philippon-Berthier, G., Holland, M.M., and Barriat, P.-Y. (2012): Constraining projections of summer Arctic sea ice; The Cryosphere, v. 6, p. 1383-1394.

Mazzotti, S., Jones, C., and Thomson, R.E. (2008): Relative and absolute sea level rise in western Canada and northwestern United States from a combined tide gauge-GPS analysis; Journal of Geophysical Research, v. 113, C11019.

Mazzotti, S., Lambert, A., Henton, J., James, T. S., and Courtier, N. (2011): Absolute gravity calibration of GPS velocities and glacial isostatic adjustment in mid-continent North America; Geophysical Research Letters, v. 38, L24311.

Mazzotti, S., Lambert, A., Van der Kooij, M., and Mainville, A. (2009): Impact of anthropogenic subsidence on relative sea-level rise in the Fraser River delta, Geology, v. 37, p. 771-774.

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R.J. and Taylor, K.E. (2007a): The WCRP CMIP3 multi-model dataset: A new era in climate change research; Bulletin of the American Meteorological Society, v. 88, no. 9, p. 1383-1394.

Meehl, G. A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J and Zhao, Z.-C. (2007b): Global Climate Projections; in Climate Change 2007:

The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Cambridge University Press.

Meier, W. N., Gerland, S., Granskog, M.A., and Key, J.R. (2011): Sea ice; in AMAP 2011, Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xii + 538 p.

Mekis, É. and Vincent, L.A. (2011a): An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada; Atmosphere-Ocean, v. 2, p. 163-177.

Mekis, É. and Vincent, L.A. (2011b): Trends in indices related to agroclimatic conditions based on homogenized temperature and adjusted precipitation in Canada; 19th Conference on Applied Climatology, 18–20 July 2011, Asheville, NC, USA. <http://ams.confex.com/ams/19Applied/webprogram/Paper190186.html>.

Melling, H. (2002): Sea ice of the northern Canadian Archipelago; Journal Of Geophysical Research, v. 107, no. C11, p. 3181.

Meyssignac, B., Becker, M., Llovel, W., and Cazenave, A. (2012): An assessment of two-dimensional past sea level reconstructions over 1950-2009 based on tide-gauge data and different input sea level grids; Surveys in Geophysics 2012, v. 33, p. 945-972.

Min, S-K., Zhang, X., Zwiers, F., and Agnew, T. (2008): Human influence on Arctic sea ice detectable from early 1990s onwards; Geophysical Research Letters, v. 35, L21701.

Min, S-K., Zhang, X., Zwiers, F.W., and Hegerl, G. (2011): Human contribution to more-intense precipitation extremes; Nature, v. 470, p. 378-381.

Mitrovica, J.X., Tamisiea, M.E., Davis, J.L. and Milne, G.A. (2001): Recent mass balance of polar ice sheets inferred from patterns of global sea-level change; Nature, v. 409, p. 1026-1029.

Mitrovica, J.X., Gomez, N., Morrow, E., Hay, C., Latychev, K., and Tamisiea, M.E. (2011): On the robustness of predictions of sea level fingerprints; Geophysical Journal International, v. 187, p. 729–742.

Mizuta, R. (2012): Intensification of extratropical cyclones associated with the polar jet change in the CMIP5 global warming projections; Geophysical Research Letters, v. 39, L19707.

Mladjic, B., Sushama, L., Khaliq, M.N., Laprise, R., Caya, D., and Roy, R. (2011): Canadian RCM projected changes to extreme precipitation characteristics over Canada; Journal of Climate, p. 2565-2584.

Monk, W.A. and Baird, D.J. (2011): Ecosystem status and trends report: biodiversity in Canadian lakes and rivers; Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 20, Canadian Councils of Resource Ministers, Ottawa, ON. vi + 79 p., online, <http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-1>.

Monk, W.A., Peters, D.L., Curry, R.A., and Baird, D.J. (2011): Quantifying trends in indicator hydroecological variables for regime-based groups of Canadian rivers; Hydrological Processes, v. 25, p. 3086-3100.

Monk, W. A., Peters, D. L., and Baird, D.J. (2012): Assessment of ecologically relevant hydrological variables influencing a cold-region river and its delta: the Athabasca River and the Peace-Athabasca Delta, northwestern Canada; Hydrological Processes, v. 26, p. 1827–1839.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P. and Wilbanks, T.J. (2010): The next generation of scenarios for climate change research and assessment; Nature, v. 463, p. 747-756.

Mucci A., Starr, M., Gilbert, D., and Sundby, B. (2011): Acidification of the hypoxic waters in the St. Lawrence Estuary: A history and potential impacts; Atmosphere-Ocean, v. 49 no. 3, p. 206–218.

Nakićenović, N., Davidson, O., Davis, G., Grübler, A., Kram, T., Lebre La Rovere, E., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R and Dadi, Z. (2000): Special Report on Emissions Scenarios; A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, 599 p.

Nerem, R.S., Chambers, D.P., Choe, C., and Mitchum, G.T. (2010): Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions; Marine Geodesy, v. 33, p. 435–446.

NRC [National Research Council] (2011): Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia; National Academies Press, Washington, DC, 286 p.

Peltier, W.R. (2004): Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE; Annual Review of Earth and Planetary Sciences, v. 32, p. 111-149.

Perovich, D., Meir, W., Maslanik, J., and Richter-Menge, J. (2011): Sea ice; in Arctic Report Card 2011, (ed.) J. Richter-Menge, M.O. Jeffries and J.E. Overland.

Perovich, D., Meier, W., Tschudi, M., Gerland, S., and Richter-Menge, J. (2012): Sea ice; in Arctic Report Card 2012, (ed.) M.O. Jeffries, J. A. Richter-Menge and J. E. Overland, online, <http://www.arctic.noaa.gov/report12/>.

Perrie, W., Yao, Y. and Zhang, W. (2010): On the impacts of climate change and the upper ocean on midlatitude northwest Atlantic landfalling cyclones; Journal of Geophysical Research, v. 115, D23110.

Peters, G.P., Andrew, R.M., Boden, T., Canadell, J.G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M.R. and Wilson, C. (2012): The challenge to keep global warming below 2º C. Nature Climate Change, v. 3, p. 4-6.

Peterson, T.C., Zhang, X., Brunet-India, M., and Vazquez-Aguirre, J.L. (2008): Change in North American extremes derived from daily weather data; Journal Of Geophysical Research, v. 113, no. D07113, 9 p.

Peterson, T.C., Anderson, D.M., Cohen, S.J., Cortez-Vázquez, M., Murnane, R.J., Parmesan, C., Phillips, D., Pulwarty, R.S. and Stone, J.M.R. (2008): Why Weather and Climate Extremes Matter; in U.S. Climate Change Science Program Synthesis and Assessment Product 3.3, "Weather and Climate Extremes in a Changing Climate", (ed.) T.R. Karl, G.A. Meehl, C.D. Miller, S. J. Hassol, A.M. Waple, and W.L. Murray.

Petrie, B. (2007): Does the North Atlantic Oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? Atmosphere-Ocean, v. 45, p. 141–151.

Petrie, B. and Yeats, P. (2000): Annual and interannual variability of nutrients and their estimated fluxes in the Scotian Shelf – Gulf of Maine region; Canadian Journal of Fisheries and Aquatic Sciences, v. 57, p. 2536-2546.

Pfeffer, W.T., Harper, J.T. and O'Neel, S. (2008): Kinematic constraints on glacier contributions to 21st-century sea-level rise; Science, v. 321, p. 1340-1343.

Pope, S., Copland, L., and Mueller, D. (2012): Loss of multiyear landfast sea ice from Yelverton Bay, Ellesmere Island, Nunavut, Canada; Arctic, Antarctic, and Alpine Research, v. 44, no. 2.

Prowse, T.D., Bonsal, B. R., Duguay, C. R., and Lacroix, M. P. (2007): River-ice break-up/freeze-up: a review of climatic drivers, historical trends and future predictions; Annals of Glaciology, v. 46, p. 443–451.

Prowse, T., Alfredsen, S. Beltaos, B. Bonsal, W.B. Bowden, C.R. Duguay, A., Korhola, A., McNamara, J., Vincent, W.F., Vuglinsky, V., Walter, K.M. and Weyhenmeyer, G.A. (2011): Effects of changes in Arctic Lake and River Ice; Ambio, (Supplement 1), v. 40, p. 63-74.

Quilbé, R., Rousseau, A.N., Moquet, J.-S., Trinh, N. B., Dibike, Y., Gachon, P., and Chaumont, D. (2008): Assessing the effect of climate change on river flow using general circulation models and hydrological modelling – Application to the Chaudière River, Quebec, Canada; Canadian Water Resources Journal, v. 33, p. 73-94.

Radić, V. and Hock, R. (2011): Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. Nature Geoscience, v. 4, p. 91-94.

Raisanen, J. (2008): Warmer climate: less or more snow?; Climate Dynamics, v. 30, p. 307-319.

Richter-Menge, J. and Jefferies, M. (ed.) (2011): The Arctic; in State of the Climate in 2010, Bulletin of the American Meteorological Society, (ed.) J.D. Blunden, S. Arndt and M.O. Baringer. v. 92, no. 6, p. S1-S266.

Robert, M., Freeland, H., Crawford, B., and Bolingbroke, N. (2012): Ocean conditions in Gulf of Alaska, p. 15-24; in State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2011, (ed.) J.R. Irvine and W.R. Crawford, Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document 2012/072, vi + 141 p.

Roberts, J., Pryse-Phillips, A. and Snelgrove, K. (2012): Modelling the Potential Impacts of Climate Change on a Small Watershed in Labrador, Canada; Canadian Water Resources Journal, v. 37, no. 3, p. 231-251.

Romanovsky, V. E., Smith, S.L., and Christiansen, H.H. (2010): Thermal state in the Polar Northern Hemisphere during the International Polar Year 2007-2009: A Synthesis; Permafrost and Periglacial Processes, v. 21, p. 106-116.

Rummukainen, M. (2012): Changes in climate and weather extremes in the 21st century; Wiley Interdisciplinary Reviews: Climate Change, v. 3, p. 115-129.

Schnorbus, M.A., Bennett, K. E., Werner, A.T., and Berland, A.J. (2011): Hydrologic impacts of climate change in the Peace, Campbell and Columbia Watersheds, British Columbia, Canada; Hydrologic Modelling Project Final Report (Part II), (ed.) University of Victoria, Pacific Climate Impacts Consortium, Victoria, B.C.

Schnorbus, M., Werner, A., and Bennett, K. (2012): Impacts of climate change in three hydrologic regimes in British Columbia, Canada; Hydrological Processes.

Sellinger, C.E., Stow, C.A., Lamon, E.C., and Qian, S.S. (2008): Recent water level declines in the Lake Michigan–Huron system; Environmental Science and Technology, v. 42, p. 367-373.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C. and Zhang, X. (2012): Changes in climate extremes and their impacts on the natural physical environment; in IPCC 2012, Special Report on Managing the risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, (ed.) C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. and P.M. Midgley, Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 p.

Serreze, M.C. and Barry, R.G. (2011): Processes and impacts of Arctic amplification: A research synthesis; Global and Planetary Change, v. 77, p. 85-96.

Sharp, M., Burgess, D.O., Cogley, J. G., Ecclestone, M., Labine, C., and Wolken, G. (2011a): Extreme melt on Canada's Arctic ice caps in the 21st century; Geophysical Research Letters, v. 38, L11501.

Sharp, M., Ananicheva, M., Arendt, A., Hagen, J-O., Hock, R., Joseberger, R.D. Moore, E., Pfeffer W.T., and Wolken, G. J. (2011b): Mountain Glaciers and Ice Caps; in AMAP, 2011, Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere; Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xii + 538 p. Sheffield, J. and Wood, E.F. (2008): Projected changes in drought occurrence under future global warming from multi-model, multi-scenario IPCC AR4 simulations; Climate Dynamics, v. 31, p. 79-105.

Shepherd, A., Gill, K.M. and Rood, S.B. (2010): Climate change and future flows of Rocky Mountain rivers: converging forecasts from empirical trend projection and down-scaled global circulation modelling; Hydrological Processes, v. 24, p. 3864-3877.

Shrestha, R. R., Schnorbus, M.A., Werner, A.T., and Berland, A.J. (2012a): Modelling spatial and temporal variability of hydrologic impacts of climate change in the Fraser River basin, British Columbia, Canada; Hydrological Processes, v. 26, no. 12, p. 1840-1860.

Shrestha, R. R., Dibike, Y.B., and Prowse, T.D. (2012b): Modelling of climate-induced hydrologic changes in the Lake Winnipeg watershed; Journal of Great Lakes Research, v. 38, p. 83-94.

Slangen, A.B.A., Katsman, C.A., van de Wal, R.S.W., Vermeersen, L.L.A., and Riva, R.E.M. (2012): Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios; Climate Dynamics, v. 38, p. 1191-1209.

Smith, S. L. (2011): Trends in permafrost conditions and ecology in northern Canada; Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 9, Canadian Council of Resource Ministers.

Smith, S.L., Romanovsky, V.E., Lewkowicz, A.G., Burn, C.R., Allard, M., Clow, G.D., Yoshikawa, K. and Throop, J. (2010): Thermal state of the permafrost in North America: A contribution to the International Polar Year; Permafrost and Periglacial Processes, v. 21, p. 117-135.

Smith, S.L., Throop, J., and Lewkowicz, A.G. (2012): Recent changes in climate and permafrost temperatures at forested and polar desert sites in northern Canada; Canadian Journal of Earth Sciences, v. 49, p. 914-924.

Sou, T. and Flato, G. (2009): Sea ice in the Canadian Arctic Archipelago: Modeling the past (1950-2004) and the future (2041-60); Journal of Climate, v. 22, p. 2181-2198.

Squire, V.A. (2007): Of ocean waves and sea-ice revisited; Cold Regions Science and Technology, v. 49, p. 110-113.

St. Jacques, J.M., Lapp, S.L., Zhao, Y. Barrow, E.M., and Sauchyn, D.J. (2012): Twenty-first century central Rocky Mountain river discharge scenarios under greenhouse forcing; Quaternary International.

Stahl, K., Moore, R. D., Shea, J. M., Hutchinson, D., and Cannon, A. J. (2008): Coupled modelling of glacier and streamflow response to future climate scenarios; Water Resources Research, v. 44, no. 2.

Stantec (2012): Assiniboine River Basin Hydrologic Model - Climate Change Assessment; prepared for Manitoba Conservation, Climate Change Branch.

Statistics Canada (2010): EnviroStats Fall 2010 Report; Trends in glacier mass balance for six Canadian glaciers, Cat. No. 16-002-X, v. 4, no. 3.

Statistics Canada (2012): EnviroStats Spring 2012 Report; Snow cover trends in Canada, Cat. No 16-002-X. v. 6, no. 1.

Steiner, N., Azetsu-Scott, K.A., Galbraith, P., Hamilton, J., Hedges, K., Hu, X., Janjua, M.Y., Lambert, N., Larouche, P., Lavoie, D., Loder, J., Melling, H., Merzouk, A., Myers, P., Perrie, W., Peterson, I., Pettipas, R., Scarratt, M., Sou, T., Starr, M., Tallmann, R.F., and van der Baaren, A. (2013): Climate change assessment in the Arctic basin Part 1: Trends and projections – a contribution to the Aquatic Climate Change Adaptation Services Program. Canadian Technical Report of Fisheries and Aquatic Sciences 3042: xv + 163 p. <http://www.dfo-mpo.gc.ca/library/350169.pdf>.

Stephenson, S.R., Smith, L.C., and Agnew, J.A. (2011): Divergent long-term trajectories of human access to the Arctic; Nature Climate Change, v.1, p. 156-160.

Stocker, T.F., D. Qin, G.-K. Plattner, L.V. Alexander, S.K. Allen, N.L. Bindoff, F.-M. Bréon, J.A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J.M. Gregory, D.L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G.A. Meehl, I.I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L.D. Talley, D.G. Vaughan and S.-P. Xie, (2013): Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stott, P.A., Gillet, N.P., Hegerl, G.C., Karoly, D.J., Stone, D.A., Zhang, X. and Zwiers, F. (2010): Detection and attribution of climate change: a regional perspective; Wiley Interdisciplinary Reviews (WIRES) Climate Change (March/April 2010), v. 1, p. 192-211.

Stow, C.A., Lamon, E.C., Kratz, T.K., and Sellinger, C.E. (2008): Lake level coherence supports common driver; EOS, v. 89, p. 389–390.

Stroeve, J., Serreze, M.C., Holland, M. M., Kay, J.E., Malanik, J., and Barrett, A.P. (2012a): The Arctic's rapidly shrinking sea ice cover: a research synthesis; Climatic Change, v. 110, p. 1005-1027.

Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., and Meier, W. N. (2012b): Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations; Geophysical Research Letters, v. 39, L16502.

Sushama, L., Khaliq, N., and Laprise, R. (2010): Dry spell characteristics over Canada in a changing climate as simulated by the Canadian RCM; Global and Planetary Change, v. 74, p. 1-14.

Taylor, K.E., Stouffer, R.J., and Meehl, G.A. (2012): An overview of CMIP5 and Experiment Design; Bulletin of the American Meteorological Society, v. 93, p. 485–498.

Thompson, K.R., Huang, J., Véronneau, M., Wright, D. G., and Lu, Y. (2011): Mean surface topography of the northwest Atlantic: Comparison of estimates based on satellite, terrestrial gravity, and oceanographic observations; Journal of Geophysical Research, v. 114, C07015.

Thomson, R.E., Bornhold, B.D., and Mazzotti, S. (2008): An examination of the factors affecting relative and absolute sea level in coastal British Columbia; Canadian Technical Report of Hydrography and Ocean Sciences 260: 49 p.

Timmermans, M.L. (2012): Sea Ice and Ocean Summary; in Arctic Report Card 2012, (ed.) M. O. Jeffries, J. A. Richter-Menge, and J. E. Overland, p. 43-55, online, <http://www.arctic.noaa.gov/report12/>.

Tivy, A., Howell, S.E.L., Alt, B., McCourt, S., Chagnon, R., Crocker, G., Carrieres, T., and Yackel, J.J. (2011): Trends and variability in summer sea ice cover in the Canadian Arctic based on the Canadian Ice Service Digital Archive, 1960-2008 and 1968-2008; Journal Of Geophysical Research, v. 116, C03007.

Trenberth, K.E. (2011): Changes in precipitation with climate change; Climate Research, v. 47, p. 123-138.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B., and Zhai, P. (2007): Observations: surface and atmospheric climate change; in Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, Tignor, M. and H.L. Miller, Cambridge University Press, Cambridge, United Kingdom. p. 235-336.

Ulbrich, U., Leckebuscg, G.C., and Pinto, J.G. (2009): Extra-tropical cyclones in the present and future climate: a review; Theoretical and Applied Climatology, v. 96, p. 117-131.

van der Kamp, G., Keir, D., and Evans, M.S. (2008): Long term water level changes in closed-basin lakes of the Canadian Prairies; Canadian Water Resources Journal, v. 33, no. 1, p. 23-38.

Van Vuuren, D.P.J., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard., K., Hurtt, C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. and Rose, S.K. (2011): The representative concentration pathways: an overview; Climatic Change, v. 109, p. 5–31.

Vermeer, M. and Rahmstorf, S. (2009): Global sea level linked to global temperature; Proceedings of the National Academy of Sciences, v. 106, no. 51, p. 21527-21532.

Vincent, L.A. and Mekis, É. (2006): Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century; Atmosphere-Ocean, v. 44, no. 2, p. 177-193.

Vincent, L. A., Wang, X. L., Milewska, E. J., Wan, H., Yang, F., and Swail, V. (2012): A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis; Journal of Geophysical Research, v. 117, D18110.

Wadhams, P., Squire, V.A., Goodman, D.J., Cowan, A.M., and Moore, S.C. (1988): The attenuation rates of ocean waves in the marginal ice zone; Journal of Geophysical Research, v. 93, no. C6, p. 6799-6818.

Wan, H., Wang, X.L., and Swail, V.R. (2010): Homogenization and trend analysis of Canadian near-surface wind speeds; Journal of Climate, v. 29, p. 1209-1225.

Wang, J., Bai, X., Hu, H., Clites, A., Colton, M. and Lofgren, B. (2012): Temporal and spatial variability of Great lakes ice cover, 1973-2010; Journal of Climate, v. 25, p. 1318-1329.

Wang, M. and Overland, J.E. (2012): A sea ice free summer Arctic within 30 years: an update from CMIP5 models; Geophysical Research Letters, v. 35, L22701.

Wang, X.L, Feng, Y., and Vincent, L.A. (2013): Observed changes in one-in-20 year extremes of Canadian surface air temperatures; Accepted to Atmosphere-Ocean.

Warren, F.J. and Egginton, P. (2008): Background Information: Concepts, Overviews and Approaches; in From Impacts to Adaptation: Canada in a Changing Climate, 2007, (ed.) D.S. Lemmen, F.J. Warren and E. Bush, Government of Canada, Ottawa, ON, p. 27-56.

Whitney, F.A., Freeland, H. J., and Robert, M. (2007): Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific; Progress In Oceanography: Time Series of the Northeast Pacific, v. 75, no. 2, p. 179-199.

Wilcox, D.A., Thompson, T.A., Booth, R.K., and Nicholas, J.R. (2007): Lake-Level Variability and Water Availability in the Great Lakes; Circular 1311, US Geological Survey, National Water Availability and Use Program, Virginia, USA.

Wiles, G.C., Krawiec, A.C., and D'Arrigo, R.D. (2009): A 265-year reconstruction of Lake Erie water levels based on North Pacific tree rings; Geophysical Research Letters, v. 36, L05705.

Williamson, C.E., Saros, J.E., and Schindler, D.W. (2009): Sentinels of Change; Science, v. 323, p. 887–888.

WMO [World Meteorological Organization] (2011): WMO Statement on the Status of the Global Climate in 2010; WMO, Geneva, Switzerland, no. 1074. ISBN 978-92-63-11074-9.

WMO [World Meteorological Organization] (2013): WMO Statement on the Status of the Global Climate in 2012; WMO, Geneva, Switzerland, no. 1108. ISBN 978-92-63-11108-1.

Wolf, E., Klemann, V., Wunsch, J., and Zheng, F.-P. (2006): A reanalysis and reinterpretation of geodetic and geological evidence of glacial-isostatic adjustment in the Churchill region, Hudson Bay; Surveys in Geophysics, v. 27, p. 19-61.

Woollings, T., Gregory, J.M., Pinto, J.G., Reyers, M., and Brayshaw, D.J. (2012): Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling; Nature Geoscience, v. 5, p. 313-317.

World Glacier Monitoring Service (2011): Glacier Mass Balance Bulletin No. 11 (2008-2009); (ed.) M. Zemp, S.U. Nussbaumer, I. Gärtner-Roer, M. Hoelzle, F. Paul and W. Haeberli.

Wu, L., Cai, W. Zhang, L., Nakamura, H., Timmermann, A., Joyce, T., McPhaden, M.J., Alexander, M., Qiu, B., Visbeck, M., Chang, P. and Giese, B. (2012): Enhanced warming over the global subtropical western boundary currents; Nature Climate Change, v. 2, p. 161-166.

Yamamoto-Kawai, M., McLaughlin, F.A., Carmack, E.C., Nishino, S., and Shimada, K. (2009): Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice melt; Science, v. 326,p. 1098-1100.

Yashayaev, I. (2007): Hydrographic changes in the Labrador sea, 1960-2005; Progress in Oceanography, v. 73, no. 3-4, p. 242-276.

Yashayaev, I. and Greenan, B. (2012): Environmental conditions in the Labrador Sea during 2011; Northwest Atlantic Fisheries Organization Scientific Research Document 12/018, N6042, 17 p.

Yasunaka, S. and Hanawa, K. (2011): Intercomparison of historical sea surface temperature datasets; International Journal of Climatology, v. 31, p. 1056-1073.

Yin, J., (2012): Century to multi-century sea level rise projections from CMIP5 models; Geophysical Research Letters, v. 39, L17709.

Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A. (2000): Temperature and precipitation trends in Canada during the 20th Century; Atmosphere–Ocean, v. 38, p. 395-429.

Zhang, X., Zwiers, F.W., and Stott, P.A. (2006): Multimodel multisignal climate change detection at regional scale; Journal of Climate, v. 19, p. 4294-4307.

Zhang, X., Zwiers, F.W., Hegerl, G.C., Lambert, F.H., Gillett, N.P., Solomon, S., Stott, P. and Nozawa, T. (2007): Detection of human influence on 20th century precipitation trends, Nature, v. 448, p. 461-465.

Zhang, X., Alexander, L., Hegerl, G.C., Jones, P., Tank, A.K., Peterson, T.C., Trewin, B., and Zwiers, F.W. (2011a): Indices for monitoring changes in extremes based on daily temperature and precipitation data; Wiley Interdisciplinary Reviews: Climate Change, v. 2, p. 6:851-870.

Zhang, X., Brown, R., Vincent, L., Skinner, W., Feng, Y., and Mekis, E. (2011b): Canadian climate trends, 1950 - 2007; Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 5, Canadian Councils of Resource Ministers, Ottawa, ON. vi+ 20 p., online, <www.biodivcanada.ca/default.asp?lang=En&n=E0DDE11F-1>.

Zorita, E., Stocker, T. F. and von Storch, H. (2008): How unusual is the recent series of warm years?; Geophysical Research Letters, v. 35, L24706.

# CHAPTER 3:
# NATURAL RESOURCES

Lead Authors:

**Donald S. Lemmen** *(Natural Resources Canada)*, **Mark Johnston** *(Saskatchewan Research Council)*, **Catherine Ste-Marie** *(Natural Resources Canada)* and **Tristan Pearce** *(University of Guelph)*

Contributing Authors:

**Marie-Amélie Boucher** *(Université du Québec à Chicoutimi)*, **Frank Duerden** *(University of Victoria)*, **Jimena Eyzaguirre** *(ESSA Technologies)*, **James Ford** *(McGill University)*, **Robert Leconte** *(Université de Sherbrooke)*, **Elizabeth A. Nelson** *(Natural Resources Canada)*, **Jeremy Pittman** *(independent researcher)*, **Élizabeth Walsh** *(Natural Resources Canada)*

Recommended Citation:

Lemmen, D.S., Johnston, M., Ste-Marie, C. and Pearce, T. (2014): Natural Resources; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 65-98.

# TABLE OF CONTENTS

# KEY FINDINGS

Natural resources are an integral component of Canadian livelihoods and national and regional economies, and will continue to be in future. While the biophysical impacts of climate change of relevance to most natural resource sectors are well understood, integration of these impacts into business planning is generally lacking. Key findings arising from recent literature relating to forestry, mining and energy – the sectors considered in this chapter – include:

- Climate change will exacerbate existing climate risks related to the planning and management of natural resource sector industries, including activities associated with exploration, development, operation, distribution, closure and reclamation/rehabilitation. These risks relate to impacts and natural hazards associated with climate extremes (e.g. heat, cold, precipitation) and to slow-onset events such as permafrost degradation, sea level rise, and plant species migration. Climate change will also present new opportunities for the natural resource sectors, particularly in relation to northern economic development.

- Consideration of multiple stressors is critical to understanding adaptation in the natural resource sectors. Climate change itself is rarely identified as a priority concern, with industry focused on other immediate stressors, such as economic drivers. Nonetheless, there are opportunities to integrate consideration of climate change into existing planning processes.

- Environmental assessment, risk disclosure, and sustainable forest management reporting are examples of processes that can help advance adaptation actions in future. These processes allow governments, investors and the public to evaluate industry understanding of changing climate risks and influence the steps taken to address those risks.

- While awareness of climate change impacts and implementation of adaptation actions is most evident in sectors where there is a clear and direct relationship between climate and resource supply, notably forestry and hydroelectricity, the application of adaptive management approaches to address climate change impacts is seen across all natural resource sectors. Adaptive management approaches involve ongoing research, monitoring and evaluation with the intent of informing future management policy and practices, and allowing for flexibility in the face of the uncertainties inherent in climate change.

# 1. INTRODUCTION

Canada possesses an abundance of natural resources that are integral to Canada's history and identity, and that constitute a significant component of national, provincial and territorial economies. This chapter focuses on three natural resource sectors – forestry, mining and energy – which together directly account for 13.3% of Canada's gross domestic product and provide almost 950 000 jobs (Table 1; Natural Resources Canada, 2013a).

| | Forestry | Mining | Energy | Total |
|---|---|---|---|---|
| GDP (2013) | 1.1% | 3.5% | 9.1% | 13.3% |
| Direct Employment | 224 410 | 401 315 | 335 580 | 948 735 |
| Domestic Exports | $25B | $90B | $119B | $224B |

**TABLE 1:** Contribution of the natural resource sectors to the Canadian economy in 2012 *(Source: Natural Resources Canada, 2013a).*

The economic significance of natural resources is magnified at the local scale. Resource-reliant communities are mostly small and remote, but also include large and medium-sized cities like Calgary in Alberta, Hamilton and Sudbury in Ontario and Prince George and Kamloops in British Columbia. Some communities are considered to be solely reliant on natural resources, deriving 80% or more of employment income from natural resource activities (Natural Resources Canada, 2009).

The climate sensitivity of natural resource development depends on the sector considered. The impacts of changing climate on economic output and productivity are most evident for forestry and hydroelectricity. All natural resource sectors face climate risks, many of which are related to extreme weather events and associated natural hazards, during exploration, development, processing, transportation and rehabilitation/decommissioning activities (e.g. Lemmen et al., 2008a). Investments by natural resource industries over the next decade will provide an opportunity to integrate climate change considerations in order to enhance the climate resilience of future operations. Over 600 major resource projects are planned for development in Canada over the next decade, representing about $650 billion in investment (Natural Resources Canada, 2012a).

This chapter provides an overview of progress made in understanding the impacts of changing climate on forestry, mining and energy sectors in Canada, and on the sectors' advances in adapting to these impacts. This overview draws predominantly on material published since the release of *From Impacts to Adaptation: Canada in a Changing Climate* (Lemmen et al., 2008a). Following a brief review of key findings from previous assessments, this chapter presents individual sections on forestry, mining and energy. Recent research strengthens confidence in previous findings and provides new insights. Particular attention is paid to advancements in adaptation, recognizing the wide range in levels of engagement levels across sectors (from increasing awareness to implementing policy and operational changes). The chapter concludes by drawing together the findings pertaining to forestry, mining and energy for an integrated perspective of natural resources as an economic sector and the implications of climate change impacts and adaptation actions on economic competitiveness in the short and long term. Other aspects of natural resources are addressed in chapters 4 (Food Production), 5 (Industry) and 6 (Biodiversity and Protected Areas) of this report.

# 2. PAST ASSESSMENTS

Natural resources figure prominently in all regional chapters of *From Impacts to adaptation: Canada in a Changing Climate* (Lemmen et al., 2008a), as well as in Chapter 9 (Canada in an International Context) of that report (Table 2). The vulnerability of resource-reliant communities is a key conclusion of national significance emerging from that report. This vulnerability is a reflection of the high climate sensitivity of many natural resource-based industries, limited economic diversification and, in many cases, restricted access to services (Lemmen et al., 2008b). This vulnerability is magnified in the Arctic, where the magnitude of climate change has been and is projected to remain the greatest, and because of the remoteness of communities and many natural resource operations.

The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) addresses forestry and energy in thematic chapters (Easterling et al., 2007; Fischlin et al., 2007; Wilbanks et al., 2007), in the North America chapter (Field et al., 2007), and in the chapter exploring linkages between climate change adaptation and mitigation (Klein et al., 2007). While there is no integrated analysis of the vulnerability of the natural resource sectors, the report does highlight the importance of understanding multiple stressors on natural resource industries (Easterling et al., 2007).

| | North | Atlantic Canada | Quebec | Ontario | Prairies | British Columbia | International |
|---|---|---|---|---|---|---|---|
| Forestry | X | X | X | X | X | X | X |
| Mining | X | | X | X | X | | X |
| Energy demand | | X | X | X | X | X | X |
| Energy supply | X | X | X | X | X | X | X |

**TABLE 2:** Content relating to natural resources within specific chapters of *From Impacts to Adaptation: Canada in a Changing Climate (Lemmen et al., 2008a)*.

## FORESTRY

Due to their northern location, Canada's forests are exposed to greater increases in temperature than the global average (IPCC, 2007) with significant impacts varying across the country. Key findings of past assessments (Lemmen et al., 2008a; Lemprière et al., 2008, Johnston et al., 2009; Williamson et al., 2009) suggest that:

- Increases in disturbance regimes (e.g. forest fires, pest and disease outbreaks) are already evident and will become more pronounced in future.
- Forest composition will change due to shifting climatic and disturbance regimes.
- Forest access will be impacted by changes in disturbance regimes, shifting infrastructure costs, and shorter winter harvesting seasons due to reduced periods of frozen ground.
- Net impacts of climate change on forest productivity will be regionally and locally specific. Productivity could be positively impacted by warmer temperatures, longer growing seasons and increasing $CO_2$ levels where other factors (e.g. soil, water or nutrients) are not limiting, but will be negatively impacted by increased drought and more frequent and severe disturbances and extreme weather events.
- Social and economic impacts on forest-based communities (e.g. safety and security costs, forest sector jobs and tourism) will be significant in some regions.

## MINING

Mining received less discussion than the other natural resource sectors in Lemmen et al. (2008a), reflecting the literature available at that time. Nonetheless, the report noted challenges to site selection, mine design, development and operations, and transport, as well as final closure and site remediation in a changing climate. Key findings suggested that:

- Extreme weather events have already negatively affected some mine operations.
- Significant vulnerabilities to climate change exist in post-operational mines, with implications for the environment and surrounding communities.
- Reductions in Arctic sea ice could lead to new opportunities for mining exploration and development in the North, related in part to decreased shipping costs. There are also challenges associated with operating in the Arctic environment, including issues surrounding environmental safeguards and social inclusion.
- Decreased viability of winter roads could affect access to many northern mine sites, and necessitate the development of alternative transport routes.
- Mine design and operational changes are likely necessary to manage the risks of environmental contamination related to permafrost degradation in the North, and the impacts of extreme weather events elsewhere.
- Many recent major mining developments in northern Canada have taken projected climate impacts into account in their design plans.

## ENERGY

Adapting to climate-related changes in energy demand and supply is a challenge for the energy sector across Canada. Specific vulnerabilities vary by geographic setting, primary energy sources and projected changes in climate. Key findings from Lemmen et al. (2008a) indicate that:

- Seasonal energy demand will shift, with decreased demand for winter heating and increased demand for summer cooling.
- Supply-demand mismatches are possible since peak summer demand for cooling may coincide with decreased hydroelectric potential in some areas.
- Hydroelectricity generation may be affected by seasonal reductions in water supply, particularly in glacier-fed systems. Accommodating changes in timing of flow and peak events will likely require adjustments in reservoir management practices.

- Transmission of electricity is sensitive to increased temperature (greater energy losses) and extreme weather (infrastructure damage leading to distribution grid failure).
- Permafrost degradation and associated land instability will pose a risk to energy infrastructure (foundations, pipelines and roads) in northern Canada.

# 3. FORESTRY

Canada is a forest nation, with forests covering more than 50% of the country's landmass (Figure 1; Natural Resources Canada, 2011a). Change in Canada's forested land is driven primarily by large-scale disturbance regimes, with fire and pest outbreaks affecting 5% of the forested area annually (Natural Resources Canada, 2011a). Climate is a key determinant of forest distribution, composition, productivity, dynamics and disturbance regimes. As such, climate change is projected to have far-reaching consequences for Canada's forest sector.

In addition to the direct economic benefits provided by the harvest of timber and fibre (Natural Resources Canada, 2012a), forests provide recreational and cultural value, as well as non-timber forest products such as mushrooms and berries. Ecosystem services provided by forests, such as clean air and water, carbon storage and soil nutrients, also have social and economic value, although this is difficult to quantify.

Provincial and territorial governments have legislative authority over the land and resource management of 77% of Canada's forests, with each province and territory setting its own policies, legislation and other regulatory matters. The

**FIGURE 1:** Forest regions of Canada *(Source: Natural Resources Canada, 2000).*

federal government has jurisdiction over 16% of the forest, and the remaining 7% of forests are privately owned among more than 450 000 landowners. Less than 0.2% of Canada's forests are harvested annually (Natural Resources Canada, 2012b). The Canadian forest sector has made a commitment to sustainable forest management (SFM), and Canada is a global leader in forest certification with over 90% of the managed forest certified under one or more of the SFM standards (Natural Resources Canada, 2011b; Box 1).

This section provides an update of key findings related to climate change risks, opportunities and adaptation of importance to the forest sector. Other aspects of Canada's forest ecosystems are covered in Chapter 6 (Biodiversity and Protected Areas) of this report.

BOX 1

### SUSTAINABLE FOREST MANAGEMENT (SFM) IN CANADA

Sustainable forest management (SFM) is defined as "management that maintains and enhances the long-term health of forest ecosystems for the benefit of all living things while providing environmental, economic, social and cultural opportunities for present and future generations" (Natural Resources Canada, 2012b). SFM promotes the responsible management of forests as a resource (e.g. for timber, services), while also protecting their continued health and diversity.

In Canada, a national framework consisting of a series of criteria and indicators has been developed by the Canadian Council of Forest Ministers (CCFM) to describe, monitor and report on trends and progress towards sustainable forest management. This includes measures pertaining to biological diversity, ecosystem condition and productivity, soil and water conditions, economic and societal benefits, and community involvement and responsibilities. Canada uses the Criteria and Indicators Framework at a national level to report on progress toward SFM in the State of Canada's Forests Annual Report (Natural Resources Canada, 2012b).

Sustainable forest management is also supported by the provinces and territories through policy and legislation, and by forestry organizations through voluntary third party certification. Canada leads the world in voluntary sustainable forest management certification; as of December 2011, close to 151 million hectares of forest had been certified through the three SFM certification programs in use in Canada (FPAC, 2012).

## 3.1 OBSERVED AND PROJECTED IMPACTS

Impacts of climate change on forests and the forest sector have already been observed in Canada. The most visible climate-related impacts are the changes in disturbance regimes, such as fire and pest outbreaks, and those associated with extreme climate events such as drought, windstorms and ice storms (Lemprière et al., 2008; Williamson et al., 2009), which can have immediate social and economic consequences. However, subtle impacts such as changes in tree species composition, phenology and productivity are increasingly being reported (Johnston et al., 2009) and will impact the forest sector on a longer time scale.

### FIRE

Fires are a natural driver of Canada's forest dynamics, with over three million hectares of forested land burned in 2009 (Natural Resources Canada, 2011a). The occurrence, extent and severity of forest fires are projected to increase in most regions of Canada with continued climate change. Increases of between 75% and 140% in the number of fires have been projected by the end of the 21st century, with significant regional variation (Wotton et al., 2010), while projections of the area burned in western Canada show a three to five-fold increase by the end of the 21st century, relative to 1991-2000 (Balshi et al., 2009). Climate change will also affect the timing of the fire season, with an earlier onset and a later seasonal peak in fire weather (Le Goff et al., 2009). Changes in fire regimes have already been observed. Since the 1980s, large fires have increased significantly in northwestern (Kasischke and Turetsky, 2006; Girardin, 2007) and northeastern (Le Goff et al., 2007; Ali et al., 2012) Canada.

### PEST EPIDEMICS AND DISEASES

Forest insects and pathogens are major disturbance agents that annually affect millions of hectares of forest in Canada (Natural Resources Canada, 2011a). The survival and spread of pests and pathogens is influenced by climate, and projected climate changes are anticipated to alter their geographical distribution and life cycle. Given that several pests and pathogens are currently limited by winter temperatures, the range and severity of diseases and pest outbreaks are likely to increase as winter temperatures rise (Lemprière et al., 2008; Johnston et al., 2009; Williamson et al., 2009).

The devastating mountain pine beetle outbreak in Canada's western forests has been widely attributed to higher winter temperatures along with other contributing factors (*see* Case Study 1). The forest tent caterpillar, spruce budworm, and spruce bark beetle are three additional forest pests that currently impact Canada's forests, and are likely to continue to damage forests in the future (Price et al., in review). The ability to predict the effects of climate change on forest diseases is limited due to the multiple factors involved: the disease organism, the method of spread (e.g. wind, insects), and the host species. However, pathogens that are currently widespread are likely to continue to affect Canada's forests in a warming climate (Sturrock et al., 2011).

### DROUGHT AND OTHER EXTREME WEATHER EVENTS

Globally, the frequency, duration and severity of drought and heat stress are projected to increase with climate change (Price et al., *in review*). Forested ecosystems may already be showing a drought-related increase in tree mortality globally (Allen et al., 2010), in the United States Pacific Northwest (Van Mantgem et al., 2009) and in Canada's boreal forests (Peng

### CASE STUDY 1
## THE MOUNTAIN PINE BEETLE OUTBREAK

Among the most dramatic impacts of climate change on Canada's forests is the mountain pine beetle (*Dendroctonus ponderosae*) outbreak in the western part of the country. The mountain pine beetle is an endemic insect of western North American pine forests, whose populations periodically increase to create large-scale outbreaks. In Canada, mountain pine beetle populations have historically been controlled by extreme winter temperature events (colder than -35 °C over several days or weeks), especially in early winter (BCMFLNRO, 2012), resulting in relatively moderate impacts on western pine forests. These cold events have become less frequent in recent years, allowing beetle populations to expand to unprecedented numbers. The abundance of mature lodgepole pine following decades of reduced area burned by fire (linked to fire suppression practices and reduced fire weather) may also have contributed to the widespread outbreak, which in 2008 was evaluated as being one order of magnitude larger in area and severity than all previous recorded outbreaks (Kurz et al., 2008; Girardin and Wotton, 2009; BCMFLNRO, 2012).

As of 2012, approximately 18.1M hectares of mature lodgepole pine-dominated forest have been affected by the mountain pine beetle, and climate change is likely a key contributing factor to the extent and severity of this outbreak (BCMFLNRO, 2012). To address the salvage of dead pine, annual allowable cuts were initially increased in the severely impacted areas, and have subsequently been reduced in several Timber Supply Areas where the annual kill has declined rapidly. As the timber supply begins to decline, output from BC forests and manufacturing sector will also decline and could lead to the loss of jobs for thousands of workers, employed both directly and indirectly by the forest sector (e.g. International Wood Markets Group BC, 2010).

The primary host of the mountain pine beetle is lodgepole pine (*Pinus contorta*); however, the beetle can also attack jack pine (*Pinus banksiana*) which ranges from Alberta to Nova Scotia (Burns and Honkala, 1990). There is concern that if climatological barriers are further reduced, the beetle could spread across Canada's boreal forests. However, unlike lodgepole pine, jack pine populations are scattered across the landscape, which may limit the mountain pine beetle's capacity to migrate to new stands and thus reduce the potential for a massive outbreak expanding to the eastern part of the country (Cullingham et al., 2011). The peak of the current outbreak is generally considered to have passed, although the pest range is still expanding (BCMFLNRO, 2012). Since 2008, the expansion has continued both northward and eastward into the boreal forest (Figure 2). In 2011, the beetle was found about 80 km from the Yukon border, and newly-attacked trees have been reported in northern parts of Alberta, not far from the Saskatchewan border (Cullingham et al., 2011).

Over the ten year epidemic, the BC and federal governments invested hundreds of millions of dollars to reduce the impact of the outbreak, to develop new markets for salvaged pine, and to create economic strategies for the future (BCMFLNRO, 2012). Initially, the focus was on limiting the spread of infestation and harvesting infested and susceptible stands. As the outbreak continued, efforts to use the beetle-killed wood intensified (BCMFLNRO, 2012). An example is the use of wood stained blue by the fungus introduced by the beetle for interior panelling (Zaturecky and Chiu, 2005). Salvage wood is also used as a source of bioenergy (BCMFLNRO, 2012).

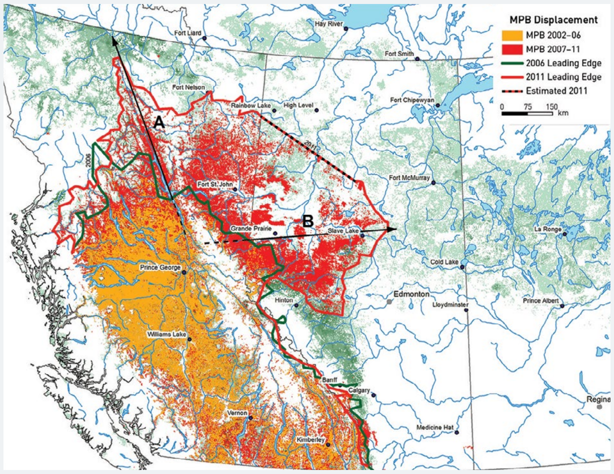


**FIGURE 2:** Map of Mountain Pine Beetle distribution, showing change for the 2002-06 and 2007-11 time periods and direction of change *(Source: Natural Resources Canada 2012c).*

et al., 2011). In the prairie region, drought was exceptionally severe during 2001-2002, resulting in dramatic dieback and decline in trembling aspen populations, with mortality increasing by over 20% compared to the long-term average (Michaelean et al., 2011). Moisture availability has also been linked to growth and productivity of forests, with moisture stress decreasing annual radial growth across a range of sites and species, including white spruce, black spruce, trembling aspen, and lodgepole pine (Barber et al., 2000; Chhin et al., 2008; Girardin et al., 2008; Hogg et al., 2008).

Extreme wind events are projected to increase with continued climate change (e.g. Haughian et al., 2012). Examples of forest impacts caused by extreme winds include widespread damage to both public forest land and private woodlots across Nova Scotia caused by Hurricane Juan in the fall of 2003 (McGrath and Ellingsen, 2009), and the destruction of old-growth and young forest stands across the lower mainland of British Columbia from a December 2006 windstorm that affected over 40 hectares in Stanley Park, a key outdoor recreation destination in Vancouver. While park restoration costs following the storm have exceeded $10 million, restoration efforts were used as an opportunity to increase public engagement and to replant for a more resilient forest (City of Vancouver, 2012).

### CHANGES IN COMPOSITION

Species distribution is strongly influenced by climate. As climate changes, the climatic envelopes of Canadian tree species are shifting northward in latitude and upslope in altitude (*see* Chapter 6 – Biodiversity and Protected Areas). Although there is high uncertainty in range-shift projections (McKenney et al., 2011), the rate of shift in the climatic envelopes of most North American tree species could be at least one order of magnitude faster than their potential migration speeds (McKenney et al., 2007; McKenney et al., 2011), raising concerns that species will not be able to keep up with their climate niche. Additional local stress factors, such as drought, disturbance and competition with existing species, could interact with climatic factors to reduce their migration potential, creating an even greater discrepancy between the shift in climatic niche and actual species distribution (Mohan et al., 2009).

### CHANGES IN PRODUCTIVITY

Growing seasons have lengthened over the past few decades, with spring phenological events such as bud burst and needle dehardening taking place earlier in the year. For example, trembling aspen bloom dates in Alberta advanced by two weeks between 1936 and 2006 (Beaubien and Hamann, 2011). Warmer climates and longer growing seasons may benefit populations in the northern portion of the species range, as evident in trembling aspen populations in eastern Canada (Lapointe-Garant et al., 2009). More southerly populations may show neutral or reduced growth under warming conditions (Ma et al., 2012), and may only show enhanced growth under ideal conditions and when trees are young (Girardin et al., 2012). Early growing seasons may also increase the risk of exposure to frost (Beaubien and Hamann, 2011), limiting productivity benefits. Increased atmospheric $CO_2$ concentrations may also result in moderate increases in productivity in very limited situations, such as sites where water and nutrients are not limiting and where competition is low (Soulé and Knapp, 2006; Wang et al., 2006).

### SOCIO-ECONOMIC IMPACTS

The combined impacts of climate change on forests affect the quality and quantity of timber supply, with significant financial impacts on the forest industry (NRTEE, 2011). These impacts will exhibit strong regional variations, with potential costs resulting from reduced timber supply (Ochuodho et al., 2012) and shortened winter harvesting seasons (when operating costs are lower and soil disturbances are minimized; Johnston et al., 2009; Ogden and Innes, 2009). Economic consequences also extend beyond impacts on timber supply, as climate change will also affect industries that rely on forest harvests, such as manufacturing and construction. Lempriere et al. (2008) provided a summary of short, medium and long term climate change impacts on the quantity and quality of timber supply in Canada and on international supply and demand.

Forest fires threaten human health, safety and security (*see* Chapter 7 – Human Health). As an example of financial damages caused by wildfire, the 2011 Slave Lake, Alberta fire resulted in an estimated $742 million in insurance claims (Flat Top Complex Wildfire Review Committee, 2012). The projected increase in fire due to climate change will translate into extra cost for protection and community evacuations. There may be only a decade or two before increased fire activity exceeds the capacity of fire management agencies to maintain current levels of effectiveness (Flannigan et al., 2009).

Forest-based communities are highly dependent on the forest resource for jobs, income and other goods and services, such as outdoor recreation. Increased occurrence of fire, pest outbreaks, and extreme weather events will translate into a reduced number of forest stands that can be sustainably managed. Monitoring and protection costs may become prohibitive in certain areas, and contribute to the reduction or elimination of local forestry economies.

Analyses of economy-wide impacts of climate change on the forest sector need to integrate consideration of non-climate stressors, including consumer demand, labour and capital supply, and markets for production inputs and outputs (NRTEE, 2011).

### IMPACT ON CARBON STORAGE

Climate change also impacts the ecological services that forests provide, such as water conservation and purification, biodiversity and carbon storage. The importance of forest ecosystems in mitigating climate change by storing carbon is increasingly recognized and valued (Pan et al., 2011). Disturbances can have major impacts on forest carbon stocks and fluxes (Hicke et al., 2012), and projected increases in drought, fire and pest disturbances would reduce the carbon storage capacity of Canada's forests (Amiro et al., 2009; Michaelian et al., 2011). For example, Kurz et al. (2008) concluded that by 2020, trees killed by the mountain pine beetle in western Canada will have released nearly one billion tonnes of carbon dioxide into the atmosphere, roughly equivalent to five years of emissions from Canada's transportation sector.

## 3.2 ADAPTATION

Climate change presents challenges to Canada's forest managers. Decisions made today will impact the forest for over 100 years, given the long generation times of tree species. Trees can cope with a certain amount of change in their environment through physiological or genetic adaptation (Aitken et al., 2008), but the rate of future climate change is likely to exceed the ability of forests to adapt sufficiently to maintain the current levels of goods and services provided to society. Therefore, planned forest adaptation will be required to maintain the competitiveness and sustainability of Canada's forest sector. The Canadian forest industry has been facing significant economic challenges, resulting in lost jobs, mill closures, and a general downturn in the forest sector. Effective adaptation must address all of these drivers of change in the forest sector.

Many papers and reports (e.g. Millar et al., 2007; Ogden and Innes, 2007; Bernier and Schoene, 2009; Johnston et al., 2009; Gauthier et al., *in review*) explore options for forest sector adaptation, and there are several examples of specific measures being implemented (e.g. *see* Case Study 2).

Forest sector adaptation in Canada has gained political attention, with the Canadian Council of Forest Ministers (CCFM, 2008) identifying climate change as one of two national priorities, and stating that consideration of climate change and future climatic variability is needed in all aspects of sustainable forest management. Subsequent work by the CCFM included case studies of vulnerability and resilience assessments covering a range of forest landscapes, management activities and policy environments (Johnston and Edwards, in press; *see* Case Study 3).

**CASE STUDY 2**

### ASSISTED MIGRATION

Assisted migration is the human-assisted movement of species in response to climate change (Ste-Marie et al., 2011). It is an adaptation option that is increasingly being considered to maintain the biodiversity, health and productivity of Canada's forests in a changing climate. Assisted migration can be used for both conservation goals (e.g. to save a species) and forestry goals (e.g. to maintain healthy and productive forest stands). Given existing knowledge and established best practices, assisted migration is more feasible for major commercial tree species than for rare species of conservation concern (Pedlar et al., 2012).

Many jurisdictions have seed transfer guidelines that recommend where seeds from specific geographical areas should be planted to ensure that they are suited to their planting environment. Some Canadian jurisdictions have begun to implement assisted migration of tree populations and species on a small scale by modifying these guidelines in response to observed and projected climate change. Current implementation of assisted migration of commercial tree species usually involves seed movements within, or slightly outside, current range limits. For example, British Columbia has extended seed transfer zones 100 or 200 metres upward in elevation for most species (BCMLFNRO, 2008), and introduced a new policy to allow for the limited planting of western larch in specific locations outside of its current range (BCMLFNRO, 2010). Through a variance application system, Alberta has extended conifer seed transfer zones by 200 metres higher in elevation and 2 degrees of latitude northward for most species (S. Kavalinas, ESRD, personal communication). In the northern part of the commercial forest of Quebec, seeds from southern seed orchards may represent up to 20% of the reforestation material (André Deshaies, Ministère des Ressources naturelles, personal communication).

CASE STUDY 3

## ANALYSIS OF FOREST SECTOR VULNERABILITY ASSESSMENTS

In 2008-2012, the Canadian Council of Forest Ministers (CCFM) conducted a study of the Canadian forest sector's vulnerability to climate change. One component of the study was a summary and synthesis of twelve vulnerability case studies across the country (Figure 3). The objectives of the case studies varied widely, from a focus on biophysical modeling, to policy analysis, to community-based assessments, to integration of climate change into forest management planning. The perceived importance of climate change relative to other issues also varied considerably among the case studies, from unimportant to extremely important.

**FIGURE 3:** Locations of vulnerability assessment case studies included in the CCFM climate change adaptation initiative. ESRD = Environment and Sustainable Resource Development (Alberta), RAC = Regional Adaptation Collaborative (Natural Resources Canada) *(Source: Johnston and Edwards, 2013).*

Key outcomes of the vulnerability assessments, in additional to technical analysis, include:

- enhanced awareness of climate change among the wide range of players involved, and the development of strong linkages between practitioners and modellers;
- forest management capacity building and increased understanding of vulnerabilities, as a foundation for future work focused on adaptation. While some case studies did include adaptation options, in general the concept of adaptation is not yet well understood;
- the development of integrated, multi-scale modeling approaches, informed by stakeholder groups, which will enhance the science base for forest management in the future;
- enhanced participant understanding of the uncertainty associated with future climate projections.

Analysis of the suite of case studies also allowed Johnston and Edwards (*in press*) to identify factors that enabled successful vulnerability assessments. These factors, which can be applied to future initiatives, include:

- adequate funding and human resources, including experts and local leaders;
- previous analyses that provide some indication of the likely impacts and pre-existing concerns of local decision makers regarding the effects of climate change and what they can do to reduce the impacts;
- synthesized "off-the-shelf" technical data (climate, ecosystems, etc.) that assist vulnerability assessment teams to move forward quickly;
- availability of natural science and social science expertise to link the biophysical and human systems;
- a champion – someone personally dedicated to the project, often a local community leader – who can bridge the gaps between scientists, stakeholders and practitioners;
- mechanisms to integrate local and/or traditional knowledge with science; and
- an initial focus on current vulnerabilities, which helps identify and address lack of knowledge at the start of the process.

### ADAPTATION BARRIERS AND CHALLENGES

Large-scale and high-profile examples of climate change impacts, such as the mountain pine beetle outbreak, and extreme climate-related events, such as the severe wild fires in Kelowna, British Columbia in 2003 and Slave Lake, Alberta in 2011 have increased awareness of climate change adaptation among forestry practitioners. Both government and industry are moving from a 'crisis management' strategy to an 'adaptive management' approach, working to proactively address the risks and take advantage of the opportunities presented by climate change (Johnston and Hesseln, 2012). However, a lack of economic incentives for adaptation can make it difficult for companies to absorb short-term costs despite potential long-term gains (NRTEE, 2012a, b). While economic pressures in the Canadian forest sector may limit the capacity of industry to focus on, and invest in, adaptation to address future climate impacts, many adaptive management strategies are also appropriate for dealing with other non-climatic stresses and to help increase system resilience.

Significant uncertainty remains about future climate conditions (Trenberth, 2010), the multiple, interacting impacts of climate change on complex forest ecosystems, and forest response to those changes. Scientific understanding of past and future climate change impacts on Canada's forests has increased substantively over the past decade, but this information is not always available, accessible, and/or applicable to prospective end-users (Johnston and Hesseln, 2012). In fact, understanding of prospective adaptation options has been identified as a knowledge gap and barrier to action by some in the Canadian forestry industry (NRTEE, 2012a, b). Networks of climate change adaptation stakeholders, such as the Forestry Adaptation Community of Practice (www.ccadaptation.ca/forestry), have emerged to help address this barrier through sharing knowledge and best practices.

The difficulty of unequivocally attributing impacts to climate change in forest systems that are subject to multiple stressors is sometimes viewed as a barrier to adaptation (Lemprière et al., 2008). Generating long time-series measurements that use multi-scale monitoring allows detection and quantification of climate-related forest changes, which facilitate the validation of models and informing of adaptation decisions. The integration of on-the-ground measurements and remote sensing data greatly increases the breadth and depth of Canada's capacity to monitor forest changes. Integration of scientific knowledge across disciplines will also allow development of a more integrated understanding of the vulnerabilities of the forest and the forest sector to a changing climate.

Because climate change significantly challenges the attainment of sustainable forest management goals, adaptation should be considered as essential to sustainable forest management. For example, the criteria and indicators of sustainable forest management adopted by the CCFM (2006) may prove to be difficult, if not impossible, to achieve because they do not factor in the impacts of a changing climate. Analysis of the criteria and indicators system by Steenberg et al. (2012) suggests that indicators may have to be revisited, adjusted and added in the context of climate change. Established sustainable forest management certification standards could provide a vehicle for mainstreaming climate change into forestry decision making. Redefining sustainable forest management to incorporate climate change is likely to be a complex process involving many players and will require detailed trade-off analyses to clarify the range of forest values represented.

# 4. MINING

The Canadian mining sector employed approximately 401 315 people in mineral extraction and in value-added smelting, fabrication and manufacturing, and contributed about $60 billion to Canada's gross domestic product in 2012 (NRCan, 2013a). In 2010, there were approximately 968 mining establishments, including 71 metal mines and 897 non-metal mines, operated in clusters in and around over 120 medium and small communities across Canada, primarily in Quebec and British Columbia (Figure 4). Mining also contributes to the economies of large cities. The Toronto Stock Exchange handled 83% of the world's mining equity transactions in the past six years; Vancouver is home to several clusters of exploration companies, Montreal to major aluminum and iron ore firms, and Saskatoon to uranium and potash ventures (Stothart, 2011).

Mining contributes to the economies of all provinces and territories (Table 3). This economic contribution varies considerably over time depending on the number of mines operating and the value of the commodity produced. According to the Mining Association of Canada the industry plans to invest over $140 billion in projects over the next decade (Marshall, 2012). This planned growth represents a potential opportunity to integrate adaptation as part of mineral exploration activities, mine construction, operations, transportation and closure.

Mining operations in Canada have long dealt with climate variability, but in recent years they have been affected by an increasing incidence of climatic hazards, several of which are likely sensitive to climate change (Lemmen et

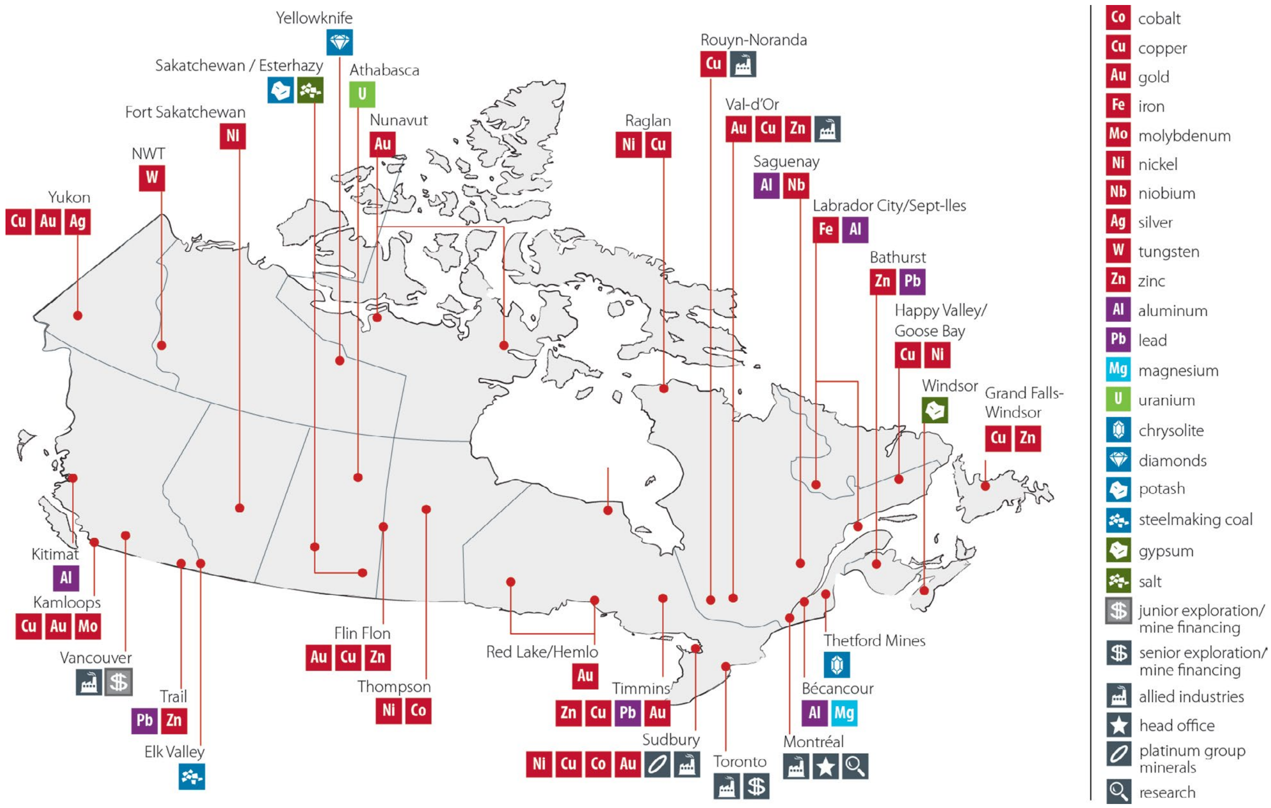


**FIGURE 4:** Canadian mining industry clusters *(modified from Stothart, 2011).*

al., 2008a; Pearce et al., 2011; Stratos, 2011; IMG-Golder Corporation, 2012; NRTEE, 2012a). Climate change presents a business risk, including public perception of a company's commitment to addressing climate change mitigation (Pearce et al., 2009). Climate change also presents new opportunities for mining exploration and development resulting from improved access to resources and new transportation options (Lemmen et al., 2008a; Prowse et al., 2009; Pearce et al., 2011; NRTEE, 2012a). The extent to which the mining sector is able to reduce its own impact on climate, adapt to climate change and take advantage of new opportunities will affect its long-term success, with economic and environmental consequences for host communities and the country.

The majority of available research on climate change impacts and adaptation in the mining sector focuses on operations located in northern regions and on issues like permafrost integrity, winter transportation networks, water management and the potential for Arctic seaways as sea ice melts. Limited information exists on climate change impacts and adaptation with regard to mining operations in southern Canada, despite the concentration of mines south of 60° (of 196 "Principal producing mines" listed in Natural Resources Canada (2012d), only 8 are located in the northern territories). The discussion in this section reflects the limitations of the information available.

| Province/Teritory | Value of mineral production by province and territory, 2000 and 2010 ($M) | |
|---|---|---|
| | 2000 | 2010 |
| Newfoundland and Labrador | 967.1 | 4584.0 |
| Prince Edward Island | 5.5 | 3.4 |
| Nova Scotia | 295.2 | 294.2 |
| New Brunswick | 772.5 | 1154.6 |
| Quebec | 3653.2 | 6770.5 |
| Ontario | 5711.4 | 7691.7 |
| Manitoba | 1268.8 | 1663.5 |
| Saskatchewan | 2282.6 | 7084.0 |
| Alberta | 1064.4 | 2347.3 |
| British Columbia | 2891.5 | 7073.8 |
| Yukon | 56.2 | 284.1 |
| Northwest Territories | 681.7 | 2032.7 |
| Nunavut | 384.6 | 305.1 |
| TOTAL | 20 034.7 | 41 288.9 |

**TABLE 3:** Value (millions of dollars) of mineral production by province and territory, 2000 and 2010 *(from Stothart, 2011).*

## 4.1 CLIMATE CHANGE IMPACTS AND OPTIONS TO ADAPT

Climate change affects all stages in the mining cycle, including planning, current and future operations, and post-operation. Studies have identified several aspects of mining operations that are currently affected by changing climatic conditions, including: a) built infrastructure; b) transportation infrastructure; c) extraction and processing; and d) daily operations.

### BUILT INFRASTRUCTURE

Permafrost degradation and resulting soil instabilities, changes in the hydrological cycle, and extreme weather events present challenges for the design, construction, operation and closure of mine infrastructure (Instanes et al., 2005; Furgal and Prowse, 2008; Prowse et al., 2009). In the past, engineering design did not consider a changing climate and most mine infrastructure was built to withstand the climate norms and conditions at the time of construction. Structures built prior to the late 1990s and some after (e.g. roads, airstrips, buildings, berms, tailings dams and containment ponds) may be susceptible to increased thaw depth and settlement beyond the original design values due to climate change, which could increase maintenance costs and require remedial work to ensure structural integrity (Prowse et al., 2009). Permafrost degradation could also compromise the stability and performance of structures such as dams and waste covers, leading to the release of contaminants into the environment (Pearce et al., 2011; Stratos, 2011).

Extreme climate events have already exceeded the ability of some mine infrastructure to operate as intended. Changes in the hydrological cycle – especially extreme precipitation events and melt patterns – have led to high river flows that can exceed the capacity of water management structures. For example, torrential rains in the Yukon Territory forced a copper-gold mine to release untreated water into the Yukon River system on multiple occasions, breaching Yukon water license standards (Pearce et al., 2011). Slope stability and the integrity of engineered berms can also be compromised by extreme precipitation (Chiotti and Lavender, 2008). Erosion of dam slopes or gullying at the base of impoundment structures can occur, causing weaknesses in dams and increasing risk of failure. Tailings dam failures, triggered by heavy rain and flood events, have been documented internationally (ICOLD, 2001; WISE Uranium Project, 2006).

There are also risks of structural failure due to climate change and weather extremes for several post-operation mines across Canada, particularly in the North. Waste containment facilities constructed several decades ago were not designed for today's warmer conditions. Failures of frozen-core dams on tailing ponds at some mine sites and degradation of permafrost underlying spoil heaps have already resulted in unanticipated erosion and contaminants being released into the surrounding environment (Stratos, 2011). The potential exists for this to happen at other mine sites across the country (Pearce et al., 2011).

Adaptation of mine infrastructure to climate change involves addressing design features of new mines and remedial work at existing and post-operation mines to ensure structural integrity. Considering climate change in the design phase of mines is commonly part of the Canadian environmental assessment process, and resources such as the Environmental Code of Practice for Metal Mines (Environment Canada, 2009) are available to help mining operations plan for climate change (Prowse et al., 2009). For example, the report suggests that surface drainage facilities should be designed to handle peak conditions at least equivalent to a once in 100-year flood event in order to account for projected increases in extreme weather events due to climate change (Environment Canada, 2009). The Canadian Standards Association has also developed a technical guide for building infrastructure on permafrost (Auld et al., 2010). This guide pertains to new infrastructure projects and addresses how to estimate and account for the potential effects of future climate on permafrost and on foundations at sites where permafrost may be present.

A number of engineering and management techniques are being employed to protect infrastructure from the impacts of permafrost warming, including the use of deeper pile foundations, thicker gravel pads (insulation of the surface), adjustable foundations, artificial cooling, thermosyphons (to remove warm air from the ground around foundations and promote cooler ground temperatures), clearance of snow around foundations (to promote colder winter ground temperatures) and use of more resilient tailings cover designs (cover thickness, use of geosynthetics) (Pearce et al., 2009; Prowse et al., 2009). Monitoring the performance of these adaptive responses and adjusting accordingly helps ensure durability and effectiveness.

Mines have a lifespan long after operations cease and structures left onsite after closure will need to withstand future changes in climate. It is likely that infrastructure that has already been abandoned, including tailings ponds and waste rock stacks, have not been designed for the full range of changing climatic conditions, and if left unaddressed some of these sites could pose serious risks to the environment and the health of surrounding communities (Pearce et al., 2011).

### TRANSPORTATION INFRASTRUCTURE

Mining operations that depend on climate-sensitive transportation infrastructure, such as winter roads and marine and freshwater transport, are especially susceptible to the warming trends documented across Canada, particularly in the north (Furgal and Prowse, 2008; Prowse et al., 2009). Warmer winters have rendered seasonal ice roads in the Northwest Territories less reliable than in the past (Prowse et al., 2009; Stratos, 2009; Pearce et al., 2011; *see also* Chapter 8 – Water and Transportation Infrastructure). The Tibbitt to Contwoyto Winter Road located north and east of Yellowknife (Northwest Territories) is the longest winter road in Canada at 600 km long, with more than 80% (495 km) located on frozen lakes. It is the main supply road for the Ekati, Diavik, Jericho and Snap Lake diamond mines, the Lupin gold mine (currently inactive) and several other mineral exploration projects (Prowse et al., 2009). In recent years the winter road has experienced shortened operating seasons as well as reduced ice thickness, which constrains the load volumes that can be safely transported (Prowse et al., 2009). The financial costs of a shortened ice-road season are significant. For example, in 2006 the road was open for only 42 days (compared to about 70 days of operation the previous season), requiring the Diavik diamond mine to spend an extra $11.25 million to fly in 15 million liters of fuel (Pearce et al., 2011).

Adaptive responses developed by road operators include the purchase of new, lighter-weight and amphibious machinery to facilitate road construction earlier in the season. In addition, alternative road routings have been developed and operational efficiencies have been achieved through measures such as concentrating truck shipping into the portion of winter when ice is thickest (Pearce et al., 2009). Alternatives to the ice road are also being explored, including construction of a seasonal overland route to the diamond mines, and the proposed Bathurst Inlet Port and Road Project which would link mine sites in Northwest Territories and Nunavut to the northern mainland coast.

Mining companies view changing climatic conditions as an opportunity with regards to changes in sea ice and marine shipping. Increased duration of the summer shipping season and opening of new Arctic shipping routes may enhance the economic viability of some northern mine developments. For example, continued warming is expected to lead to further opening of the Northwest Passage, resulting in longer or eventually year-round shipping seasons (Leong et al., 2005; Prowse et al., 2009). However, in the near term, ice hazards will remain high due to the more rapid drift of multiyear ice through the Arctic Archipelago (Prowse et al., 2009; *see also* Chapter 2). Non-climatic factors such as insurance costs, reduced shipping speeds and lack of supporting infrastructure, may also limit the use of the Northwest Passage for marine shipping. More specific issues related to transportation are likely to be identified as specific sites are developed (*see* Case Study 4).

### CASE STUDY 4
## VOISEY'S BAY NICKEL-COPPER-COBALT MINE, NUNATSIAVUT

The Voisey's Bay Nickel-Copper-Cobalt Mine, owned and operated by Vale, is located roughly 35 km southwest of the community of Nain on the northern coast of Labrador. It is a remote, sub-arctic location on land subject to Aboriginal land claims by the Innu and Inuit of Nunatsiavut. The main ore body of the project contains nickel, copper and cobalt, and is recognized as one of the largest nickel deposits in the world. The mine ships mining concentrate to its processing facilities in Long Harbour, Newfoundland during the ice-free open water season and also through sea ice between January and March (Vale, 2013).

During the environmental impact assessment (EIA) of the mine, the Labrador Inuit Association and the Innu Nation raised concerns over the mine shipping through landfast ice, and the potential for disruption to people travelling over the ice to other communities or to hunting grounds. Agreements were reached with these groups to help address these issues by not shipping during the initial freeze-up period or during the seal-hunting period in the early spring (April and May). The mine also allows the initial ice to become 20 cm thick before beginning icebreaking, in order to avoid disturbing travel routes on the sea ice used by local people and wildlife (Bell et al., 2008).

When the EIA of the Voisey's Bay mine was conducted in 1997, the climate models used projected minimal changes in climate over the approximately 25-year lifespan of the mine. The environmental impact statement acknowledged that changes to ice and sea conditions could occur over the mine's lifespan, but that these changes were difficult to predict (Bell et al., 2008). Over the last decade, global sea ice cover has declined at rates far exceeding climate model projections (Stroeve et al., 2012). Although reduced sea ice cover and associated later freeze-up and earlier break-up dates may be beneficial for some marine shipping operations, this could negatively affect the Voisey's Bay mine with regards to its agreement with local communities to maintain access to sea-ice routes and traditional hunting grounds. If sea ice continues to take longer to freeze up and achieve thicknesses suitable for icebreaking as per the agreement with the Inuit and Innu, mine shipping may be stalled during winter months (Pearce et al., 2009).

Vale recognizes the issue of climate change and the need to reduce greenhouse gas emissions, but the Voisey's Bay mine does not currently have a proactive plan for adapting to likely future climatic changes, including changing sea ice dynamics (CVRD Inco, 2006). The mine undertakes adaptive management practices by conducting monitoring, observation and risk assessment to track the implications of sea ice changes on the coastal and social activities of local Aboriginal people, and plans to respond when documented climatic changes begin to have a discernible impact on company operations (CVRD Inco, 2006). This approach to adaptation appears typical of the strategies employed by most mining operations in Canada to deal with changing climatic conditions, and has sometimes resulted in financial costs to companies, environmental damage or both, as described previously. A challenge in planning for adaptation is determining the correct balance between collecting new data to better understand the likely negative future impacts of changing climatic conditions and achieving the best short-term outcome based on current knowledge (Allan and Stankey, 2009).

### EXTRACTION AND PROCESSING

Climate conditions also impact the extraction and processing of some minerals. Dust emissions and associated dust control regulations are of particular concern for sand, gravel, limestone and dolomite mines. Warm, dry conditions exacerbate dust emissions, requiring mine operators to employ dust control measures, such as water spraying and covered storage areas. Increased precipitation associated with climate change in some areas could be beneficial to these mining operations in that it helps to control dust emissions. Conversely, too much precipitation impedes the drying of the mined materials, which subsequently requires more energy, resulting in higher costs (Pearce et al., 2009; Case Study 5).

### DAILY OPERATIONS

Daily operations at mine sites are sensitive to extreme weather conditions, including intense rain and snowfall, flooding, drought, changing ice conditions, extreme cold and forest fires, all of which can reduce operational capacity (Pearce et al., 2009; NRTEE, 2012a). Mining operations are often located in remote areas with limited services and access infrastructure, which are also climate sensitive. For example, in May 2012 several gold mining operations located near Timmins, Ontario halted operations due to forest fires which caused power outages, blocked highway access to the mines, and threatened the mine sites themselves (CBC, 2012). Mine operations located in mountainous terrain in British Columbia are sensitive to rainfall-initiated mud and debris flows, and transportation routes are at risk of washout, particularly if heavy rainfall occurs during spring melt. Freezing rain, flooding, and extreme cold and storms have interrupted production at mine operations in central Canada, and changes in the frequency and intensity of these conditions are projected to continue in the future with implications for mine operations (Pearce et al., 2009).

## 4.2 STATUS OF ADAPTATION IN THE CANADIAN MINING INDUSTRY

The attention given to climate change adaptation – long-term planning that considers present and projected climate change impacts – varies considerably within the mining

CASE STUDY 5

### SODIUM SULPHATE MINING, CHAPLIN, SASKATCHEWAN

Sodium sulphate is mined and sold for use in powdered laundry detergents, glass making, textiles, modified corn starches, carpet deodorants, kraft pulp mills and mineral feeds for livestock. In ideal climate conditions, sodium sulphate mining utilizes heat from the sun to evaporate water from a solution of sodium compounds until the compounds precipitate out and can be gathered from reservoir bottoms. This process requires sufficient water supply in spring, hot dry summers to optimize brine strength and cold winters to facilitate the collection of sodium sulphate from reservoir floors. Under these ideal conditions, energy inputs to the system are minimal, reducing production costs and increasing the competitiveness of the mine. Variable climate conditions pose several operational challenges. For example, too much summer precipitation can necessitate the use of pumps to remove excess water, increasing production costs. Warmer winters, in which freezing of ground beneath the reservoir is delayed, limit the operation of heavy equipment and increase the cost of recovering the sodium sulphate.

The Saskatchewan Mining and Minerals Inc. mine at Chaplin, Saskatchewan is an example of a small sodium sulphate mine. Its success is related to favourable temperature, precipitation and runoff conditions, and to access to Chaplin Lake, an 18 km$^2$ saline lake (Figure 5).

The primary sources of water for the Chaplin mine are local precipitation and spring runoff. Access to a secondary source of water has been developed to aid in times of water shortages; water can be diverted from the Wood River to the Chaplin Creek and then used by the mine in Chaplin Lake. This delivery system is managed in partnership with Ducks Unlimited Canada and also benefits local waterfowl. In addition, the mine has built water storage areas that can be used during dry years. Water use efficiencies have also increased over the last twenty years through the development of small dikes throughout Chaplin Lake, which divide it into smaller sections and increase the control that mine operators have over water levels, allowing them to optimize brine concentrations during extraction. The sections allow operators to add water only where it is needed, improving water-use efficiency. In times of excess moisture, pumps can be used to remove surplus water and control brining concentrations. These techniques allow the mine to enhance its brining and recovery processes under variable and changing climate conditions.

**FIGURE 5:** Chaplin sodium sulphate mine site, southwest Saskatchewan *(Photo courtesy of Saskatchewan Mining and Minerals Inc)*.

sector. The apparent lack of proactive adaptation planning for climate change in the mining sector suggests that some mine stakeholders view it as a minor concern in relation to immediate issues, such as meeting regulatory and human resource requirements, and managing fluctuating market conditions (Ford et al., 2011). In some instances, limited understanding and knowledge of current and projected future climate change among mine decision makers may be constraining adaptation planning. Additionally, climate change is sometimes viewed as something that may occur beyond the operational lifespan of the mine, and therefore is of limited immediate importance (Ford et al., 2010).

Environmental impact assessment is one mechanism that has served to increase awareness of climate change impacts and adaptations in the mining sector as companies move from advanced exploration into production. These assessments often use climate scenarios to identify potential impacts on mine site infrastructure and the surrounding environment. Monitoring and adaptation strategies are then identified. However, the extent to which mining projects implement adaptation strategies and make operational adjustments remains limited (Bell et al., 2008).

Actions such as strengthening or redesigning infrastructure can be costly and are sometimes deemed unnecessary by mine operators due to the short operating lives of many mines. Furthermore, uncertainty about future climate change projections is considered a barrier in making investment decisions regarding adaptation (Ford et al., 2010). Nonetheless, advances have been made, and some mine designers have included climate change parameters into their plans (Ford et al., 2011). Proactive adaptation planning, however, takes place in a select few mining operations, primarily those located in the North (Ford et al., 2011).

A number of factors shape the ability of mining operations to adapt to a changing climate. These include climate change information, regulations, and access to engineering solutions.

*Climate change information* – Decision makers responsible for designing, building, maintaining and decommissioning mining infrastructure need improved understanding of the likely impacts of future climate changes at mine sites, and how engineering techniques can be adopted to manage these changes. There are concerns that available climate scenarios are not sufficiently refined to inform decision making. Needs include ensuring climate information is available in a format that is readily usable by mine developers and operators, as well as guidance for interpreting a range of climate change scenarios and factoring them into infrastructure and closure design (Ford et al., 2011).

*Regulations* – Adaptation planning in the mining sector has been largely voluntary. Despite recent attention to climate change as part of the environmental assessment process for many mine developments, there are no widespread requirements to consider climate change in mine planning or in mine closure plans. Regulations, developed in consultation with mine proponents, could be utilized to help ensure that available knowledge of current and expected future climate change is integrated into mine planning (NRTEE, 2012a).

*Engineering solutions* – In many instances the technologies and engineering strategies necessary for adapting mining operations to address changing climate conditions already exist. For example, in operations where maintaining frozen conditions is necessary, thermosyphon technology is commonly employed (Pearce et al., 2011). Similarly, tailings covers can be modified to ensure below-ground materials stay frozen, and ground-based transportation networks can be built in ways to minimize disturbance to the frozen soil layers below. In other cases, holding ponds, berms and other containment infrastructure can be strengthened to withstand more frequent extreme precipitation during the life of the mine and beyond. Engineering solutions that could reduce the negative impacts of climate change on mine operations exist, however, they are not always cost-effective and there are limited financial or regulatory incentives to encourage their uptake.

# 5. ENERGY

Canada's abundant and diverse energy resources are integral to the country's economy. Canada has the world's third largest proven reserves of crude oil, the fourth largest proven reserves of uranium, and is the second largest producer of uranium. In addition, Canada is the world's third largest producer of hydroelectricity, the fifth largest producer of both oil and natural gas, and the second largest net exporter of uranium (Natural Resources Canada, 2013b). In 2012, the energy sector contributed approximately $155 billion, or 9%, to Canada's GDP. Energy exports in 2012, 90% of which went to the United States, comprised more than 27% of Canada's total exports (Natural Resources Canada, 2013b). Canada's primary energy production is dominated by crude oil and natural gas (Figure 6). Alberta is by far the largest producer of primary energy in Canada (Figure 7).

Many aspects of energy supply, transmission and demand are sensitive to climate variability and will be impacted by various dimensions of climate change, including higher temperatures, changing frequency and intensity of extreme events and changes in water availability (Figure 8). However, with the exception of the hydroelectricity subsector, adaptation to climate change in the energy sector has received much less attention by industry and researchers than have issues of greenhouse gas mitigation (Wilbanks et al., 2007; ICF Marbek, 2012).

## 5.1 ENERGY DEMAND

Long-term trends in energy demand are influenced primarily by changes in population, economic activity, energy prices and energy efficiency (IEA, 2011a; Natural Resources Canada, 2011b). In Canada and worldwide, climate change will mean reduced energy demand for winter heating and increased demand for summer cooling (where other factors are held constant, e.g. Zmeureanu and Renaud, 2008; Isaac and van Vuuren, 2009; Schaeffer et al., 2012). The net annual result of climate change-induced shifts in energy demand will be country and region specific (Schaeffer et al., 2012).

The reduced demand for heating will primarily impact fuels such as natural gas and heating oil, while the increased demand for cooling will increase electricity consumption (the main energy source for space cooling; Wilbanks et al., 2007). This impact will be felt mainly in the residential and commercial sectors (Mideksa and Kallbekken, 2010). Capacity to meet the higher summer peak load associated with climate change-related shifts in energy demand is a significant challenge for the energy sector (ICF Marbek, 2012), and could require significant investments in new generating capacity (Mills, 2007).

Ontario is the only province where the current annual peak load occurs in summer (NERC, 2012). While recent studies continue to show the sensitivity of electricity demand in Ontario to climate variability and change, as well as a trend toward more frequent extreme heat days in several cities (*see* Chapter 7 – Human Health), the magnitude of impacts on energy demand may not be high (e.g. Lin et al., 2011). Furthermore, peak load in Ontario has declined substantially after reaching record levels in 2004-2006 (IESO, 2009), suggesting that the province may be less vulnerable to changes in annual peak load than previously thought. While Ontario's electricity system is believed to have a sufficient reserve margin to remain reliable under unexpected stress, including severe weather (NERC, 2012), the Environmental Commissioner of Ontario (ECO, 2012) has called for an in-depth assessment of the matter to ensure that the grid remains reliable in a changing climate.

The potential influence of climate change on electricity trade between Canada and the United States is recognized (e.g. Scott and Huang, 2007; Hamlet et al., 2009; Ouranos, 2010), but quantitative analyses are lacking. Summer electricity demand in the US is projected to increase as a result of climate change, but it is unclear whether Canadian utilities will be able to respond to this export opportunity since they will also be facing a higher domestic demand in the summer (Scott and Huang, 2007).

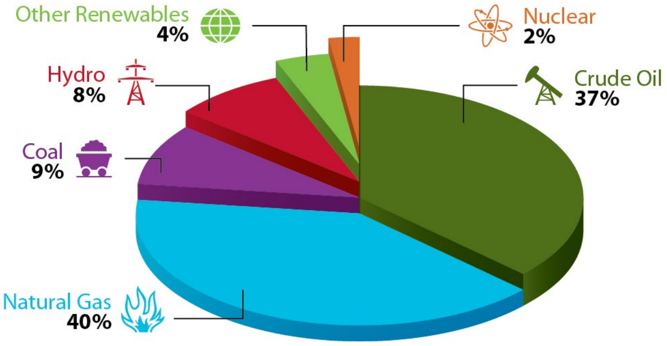


**FIGURE 6:** Canada's primary energy production. All numbers refer to 2010 production *(Source: Natural Resources Canada, 2012e)*.

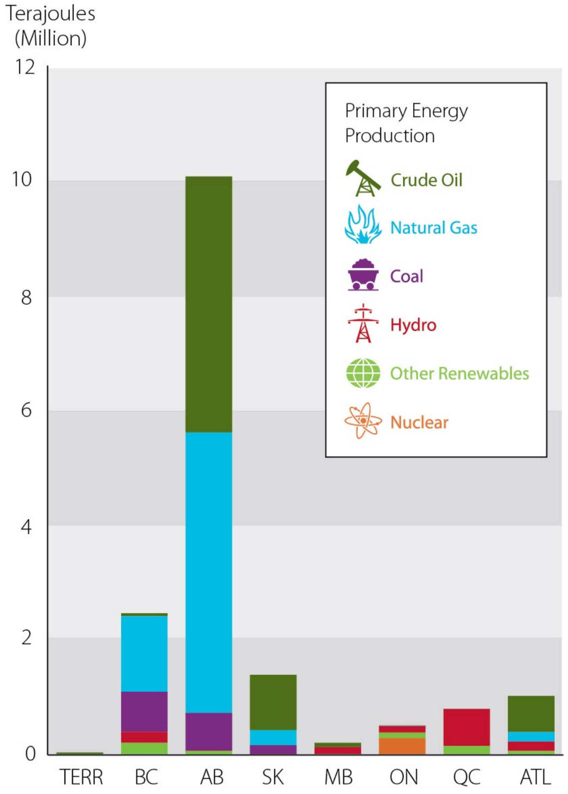


**FIGURE 7:** Primary energy production by province (note that the Northwest Territories are combined, as are the four Atlantic provinces; *data from Natural Resources Canada, 2012e*).

BOX 2

## KEY DEFINITIONS OF ENERGY TERMINOLOGY

**Energy sector –** industries involved in the production, transformation and transportation of energy (Natural Resources Canada, 2012e).

**Energy source –** any substance that supplies heat or power (modified from Natural Resources Canada, 2011b).

**Renewable energy –** energy obtained from natural resources that can be naturally replenished or renewed within a human lifespan (Natural Resources Canada, 2012f).

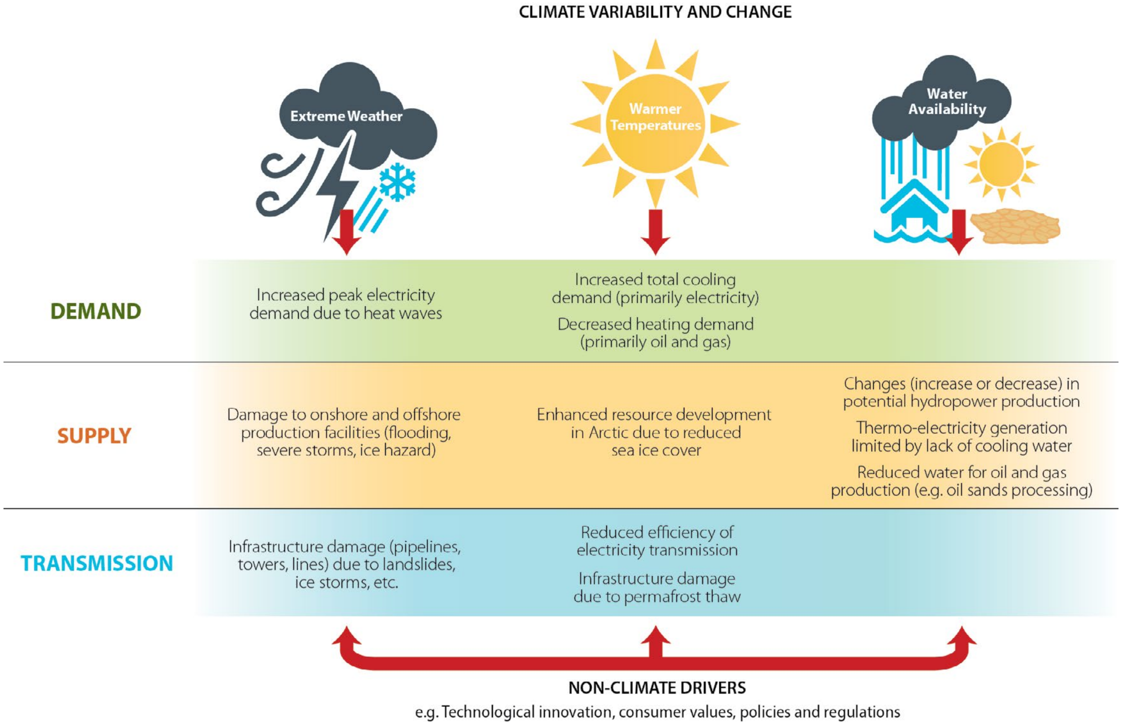
**Non-renewable energy –** energy generated from finite resources, the stocks of which could deplete or become too costly or challenging to access. This includes oil and petroleum products, natural gas, coal and uranium (modified from Natural Resources Canada, 2012g).

**Primary energy –** energy that has not yet been transformed (modified from OECD, 2012).

**Secondary energy –** energy generated by conversion of primary energies, e.g. electricity from gas, nuclear energy, coal, oil, fuel oil, and gasoline from mineral oil.

**Primary energy production –** all primary energy that is produced in a country, including energy that will be exported (modified from Natural Resources Canada, 2011b).

**Peak load –** the maximum load consumed or produced by an electricity-generating unit or group of units over a measure of time (daily, monthly or yearly). As electricity generally cannot be stored, some generating capacity must exist exclusively for meeting periods of peak demand (modified from National Energy Board, 2004).



| | Extreme Weather | Warmer Temperatures | Water Availability |
|---|---|---|---|
| **DEMAND** | Increased peak electricity demand due to heat waves | Increased total cooling demand (primarily electricity)<br>Decreased heating demand (primarily oil and gas) | |
| **SUPPLY** | Damage to onshore and offshore production facilities (flooding, severe storms, ice hazard) | Enhanced resource development in Arctic due to reduced sea ice cover | Changes (increase or decrease) in potential hydropower production<br>Thermo-electricity generation limited by lack of cooling water<br>Reduced water for oil and gas production (e.g. oil sands processing) |
| **TRANSMISSION** | Infrastructure damage (pipelines, towers, lines) due to landslides, ice storms, etc. | Reduced efficiency of electricity transmission<br>Infrastructure damage due to permafrost thaw | |

**FIGURE 8:** Key climate change impacts in the energy sector, recognizing the importance of non-climate drivers in determining adaptation actions.

### ADAPTATION

Measures to reduce future electricity consumption include programs and standards that promote energy efficiency in buildings, appliances and equipment (Geller et al., 2006), and energy conservation practices such as user-controlled shading, enhanced natural ventilation, or accepting higher indoor temperatures in the summer (Levine et al., 2007; Gupta and Gregg, 2012). Projected increases in the use and market penetration of air conditioning units with climate change suggests that improving the efficiency of these units will be particularly valuable (Scott et al., 2008). Smart grid technologies, which facilitate enhanced coordination of electricity networks to respond to changing supply and demand, may also be an important adaptation measure as they maximize system reliability and stability (Newsham et al., 2011; Lilley et al., 2012). A high level of deployment of smart grid technologies has the potential to keep peak load in North America at today's level until 2050 (IEA, 2011b). Urban design measures that reduce heat island effects can also help to reduce electricity demand for cooling (Smith and Levermore, 2008; Xu et al., 2012). All of these measures provide adaptive benefits and many contribute to, or may be triggered by, other policy goals, such as economic competitiveness, energy security and health and well-being (e.g. Levine et al., 2007; Sathaye et al., 2007; Ürge-Vorsatz and Tirado Herrero, 2012).

## 5.2 ENERGY SOURCES

Canada's energy supply includes both renewable and non-renewable sources. Most renewable energy sources (e.g. hydroelectricity, wind, solar, and biomass) are inherently sensitive to climate variability and change, whereas non-renewable sources (e.g. oil, natural gas, uranium and coal) are intrinsically less sensitive. However, energy supply derived from all sources is affected by changing climate when the full process from exploration to development and distribution is considered. Increasing the diversity of energy sources, by using varied types of renewable and non-renewable energy sources, as well as multiple sources of the same type of energy, can increase the climate resilience of energy supply.

### 5.2.1 RENEWABLE ENERGY

Renewable energy sources provide about 12% of Canada's total primary energy supply, with hydroelectricity being by far the most significant renewable energy source (Natural Resources Canada, 2012e).

### HYDROELECTRICITY

Hydroelectricity currently accounts for 59% of Canada's electricity generation (Statistics Canada, 2013). More than 90% of total electricity production in Quebec, British Columbia, Manitoba and Newfoundland and Labrador comes from hydro. Ontario, Alberta and New Brunswick also produce significant quantities of hydroelectricity, while the Yukon and Northwest Territories rely on hydro to help meet local energy demand. The majority of Canada's hydro production comes from large reservoir systems (Figure 9), with additional capacity provided by small run-of-river power stations. Transboundary electricity markets, both inter-provincial and international (United States) are large. The availability of abundant sources of hydro power allows Canada to support industries reliant on high energy consumption, such as aluminum smelters (*see* Case Study 6).

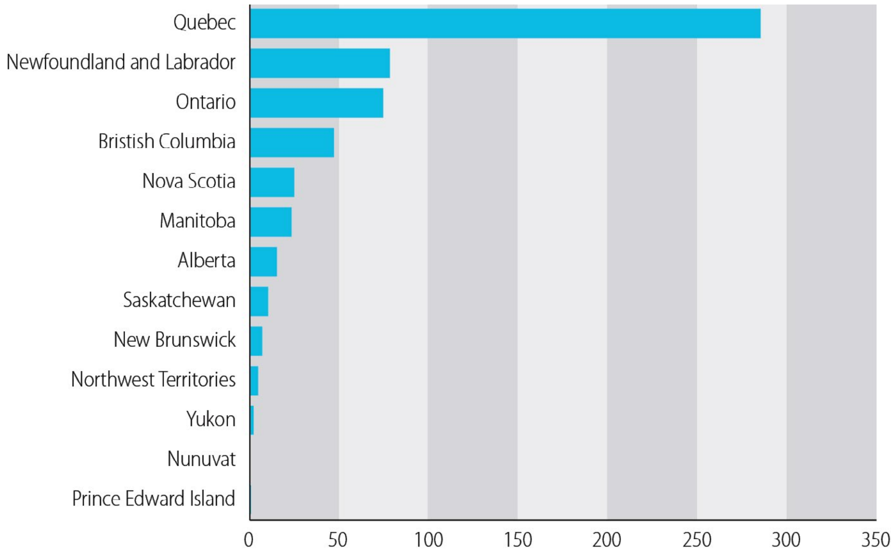


**FIGURE 9:** Large (higher than 15 m) dams associated with hydropower reservoirs in Canada *(Source: Global Forest Watch, 2012)*.

To date, most Canadian research relating to climate change and hydroelectricity has focused on the hydrological consequences of a changing climate, such as shifts in the timing and magnitude of river flows. Climate projections and hydrological modeling indicate a likely decrease in summer flows, an increase in winter flows, a decrease in spring water levels, and changes in the timing of peak flows for most Canadian watersheds, due in large part to increased frequency of winter rain and reduced snowfall amounts (e.g. Fortin et al., 2007; Boyer et al., 2010; Rodenhuis et al., 2011; Kienzle et al., 2012). The magnitude of projected changes varies significantly between regions and within drainage basins. In some regions, such as northern Quebec, increasing mean annual runoff (Figure 10) could present opportunities for established hydro generation facilities. However, greater hydrologic variability linked to climate change will likely increase the risk of overflows (non-productive discharge), particularly during winter and spring melt, with greatest impacts on run-of-river power plants (e.g. Minville et al., 2010b).

Important differences will occur within individual drainage basins where significant hydroelectric generation occurs (*see* Table 4). Even where increases in annual average precipitation are projected, increased evaporation and evapotranspiration may lead to lower water levels and negatively impact hydropower generation (e.g. Buttle et al., 2004). Increased winter rainfall could cause difficulties in basins where reservoir storage capacity is limited (e.g. Fortin et al., 2007; Shrestha et al., 2012). Rivers fed by glaciers will also see regime changes affecting late summer and fall flows. For example, glacier extent in the Columbia River basin of British Columbia is projected to be reduced by 40% by 2060 (Jost et al., 2012). In northern Canada, integration of permafrost and hydrological modeling is needed to enhance understanding of the potential impacts for hydroelectricity generation in this region (Goulding, 2011).

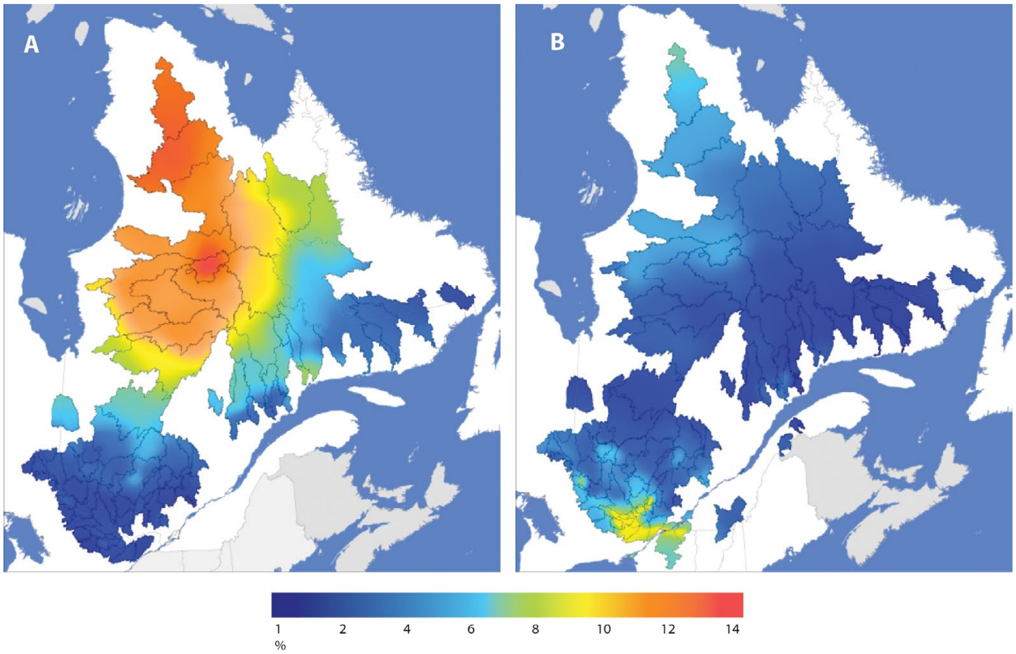


**FIGURE 10:** **a)** Average increase in annual runoff in Quebec watersheds between 2040-2070 relative to 1961-1990. **b)** Standard deviation for change in runoff. Average increase is statistically significant when it surpasses uncertainty associated with projections, represented by standard deviation *(from Desrochers et al., 2009)*.

| Province | River basin | Significance | Methodology - observations / models / assumptions | Climate trends and projections | Key references |
|---|---|---|---|---|---|
| British Columbia | Upper Columbia | • 12 hydro facilities in total<br>• Mica and Revelstoke dams produce 25% of BC hydro requirement | • Baseline period 1961-1990<br>• Future period 2041-2070<br>• Scenarios: A1B, A2, B1<br>• 8 Global Climate models | • General increase in flows except for end of summer and fall<br>• Peak flows one month earlier (June rather than July) | Zweirs et al. (2011); Shrestha et al. (2011) |
| British Columbia | Upper Peace | • 2 facilities<br>• G.M. Shrum (WAC Bennett Dam) and Peace Canyon produce 29% of BC hydro requirement |  | • Increase in annual flow up to 12%, greatest increase in winter<br>• Decreased flows end of summer and fall<br>• Spring floods not significantly earlier | Zweirs et al. (2011); Shrestha et al. (2011) |
| British Columbia | Fraser | • Home to 63% of BC population<br>• Two tributaries important for hydro generation, several smaller facilities |  | • Increase total annual flow<br>• Decrease annual maximum flow<br>• Earlier spring floods | Shrestha et al. (2012) |
| British Columbia | Campbell | • Strathcona dam – largest facility on Vancouver Island |  | • Average flow unchanged<br>• Increase in winter flow, reduction in spring and summer flows | Shrestha et al. (2012) |
| Alberta | Cline | • Tributary that generates 40% of North Saskatchewan River flows<br>• Upstream of Bighorn Dam, TransAlta's highest performing hydro plant | • Baseline period 1961-1990<br>• Future periods 2010-2039, 2040-2069 and 2070-2099.<br>• Scenarios: A1B, A2, B1<br>• 5 Global Climate models | • Decreased annual flows – 25% by 2020, 30% by 2080<br>• Peak flows to occur one month earlier by 2050 | Zweirs et al. (2011) |
| Manitoba | Winnipeg | • Directly or indirectly influences the production of 4600 MW | • Streamflow observation period 1924-2003<br>• 9 gauging stations | • Historic trend (80 years) of increased summer and fall flows | Kienzle et al. (2012) |
| Ontario | Nipigon, Abitibi, Mattagami | • Identified as priority basins by Ontario Power Generation | • Baseline period 1961-1990<br>• Future period 2041-2070<br>• 24 Regional Climate Models<br>• 4 Global Climate Models<br>• Scenarios A2 and A1B | • Historic trend (80 years) of increased summer and fall flows | St. George (2007) |
| Quebec | North of 49° N | • Region contains most of Quebec's large hydroelectric generation facilities | • Baseline period 1961-1990<br>• Future period 2041-2070<br>• 2 Regional Climate Model | • Historic trend (80 years) of increased summer and fall flows | Music and Sykes (2011) |

**TABLE 4:** Findings of recent studies concerning hydrologic impacts on river basins of importance for hydroelectricity generation in Canada.

Although many of the studies summarized in Table 4 conclude that there will be no change or an increase in total annual flow, the need for hydropower operations to adapt to climate change is crucial (*see* Case Study 6). While increased flow could be beneficial, it may also lead to flooding if reservoirs are not managed properly. Most importantly, projected climate impacts almost always involve major changes in the distribution of flow throughout the year, which presents challenges to most current dams and reservoir management. For instance, reservoirs are currently kept very low during winter in order to store melt water in spring. With increasing winter flows and earlier and lower spring flows, a new strategy could involve storing water throughout the winter as well, to help offset the impacts of lower summer flows.

Recent research has expanded beyond hydrologic analysis to multi-criteria analysis, which involves consideration of economic, political, social and environmental aspects to analyze potential adaptation measures and associated costs and benefits (Webster et al., 2008). A few published studies (e.g. Raje and Mujumdar, 2010; Soito and Freitas, 2011; Georgakakos et al., 2012) have examined how adaptation strategies for the hydropower industry can integrate perspectives of multiple water users and changing resource demands. Adaptive management is a powerful tool in addressing water-related conflicts and can both provide a more robust performance than traditional management approaches, and significantly reduce negative impacts resulting from climate change (Georgakakos et al., 2012). Adaptive management can include risk analysis and re-optimizing of regulations for reservoir operation to account for variability and uncertainty of hydrologic input forecasts (Georgakakos et al., 2012; *see* Case Study 6).

Adaptation measures related to hydro power can involve structural and non-structural approaches. Structural approaches refer to physical modifications of infrastructure and assets to reduce their climate vulnerability, whereas non-structural (or soft) approaches involve modifications to the way energy systems operate. Examples of structural measures include expanding the capacity of existing hydro power plants and revising design criteria for new facilities. Increasing the current capacity of power plants should help reduce non-productive discharge. However, this approach can be costly to implement or even technically impossible for existing power plants that were not designed for capacity expansion. Construction and maintenance costs, as well as the benefits resulting from increased hydroelectric generation, are considerations in assessing the value of applying structural approaches (Webster et al., 2008; Beauchamp, 2010).

Examples of non-structural approaches include use of resource management to adjust to hydrologic changes, as well as to policy or regulatory reforms. Ongoing studies suggest that taking into account the seasonal variability of flows and the uncertainty of future hydrological projections should lead to management approaches capable of increasing hydroelectric generation (Haguma, 2012). For example, Côté et al. (2011) showed that using a variety of climate scenarios allowed for better efficiency in power plants compared to classic methods that only rely on current climate (and which are usually recommended and used for establishing management regulations for hydroelectric systems). Non-structural adaptation also includes the protection or restoration of natural flow regulators such as wetlands to provide buffering capacity during times of low and peak flows (e.g. Jones et al., 2012).

#### OTHER RENEWABLE SOURCES

Together, non-hydro (alternative) renewable energy sources contribute about 4% of Canada's primary energy production. Wood and wood waste are the main source, with smaller contributions from biogasoline, wind, municipal waste and landfill gas, industrial and other waste, and solar and tidal sources. Few Canadian studies have examined the impacts of a changing climate on these energy sources (*see* Yao et al. (2012) for analysis of projected climate changes on wind power generation in Ontario).

Research outside of Canada has tended to focus on the impact of extreme weather, including wind and precipitation, on alternative renewable energy production (Wilbanks et al., 2007; Ebinger and Vergara, 2011; McColl et al., 2012). For example, where increased wind speeds exceed the maximum design value for turbines, equipment could be damaged or shut down, resulting in reduced effective generating capacity (Ebinger and Vergara, 2011; McColl et al., 2012). An increase in average air temperatures beyond certain thresholds negatively affects wind (decreased air density) and solar production (decreased efficiency of panels) (Ebinger and Vergara, 2011), but the magnitude of these impacts is unclear. Changes in cloud cover and wind regimes also affect solar and wind energy production, either negatively or positively, depending on the direction of change. Assessing the impacts of climate change on wind, solar and biomass energy production in Canada requires further research.

### 5.2.2 NON-RENEWABLE ENERGY

#### OIL AND GAS

The oil and gas industry operates across Canada. The remote nature of much of the sector's activity, including sites in the far north and offshore, presents challenges for the sector value chain. Canadian literature on climate impacts in this sector emphasizes risks to, and opportunities for, upstream activities (e.g. exploration, extraction and production), with

### CASE STUDY 6

## ADDRESSING CLIMATE CHANGE IMPACTS THROUGH ADAPTIVE MANAGEMENT: HYDROPOWER PRODUCTION IN THE PERIBONKA RIVER BASIN

Minville et al. (2008, 2009, 2010b and 2012) have undertaken extensive analysis of hydroelectricity generation along the Peribonka River, in south-central Quebec. The watershed is 27 000 km$^2$ and runoff is snowmelt dominated; spring melt produces 43% of the annual runoff volume. The existing hydro facilities include two large reservoirs (Lake Manouane and Passes Dangereuses) that store water and feed three hydropower generating stations (Figure 11). The electricity generated is used to meet the energy requirements of Rio Tinto Alcan's aluminum smelters.

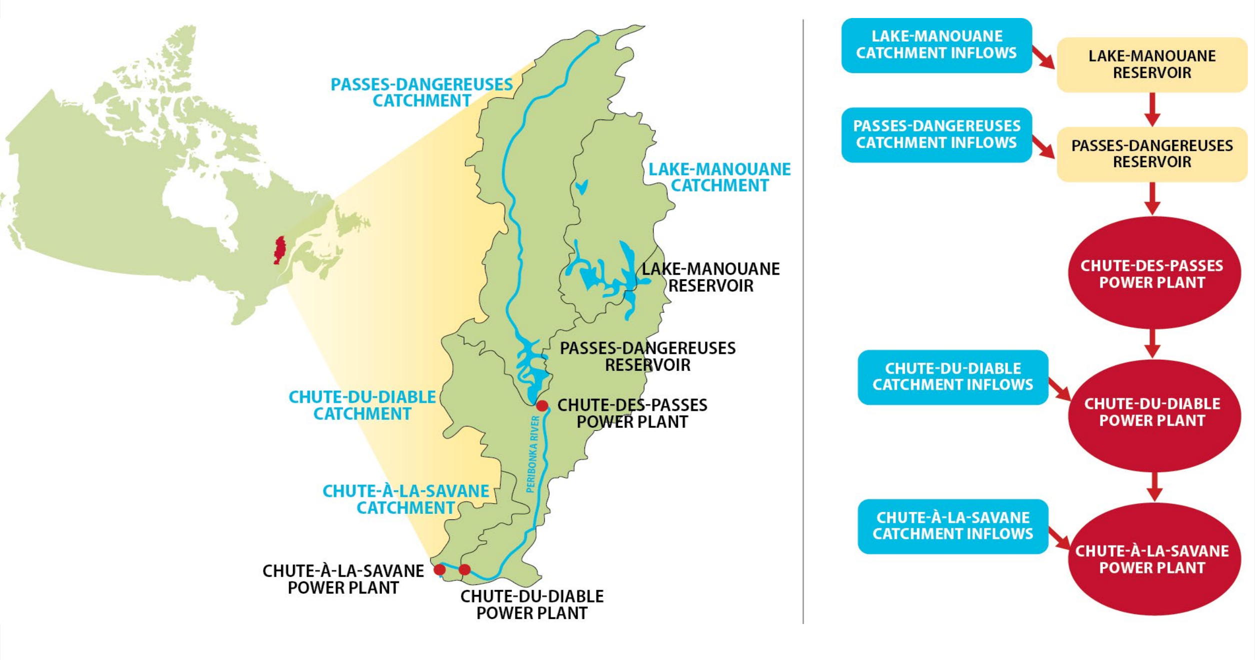


**FIGURE 11:** The Peribonka River watershed and hydrological system *(Source: Minville et al., 2010a)*.

The impact of climate change on the hydrology of the Peribonka River watershed was investigated by developing temperature and precipitation projections from combinations of five global climate models and three emission scenarios downscaled to the watershed level, as well as from the Canadian Regional Climate Model (CRCM; Caya and Laprise, 1999), to simulate hydrologic regimes under current and projected climates. Results indicate earlier spring floods, increased winter flows and reduced flows during summer and fall as a result of a changing climate. These shifts are accentuated over time and vary between northern and southern sub-basins (Figure 12). Uncertainty in these projections largely relates to changes in the snowpack and is, correspondingly, of most significance during winter and spring flooding.

Analysis also involved developing optimal management policies for the system reservoirs by simulating and assessing system performance under current and projected future climate conditions. Modelling results show higher spring water levels at Lake Manouane for all future periods relative to the baseline period (Figure 13). Summer water levels at Manouane tend to decrease by 2070-2099 as a result of reduced inflow and the need to maintain the Passes-Dangereuses reservoir at its highest level to maximize the hydroelectric generation. The behaviour of the Passes-Dangereuses reservoir is similar to that of Lake Manouane, except that the shift in the reservoir lowering period is more pronounced as a result of earlier spring flooding.

*Case Study 6 continued on next page*

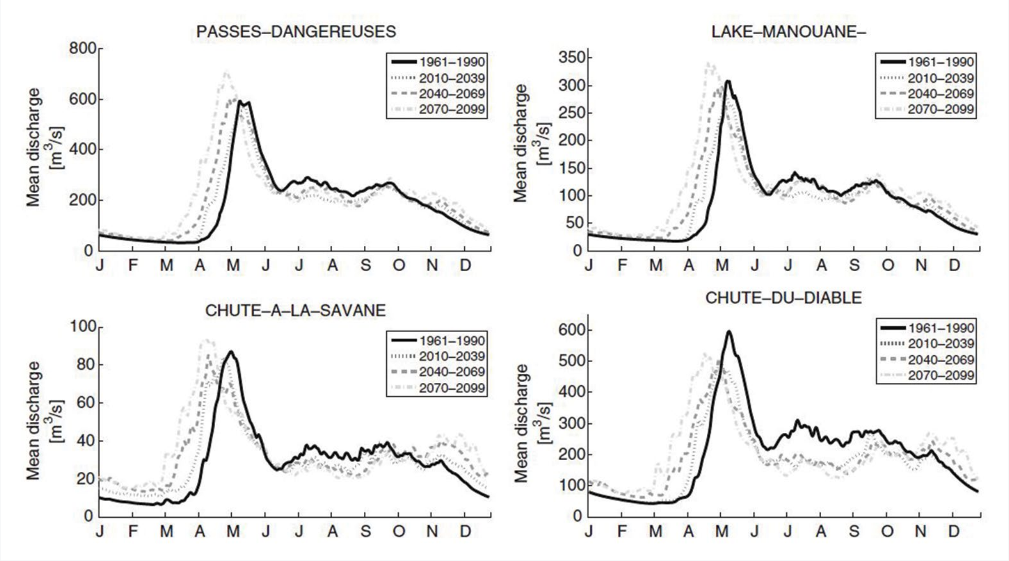


**FIGURE 12:** Average annual hydrographs for the Peribonka River sub-basins for the future periods 2010-2039, 2040-2069 and 2070-2099, compared to the 1961-1990 baseline, simulated using CRCM projections with SRES A2 (*from Minville et al., 2009*).

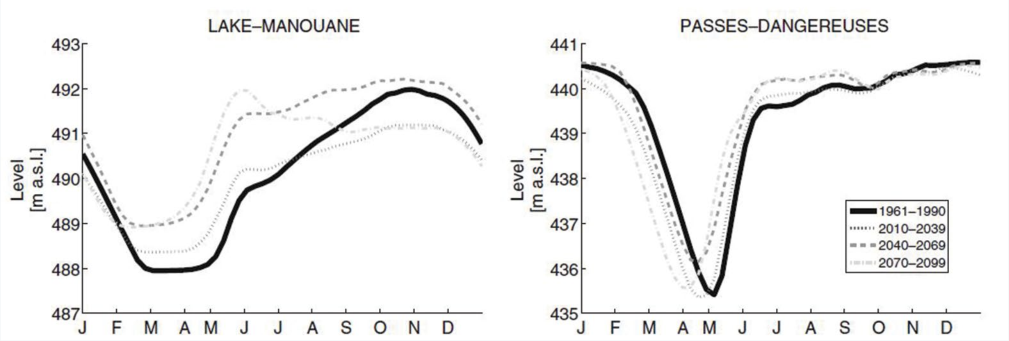


**FIGURE 13:** Reservoir water level for the future periods 2010-2039, 2040-2069 and 2070-2099, compared to the 1961-1990 baseline *(from Minville et al., 2009)*.

All climate projections indicate a future increase in annual runoff, so average hydroelectric generation should also increase. This increase could range from 1 to 15% in the period 2040-2069 at the Chute-des-Passes power plant, depending on the climate scenario used and assuming optimal management. However, if the current management policies remain unchanged, hydroelectric generation would decrease by 1 to 14% due to the inability to contain earlier snowmelt and resulting unproductive spilling. By practicing adaptive management and non-structural adaptation approaches, such as updating management policies on a regular basis, producers should be able to capitalize on the effects of climate change on hydrologic regimes.

a particular focus on the North (e.g. Furgal and Prowse, 2008). Risks include a shortened season for both exploration activities reliant on frozen ground, and for transporting supplies via winter roads. Longer term risks of climate change at northern sites relate to effects of permafrost degradation on the stability of infrastructure (e.g. ground subsidence affecting access roads, buildings and pipelines) as well as on the management of drilling wastes (which commonly rely on storage in permanently frozen ground to prevent mobilization of contaminants; Furgal and Prowse, 2008). Risks to off-shore production facilities relate to increased storminess (including Atlantic hurricanes) and changes in ice-risk (icebergs and multi-year sea ice; e.g. Stantec, 2012), and potential environmental and human impacts associated with oil spills (e.g. NEB, 2011).

The oil and gas industry routinely undertakes actions to address climate risks, but these are rarely documented systematically in publically available sources. Where available, evidence indicates that industry generally feels the sector is well positioned to adapt to climate change, largely in a responsive manner (NRTEE, 2012a, also *see* Case Study 7).

Research in the past five years has highlighted that climate change impacts on water resources will have significant implications for the oil and gas sector (e.g. PRI, 2009). Many upstream and midstream (e.g. processing, upgrading, storage and transport) activities associated with the production of oil, gas and coal are water-intensive, and, unlike thermal power generation, are made up almost exclusively of consumptive uses (Natural Resources Canada, 2010). Regional impacts may be most significant in areas that are already water-stressed, such as the southwestern Prairies (e.g. Sauchyn and Kulshreshtha, 2008). Recent attention has focused on water usage for oil sands processing and hydraulic fracturing.

While 75 to 90% of the water used in oil sands processing is recycled, the remainder is derived from surface and groundwater sources. With respect to climate change impacts, attention has focused on the ability of the Athabasca River in Alberta to provide water for expanded oil sands development while maintaining sufficient downstream flows to avoid ecosystem impacts. Analysis of historic flow variability and trends concluded that short term ecosystem impacts would have occurred under historic low flow conditions, and that management responses are needed to avoid longer term impacts under projected climate change (Bruce, 2006; Schindler et al., 2007). An expert panel of the Royal Society of Canada (RSC, 2010) concluded that concerns about withdrawals during low-flow periods could be addressed through additional off-stream water storage captured during spring peak flows. The Panel's report notes that "substantial reductions in Athabasca River flow resulting from climate change would drive implementation of this option [additional off-stream water storage] to a great degree" (RSC, 2010, p. 284). A detailed analysis of projected climate changes on Athabasca River water flows was conducted as part of a multi-stakeholder committee analysis examining water withdrawls (Ohlson et al., 2010; *see also* Lebel et al., 2009) concluded that significant uncertainties and knowledge gaps on this and other topics highlighted the importance of adaptive and flexible management approaches.

To adapt to water availability risks, the oil sands industry emphasizes technological innovation and notes the significant gains in water-use efficiency in the past decade (CAPP, 2012). While off-stream water storage represents one possible adaptation, fundamental changes in the methods used to separate bitumen in ways that greatly reduce water use are also being investigated (CAPP, 2012). From a regulatory perspective, the Water Management Framework for the Lower Athabasca River, introduced by the Government of Alberta in 2007 to limit, monitor and adjust freshwater withdrawal from the river on a weekly basis, provides a mechanism to protect environmental integrity under both current and future climate conditions (ESRD, 2013).

### ELECTRICITY GENERATION (FROM NON-RENEWABLE SOURCES)

Nuclear energy constitutes 15%, and coal-fired power plants represent 13%, of electricity generation in Canada (Statistics Canada 2012, 2013). Climate impacts of greatest concern to non-renewable electricity generation relate to possible impacts of extreme climate events on infrastructure, as well as impacts on the availability and temperature of cooling water (e.g. Wilbanks et al., 2008; Rübbelke and Vögele, 2011). While detailed information for Canadian facilities is publicly available through findings of regulatory hearings, this information has not been broadly captured by the scientific literature. The following discussion draws heavily on analyses from Europe and the United States.

Discussion of infrastructure risks for power plants focuses on intense storms and extreme precipitation, which can cause flooding of facilities or make access routes to them impassable, potentially leading to decreased generation, shutdowns or increased costs to handle drainage and clean-up (Wilbanks et al., 2007; Ebinger and Vergara, 2011). Both thermal and nuclear power plants also face the potential of reduced generation in the case of extremely low water levels (McColl et al., 2012). A rise in water temperatures reduces the cooling efficiency at power plants (Harrison et al., 2009), resulting in a proportionate increase in the demand for cooling water. European research has documented failures to meet the cooling needs of thermal power plants due to high water temperatures during summer heat waves (McColl et al.,

CASE STUDY 7

## ADAPTATION TO CLIMATE CHANGE IN THE OIL AND GAS SECTOR

The Carbon Disclosure Project (CDP) is an international effort to track corporate progress on managing climate change risks and opportunities. Relying on voluntary responses to an annual survey targeting the largest firms based on market capitalization, the CDP has an extensive database of business responses dating back to 2003. The CDP's primary focus is on mitigation, but adaptation-relevant questions are also included. Recent reports illustrate a shift in how Canadian businesses perceive the physical impacts of climate change. For example, opportunities outnumbered risks stemming from a changing climate in the CDP Canada reports from 2008 to 2010 (CDP, 2010). Sectoral differences in perception of risk and opportunity are also evident. Of all the sectors represented in CDP, energy businesses were found to be the least likely to report on possible opportunities arising from climate change and the second least likely of all sectors to report on exposure to physical risks, based on analysis of responses in reports from 2003 to 2010 (NRTEE, 2012b).

The 2010 survey included questions addressing current and/or anticipated risks associated with physical impacts of climate change, the timescale of these risks, possible financial implications and actions planned or taken to manage the risks. Examples of adaptation actions identified by Canadian oil and gas companies to address current and anticipated future climate risks are presented in Table 5.

| Internal policy, programs and operating standards |
|---|
| • Engineering and construction standards that ensure facilities can operate in extreme conditions, including potential temperature and weather-related shifts<br>• A capital approval process characterized by project evaluation that includes engineering, environment, and business risks; identification and sharing of key learnings from past capital projects; and incorporation of these learnings in plans to manage operational risks<br>• Programs that promote system integrity and ongoing preventive maintenance for each component of the gas system<br>• Business continuity planning and emergency preparedness to ensure the continued supply of transportation fuels<br>• An insurance program that includes coverage for physical damage, business interruption and third party liabilities, also serving to manage commercial risks of climate change-related hazards |
| **Actions to build resilience** |
| • Design and application of wooden mats so producers can drill during warm-weather months in muskeg and wet areas, while minimizing environmental disturbance<br>• System interconnectedness allowing redirection of gas from one plant to another in case of shut downs, minimizing revenue loss to the company and production losses to customers<br>• Enhancing water-use efficiency in the design and operation of existing and new facilities, including expanded recycling and reuse of water, reassessment of freshwater licence allocations for return to the Crown and collaboration with industry to reduce impacts on local water resources |
| **Stakeholder engagement** |
| • A Water Strategy that includes getting involved in policy and regulatory development, and working with local stakeholders on site-specific water issues as ways to address the potential impacts of climate change |

**TABLE 5:** Selected examples of actions to manage the physical impacts of climate change highlighted by Canadian oil and gas companies in their 2010 responses to the Carbon Disclosure Project *(Source: CDP, 2010)*.

The limited number of respondents to the CDP prevents generalizations for the sector as a whole, but responses can provide insights on individual oil and gas companies' perceptions of risk and sense of urgency to adapt. For example, in its 2012 CDP response, Encana noted risks to water availability related to changes in precipitation and drought, as well as impacts of extreme weather on exploration and production activities. The risks were considered difficult to quantify, with timeframe and magnitude of impact stated as "unknown", and likelihood deemed "unlikely". In accompanying descriptions, the company notes that it currently operates in a range of extreme environments across North America, that its facilities are engineered and constructed to operate within wide ranges of weather conditions, and that they annually conduct a "look-back and learning" process that allows steps taken to address negative impacts at any one site to be shared across the company. With respect to risks associated with water availability, the company noted that if managed, this risk would have a negligible effect on exploration and production.

2012). In addition, temperatures of cooling water discharges from power plants could increase, with the risk of violating regulatory thresholds established to protect ecosystem services. Both regulatory and safety violations could result in shutdowns. Current Canadian nuclear power plants are cooled by very large bodies of water (Lake Huron, Lake Ontario and the Atlantic Ocean) so the same risks may not apply in Canada. Nonetheless the impact of climate change is one factor to be considered when locating future plants.

Adaptation responses to warmer water temperatures will depend in large part on the type of cooling technology currently deployed. Once-through cooling (OTC) systems, the most common type of system in Canada (Natural Resources Canada, 2010), feature a continuous intake and discharge of cooling water. One option to decrease the amount of cooling water used in lakeside OTC systems is relocating the water intake to a deeper (and colder) part of the lake. Where facilities are located on shallow lakes, such as in the Canadian prairies, there may be fewer options to deal with climate change and drought. New technologies to reduce water consumption, enhance water reuse, and develop dry cooling techniques are opportunities for innovation that will be partly driven by the need to adapt to climate change impacts (ICF Marbek, 2012).

### 5.3 ENERGY TRANSMISSION

Infrastructure for energy transmission is a major, long-lived and climate-sensitive investment for both the electricity and oil and gas sectors. Canada has over 140 000 km of electricity transmission grid, with Quebec, Ontario and Alberta representing about 60% of the national total. This infrastructure provides interconnections between energy markets in other provinces and in the United States (ICF Marbek, 2012). There are more than 825 000 km of oil, refined products and natural gas pipelines in Canada, including both delivery and transmission pipelines (CEPA, 2012). Major new pipelines have been proposed to enhance access to Canadian and US markets, and to expand into Asian markets. The distribution network for oil, gas and coal also includes road, rail, barge and tanker transport.

Severe weather is a common cause of interruptions in power supply. The 1998 ice storm in eastern Canada, which had estimated costs of more than $5 billion, provides an extreme example of the vulnerability of electricity transmission infrastructure. Extreme temperatures can affect the performance of a large amount of infrastructure, including electricity transmission (reduced efficiency and increased line drag), pipelines (reduced efficiency of compressors and fan coolers) and railroads (heat buckling), which are particularly important for coal transport (ICF Marbek, 2012). Climate-related natural hazards also present risks to energy transport. For example, extreme rainfall can cause flooding and trigger landslides that can interrupt road and rail transport. Permafrost thaw can lead to surface subsidence or destabilized slopes that can result in pipeline buckling or rupture. Engineering solutions exist to reduce many of these risks.

## 6. SYNTHESIS

The natural resources sector routinely manages climate risks. Adapting to the reality of a changing climate is in the best interest of both natural resource companies and the communities in which they operate. As with other sectors, governments, industry and non-government organizations all have a role to play in adaptation in the natural resource sectors. Since provincial governments have legislative authority for natural resources within their jurisdiction (PCO, 2010), there are differing approaches and levels of activity across Canada. Intergovernmental processes provide a mechanism for sharing experiences, tools and development of best practices for adaptation, as demonstrated by recent activities under the Canadian Council of Forest Ministers (CCFM, 2013a, 2013b, 2013c, 2013d). The federal government is responsible for cross-jurisdictional issues, including international trade, and plays a strong role in research and development. Industry associations are increasingly engaged in building awareness of climate change impacts and the value of adaptation. In instances where a strong link between climate variability and change and resource production exists, such as with hydroelectricity, there are several examples of industry being a leader in analyzing impacts and funding related research.

The first-order biophysical impacts of a changing climate on resource exploration, physical infrastructure and distribution systems – including impacts related to weather extremes, regional hydrologic changes, permafrost degradation, sea level rise and others – are fairly well understood for many aspects of natural resources, and have not evolved significantly in the past five years.

Application of this understanding is most developed in the forestry and hydroelectricity sectors. Significant gaps in biophysical impact research still remain, including understanding changes in wind patterns and cloud cover and the potential impacts on wind and solar power generation, the implications of reduced water availability on oil and gas activities, and the effect of novel climates on forest ecosystems. Detailed study of downstream impacts, including economic analysis related to international trade and global competitiveness, remains very limited. However, new insights have emerged on dealing with climate change impacts as part of business planning. Gauthier et al. (*in review*) offer four key principles for adaptation in the forest sector, which equally apply to other natural resource sectors. These are:

1. Efficient incorporation of climate change risks into planning and operations. Risk management approaches involve moving from optimal production targets to achieving the most robust outcome under a range of conditions.
2. Integration of no-regret options that provide benefits under a range of potential futures.
3. Adoption of an adaptive management framework. Given the uncertainty associated with climate change, management systems must be flexible and responsive to changes.
4. Monitoring to identify climate-related changes and potential deviation from management goals.

Many frameworks for adaptation exist; however, examples of their application and documentation of implemented measures remain relatively few. The adaptation that is occurring in the natural resources sector has been primarily through ad hoc, reactive responses to climatic events. Examples include flying supplies to northern mine sites when the ice road season is shortened due to warm temperatures, shifting of forest harvest operations to cope with unfrozen ground conditions, and making use of the increased quantity of salvage logging. Examples of proactive adaptation planning for future climate change are fewer. Case studies compiled by the National Roundtable on the Environment and Economy (NRTEE, 2012a) documented the climate change adaptation activities of a number of resource-based companies (J.D. Irving and Tolko Industries in the forestry sector, Rio Tinto Alcan in mining and Entergy Corporation, BC Hydro and Hydro Quebec in the energy sector). Those examples highlight that adaptation is starting to infiltrate the culture of the natural resource industry, as it has for other sectors of the Canadian economy.

A number of barriers and enablers of adaptation are evident across the natural resource sectors. Recent changes of significance to Canada primarily relate to near-term economic drivers such as global economic performance, commodity prices, and international trade issues. To remain competitive in both continental and global markets, investments in longer-term sustainability are sometimes viewed as a low priority. However, the fact that rapid changes are taking place in the natural resource sectors, particularly in the context of northern economic development, also provides opportunities for adaptation if climate change is integrated as part of broader decision-making processes.

Limited awareness in the natural resource sectors of the potential scope, scale and business relevance of climate change impacts, as well as uncertainties regarding the projection of specific climate changes, have been cited as reasons for limited progress on adaptation (NRTEE, 2012b). In addition, the fact that most of these industries operate in a wide range of climate extremes makes them comparatively resilient to many projected climate changes. Nonetheless, comprehensive risk assessments can identify new vulnerabilities, including those related to disruptions in public infrastructure.

Processes that are emerging as enablers of adaptation action in the natural resource sectors include environmental assessment, public risk disclosure, and reporting associated with sustainable forest management. The former is a legislated requirement (updated in 2012 for federal jurisdiction) for major development projects with the goal of reducing a project's potential impact on the environment before it begins and to ensure that measures to mitigate risks are applied once the project is initiated. Such assessments routinely consider the impacts of climate change on the proposed development, with guidance and case studies provided by the Federal-Provincial-Territorial Committee on Climate Change and Environmental Assessment (2003). Public disclosure, such as the Carbon Disclosure Project (*see* Case Study 7), exists to inform investors on how publicly traded companies evaluate and manage material risk in a changing climate (CDP, 2010). Although analysis of US Securities and Exchange Commission disclosures indicated that the quality of disclosure regarding climate risk is generally inadequate to allow investors to accurately assess future risks and performance (Ceres, 2012), it also highlights the potential value of this process for promoting adaptation, encouraging both investors and regulators to push for improvements in disclosure quality.

In many instances, the engineering and planning solutions to help natural resource companies and local communities prepare for and adapt to climate change exist. The potential for developing effective adaptation strategies in the Canadian natural resources sector is substantial, and collaboration among companies, regulators, scientists and other stakeholders to develop practical adaptation strategies that can be mainstreamed into existing planning and operations will greatly enhance likelihood of success. There is an opportunity for Canadian natural resource managers to share their experiences in climate change adaptation with planners and managers in other sectors in Canada and internationally.

# REFERENCES

Aitken, S. N., Yeaman, S., Holliday, J. A., Wang, T., and Curtis-McLane, S. (2008): Adaptation, migration or extirpation: Climate change outcomes for tree populations; Evolutionary Applications, v. 1, no. 1, p. 95-111.

Ali, A.A., Blarquez, O., Heĺy, C., Tinquaut, F., El Guellab, A., Valsecchi, V., Terrier, A., Bremond, L., Genries, A., Gauthier, S., and Bergeron, Y. (2012): Control of the multimillennial wildfire size in boreal North America by spring climatic conditions; Proceedings of the National Academy of Sciences of the United States of America, v. 109, no. 51, p. 20966-20970.

Allan, C., and Stankey, G.H. (2009): Adaptive environmental management: A practitioner's guide; Springer, 352 p.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., and Cobb, N. (2010): A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests; Forest Ecology and Management, v. 259, no. 4, p. 660-684.

Amiro, B. D., Cantin, A., Flannigan, M. D., and De Groot, W. J. (2009): Future emissions from Canadian boreal forest fires; Canadian Journal of Forest Research, v. 39, no. 2, p. 383-395.

Auld, H., Comer, N., and Fernandez, S. (2010): Technical guide - Infrastructure in permafrost: A guideline for climate change adaptation; Canadian Standards Association (CSA) Special Publication, 112 p.

Balshi, M. S., McGuire, A. D., Duffy, P., Flannigan, M. D., Walsh, J., and Melillo, J. M. (2009): Assessing the response of area burned to changing climate in western boreal North America using a multivariate adaptive regression splines (MARS) approach; Global Change Biology, v. 15, no. 3, p. 578-600.

Barber, V. A., Juday, G. P., and Finney, B. P. (2000): Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress; Nature, v. 405, no. 6787, p. 668-673.

BCMFLNRO [British Columbia Ministry of Forests, Lands and Natural Resources Operations] (2008): Climate based upward elevation changes; <http://www.for.gov.bc.ca/code/cfstandards/amendmentNov08.htm>.

BCMFLNRO [British Columbia Ministry of Forests, Lands and Natural Resources Operations] (2010): Assisted range and population expansion of western larch for use as a climate change adaptation strategy in British Columbia; <http://www.for.gov.bc.ca/code/cfstandards/amendmentJun10.htm>.

BCMFLNRO [British Columbia Ministry of Forests, Lands and Natural Resources Operations] (2012): A history of the battle against the mountain pine beetle. 12 p.

Beaubien, E., and Hamann, A. (2011): Spring flowering response to climate change between 1936 and 2006 in Alberta, Canada; Bioscience, v. 61, no. 7, p. 514-524.

Beauchamp, J. (2010): Estimation d'une PMP et d'une CMP d'un bassin versant septentrional, en contexte de changements climatiques; École de technologie supérieure, Montréal.

Bell, T., Jacobs, J.D., Munier, A., Leblanc, P., and Trant, A. (2008): Climate change and renewable resources in Labrador: Looking toward 2050; Proceedings and Report of a Conference held in North West River, Labrador, 11–13 March, St. John's: Labrador Highlands Research Group, Memorial University of Newfoundland, 95 p. and CD-Rom, 31 March.

Bernier, P., and Schoene, D. (2009): Adapting forests and their management to climate change: An overview; Unasylva, v. 60, no. 231-232, p. 5-11.

Boyer, C., Chaumont, D., Chartier, I., and Roy, A.G. (2010): Impact of climate change on the hydrology of St. Lawrence tributaries; Journal of Hydrology, v. 384, p. 65–83.

Bruce, J.P. (2006): Oil and water – will they mix in a changing climate? The Athabasca River story; in Implications of a 2°C Global Temperature Rise on Canada's Water Resources, Athabasca River and Oil Sands Development, Great Lakes and Hydropower Production, (ed.) T. Tin; report prepared for the Sage Centre, p. 12-34; <http://tidescanada.org/wp-content/uploads/files/papers/sagereport_nov0106.pdf>.

Burns, R. M., and Honkala, B. H. (1990): Silvics of North America: 1. Conifers, 2. hardwoods; Agriculture handbook 654, Department of Agriculture, Forest Service, Washington, DC.

Buttle, J., Muir, T., and Frain, J. (2004): Economic impacts of climate change on the Canadian Great Lakes hydro-electric power producers: a supply analysis; Canadian Water Resources Journal, v. 29, no. 2, p. 89-110.

CAPP [Canadian Association of Petroleum Producers] (2012): Oil sands today: Water use; <http://www.oilsandstoday.ca/topics/WaterUse/Pages/Default.aspx>.

Caya, D. and Laprise, R. (1999): A Semi-implicit semi-lagrangian regional climate model: the Canadian RCM; Monthly Weather Review, v. 127, no. 3, p. 341–362.

CBC [Canadian Broadcasting Corporation] (2012, May 24): Forest fire smoke blankets Timmins, Ontario; CBC News.

CCFM [Canadian Council of Forest Ministers] (2006): Criteria and indicators framework 2005; Canadian Council of Forest Ministers, Ottawa. <http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/32560.pdf>.

CCFM [Canadian Council of Forest Ministers] (2008): A vision for Canada's forests: 2008 and beyond; Ottawa, Ontario: Natural Resources Canada, Canadian Forest Service.

CCFM [Canadian Council of Forest Ministers] (2013a): Adapting sustainable forest management to climate change: Preparing for the future; Climate Change; <http://www.ccfm.org/pdf/Edwards_PreparingForFuture_FinalEng.pdf>.

CCFM [Canadian Council of Forest Ministers] (2013b): Adapting sustainable forest management to climate change: A systematic approach for exploring organizational readiness; <http://www.ccfm.org/pdf/Gray_OrganizationReadiness_FinalEng.pdf>.

CCFM [Canadian Council of Forest Ministers] (2013c): Adapting sustainable forest management to climate change: A framework for assessing vulnerability and mainstreaming adaptation into decision making; <http://www.ccfm.org/pdf/WilliamsonVulnerability_Eng_Final.pdf>.

CCFM [Canadian Council of Forest Ministers] (2013d): Adapting sustainable forest management to climate change: Scenarios for vulnerability assessment; <http://www.ccfm.org/pdf/PriceIsaac_Vulnerability_En.pdf>.

CDP [Carbon Disclosure Project] (2010): Carbon disclosure project report 2010; Canada; <https://www.cdproject.net/CDPResults/CDP-2010-Canada-Report-english.pdf>.

CEPA [Canadian Energy Pipelines Association] (2012): About Pipelines 2012 – our energy connections.

Ceres (2012): Sustainable extraction? An analysis of SEC disclosure by major oil and gas companies on climate risk and deepwater drilling risk; Ceres Inc., Boston MA, 42 p.

Chhin, S., Hogg, E. H., Lieffers, V. J., and Huang, S. (2008): Potential effects of climate change on the growth of lodgepole pine across diameter size classes and ecological regions; Forest Ecology and Management, v. 256, no. 10, p. 1692-1703.

Chiotti, Q., and Lavender, B. (2008): Ontario; in From Impacts to Adaptation: Canada in a Changing Climate 2007, edited by D. Lemmen, F. Warren, J. Lacroix, and E. Bush, Government of Canada, Ottawa, ON, p. 227-274.

City of Vancouver (2012): Stanley park restoration; <http://vancouver.ca/parks-recreation-culture/stanley-park-restoration.aspx>.

Côté, P., Haguma, D., Leconte, R., and Krau, S. (2011): Stochastic optimisation of hydro-Quebec hydropower installations: A statistical comparison between SDP and SSDP methods. Canadian Journal of Civil Engineering, v. 38, no. 12, p. 1427-1434.

Cullingham, C. I., Cooke, J. E. K., Dang, S., Davis, C. S., Cooke, B. J., and Coltman, D.W. (2011): Mountain pine beetle host-range expansion threatens the boreal forest; Molecular Ecology, v. 20, no. 10, p. 2157-2171.

CVRD Inco (2006): Toward sustainability; <http://nickel.vale.com/sustainability/pdf/Toward_Sustainability_20007.pdf>.

Desrochers, G., Roy, R., Roy, L., Pasher, G., Guay, F., and Tapsoba, D. (2009): Comparing methods to investigate the impacts of climate change; Paper presented at the 2009 AWRA Spring Specialty Conference: Managing Water Resources Development in a Changing Climate, Anchorage, Alaska. 22 p.

Easterling, W.E., Aggarwal, P.K., Batima, P., Brander, K.M., Erda L., Howden, S.M., Kirilenko, A., Morton, J., Soussana, J.-F., Schmidhuber, J., and Tubiello, F.N. (2007): Food, fibre and forest products; Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson; Cambridge University Press, Cambridge, United Kingdom, p. 273-313.

Ebinger, J., and Vergara, W. (2011): Climate impacts of energy systems: key issues for energy sector adaptation; The World Bank, Washington, DC, 178 p.

ECO [Environmental Commissioner of Ontario] (2012): Ready for change? An assessment of Ontario's climate change adaptation strategy; Toronto, Ontario, Environmental Commissioner of Ontario.

Environment Canada (2009): Environmental Code of Practice for Metal Mines; Ottawa, ON; <http://www.ec.gc.ca/lcpe-cepa/documents/codes/mm/mm-eng.pdf>.

Environment Canada (2012): Water Withdrawal and Consumption by Sector; <https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=5736C951-1>.

ESRD [Alberta Environment and Sustainable Resource Development] (2013): Athabasca River conditions and use; Alberta Environment and Sustainable Resource Development; <http://www.environment.alberta.ca/apps/OSEM>.

Federal-Provincial-Territorial Committee on Climate Change and Environmental Assessment (2003): Incorporating Climate Change Considerations in Environmental Assessment: General Guidance for Practitioners; <http://www.ceaaacee.gc.ca/Content/A/4/1/A41F45C5-1A79-44FA-9091-D251EEE18322/Incorporating_Climate_Change_Considerations_in_Environmental_Assessment.pdf >.

Field, C.B., Mortsch, L.D., Brklacich, M., Forbes, D.L., Kovacs, P., Patz, J.A., Running, S.W., and Scott, M.J., (2007): North America; Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson; Cambridge University Press, Cambridge, United Kingdom, p. 617-652.

Fischlin, A., Midgley, G.F., Price, J.T., Leemans, R., Gopal, B., Turley, C., Rounsevell, M.D.A., Dube, O.P., Tarazona, J., and Velichko, A.A. (2007): Ecosystems, their properties, goods, and services; Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson; Cambridge University Press, Cambridge, United Kingdom, p. 211-272.

Flannigan, M., Stocks, B., Turetsky, M., and Wotton, M. (2009): Impacts of climate change on fire activity and fire management in the circumboreal forest; Global Change Biology, v. 15, no. 3, p. 549-560.

Flat Top Complex Wildfire Review Committee (2012): Flat top complex: Final report from the flat top complex wildfire review committee; Alberta Ministry of Environment and Sustainable Resource Development, Edmonton, Alberta.

Ford, J.D., Pearce, T., Prno, J., Duerden, F., Berrang Ford, L. Beaumier, M., and Smith, T. (2010): Perceptions of climate change risks in primary resource use industries: a survey of the Canadian mining sector; Regional Environmental Change, v. 10, no. 1, p. 65-81.

Ford, J. D., Pearce, T., Prno, J., Duerden, F., Ford, L. B., Smith, T. R., and Beaumier, M. (2011): Canary in a coal mine: Perceptions of climate change risks and response options among Canadian mine operations; Climatic Change, v. 109, no. 3-4, p. 399-415.

Fortin, L.G., Turcotte, R, Pugin, S., Cyr, J.-F., and Picard, J.-F. (2007): Impact des changements climatiques sur les plans de gestion des lacs St-François et Aylmer au sud du Québec, Revue Canadienne de Génie Civil, v. 34, p. 934-945.

FPAC [Forest Products Association of Canada] (2012): Certification Canada; <http://www.certificationcanada.org/english/what_is_certification>.

Furgal, C., and Prowse, T.D. (2008): Northern Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, ON, p. 57-118.

Gauthier, S., Bernier, P., Burton, P. J., Isaac, K., Isabel, N., Williamson, T., Le Goff, H. (in review): Adaptation in the managed Canadian boreal forest; Environmental Reviews.

Geller, H., Harrington, P., Rosenfeld, A. H., Tanishima, S., and Unander, F. (2006): Polices for increasing energy efficiency: Thirty years of experience in OECD countries. Energy Policy, v. 34, no. 5, p. 556-573.

Georgakakos, A. P., Yao, H., Kistenmacher, M., Georgakakos, K. P., Graham, N. E., Cheng, F.-Y., Spencer, C., and Shamir, E. (2012): Value of adaptive water resources management in northern California under climatic variability and change: Reservoir management; Journal of Hydrology, v. 412-413, p. 34-46.

Girardin, M. P. (2007): Interannual to decadal changes in area burned in Canada from 1781 to 1982 and the relationship to northern hemisphere land temperatures; Global Ecology and Biogeography, v. 16, no. 5, p. 557-566.

Girardin, M.P., Raulier, F., Bernier, P. Y. and Tardif, J. C. (2008): Response of tree growth to a changing climate in boreal central Canada: A comparison of empirical, process-based and hybrid modelling approaches; Ecological Modelling, v. 213, no. 2, p. 209-228.

Girardin, M.P., and Wotton, B.M. (2009): Summer moisture and wildfire risks across Canada; Journal of Applied Meteorology and Climatology, v. 48, no. 3, p. 517-533.

Girardin, M.P., Guo X. J., Bernier, P.Y., Raulier, F., and Gauthier, S. (2012): Changes in growth of pristine boreal North American forests from 1950 to 2005 driven by landscape demographics and species traits; Biogeosciences, v. 9, no. 7, p. 2523-2536.

Global Forest Watch (2012): Hydropower Developments in Canada: Number, Size and Jurisdictional and Ecological Distribution; <http://www.globalforestwatch.ca/pubs/2012Energy/02Hydro/Hydro1_Number_Size_Distribution.pdf>.

Goulding, H.E.A. (2011): Yukon water: A summary of climate change vulnerabilities; Environment Yukon, Government of Yukon, Canada.

Gupta, R. and Gregg, M. (2012): Using UK climate change projections to adapt existing English homes for a warming climate; Building and Environment, v. 55, p. 20-42.

Haguma, D. (2012): Gestion des ressources hydriques adaptée aux changements climatiques pour la production optimale d'hydroélectricité; Étude de cas: bassin versant de la rivière Manicouagan, Doctoral thesis, Université de Sherbrooke. 237 p.

Hamlet, A.F., Lee, S.Y., Mickelson, K.E.B., and Elsner, M.M. (2009): Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State; Chapter 4 in The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate, Climate Impacts Group, University of Washington, Seattle.

Harrison, G.P., Cradden, L.C., Zacheshigriva, A., Nairn, S., and Chick, J.P. (2009): Sensitivity of Thermal Power Generation to Climate Change; UK Met Office, 2 p.

Haughian, S. R., Burton, P. J., Taylor, S. W., and Curry, C. L. (2012): Expected effects of climate change on forest disturbance regimes in British Columbia; BC Journal of Ecosystems and Management, v. 13, no. 1, p. 16-39.

Hicke, J. A., Allen, C.D., Desai, A.R., Dietze, M.C., Hall, R.J., Hogg, E.H.T., and Vogelmann, J. (2012): Effects of biotic disturbances on forest carbon cycling in the United States and Canada; Global Change Biology, v. 18, no. 1, p. 7-34.

Hogg, E. H., Brandt, J. P., and Michaelian, M. (2008): Impacts of a regional drought on productivity, dieback and biomass of western Canadian aspen forests; Canadian Journal of Forest Research, v. 38, no. 6, p. 1373-1384.

ICF Marbek (2012): Adaptation to a changing climate in the energy sector; Report to the Climate Change Impacts and Adaptation Division, Natural Resources Canada, 88 p.

ICOLD [International Commission on Large Dams] (2001): Tailings dams: risk of dangerous occurrences; Lessons learnt from practical experiences; Bulletin 121, ICOLD Committee on Tailings Dams and Waste Lagoons; <http://www.unep.fr/shared/publications/pdf/2891-TailingsDams.pdf>.

IEA [International Energy Agency] (2011a): World Energy Outlook 2011, Paris.

IEA [International Energy Agency] (2011b): Impact of Smart Grid Technologies on Peak Load to 2050; Paris.

IESO [Independent Electricity System Operator] (2009): The Ontario Reliability Outlook; Toronto; <http://www.ieso.ca/imoweb/pubs/marketReports/ORO_Report-Dec2009.pdf>.

International Wood Markets Group (2010): BC Interior Mountain Pine Beetle Report; 154 p.

IPCC [Intergovernmental Panel on Climate Change] (2007): Summary for Policymakers, in Climate Change 2007: The Physical Science Basis; Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller; Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IMG-Golder Corporation (2012): Vulnerability assessment of the mining sector to climate change; Nunavut Regional adaptation Collaborative, 98 p.

Instanes, A., Anisimov, O. A., Brigham, L., Goering, D., Khrustalev, L., Ladanyi, B., and Larsen, J. O. (2005): Infrastructure: Buildings, support systems and industrial facilities (chapter 16); in Arctic Climate Impact Assessment. Cambridge University Press, Cambridge, United Kingdom.

Isaac, M., and van Vuuren, D.P. (2009): Modeling global residential sector energy demand for heating and air conditioning in the context of climate change; Energy Policy, v. 37, no. 2, p. 507-521.

Johnston, M., Campagna, M., Gray, P., Kope, H., Loo, J., Ogden, A. M., O'Neill, G.A., Price, D. and Williamson, T. (2009): Vulnerability of Canada's tree species to climate change and management options for adaptation: An overview for policy makers and practitioners; Canadian Council of Forest Ministers, Ottawa, ON.

Johnston, M.H. and Edwards, J.E. (in press): Adapting sustainable forest management to climate change: an analysis of Canadian case studies, Canadian Council of Forest Ministers, Ottawa, ON.

Johnston, M. and Hesseln, H. (2012): Climate change adaptive capacity of the Canadian forest sector; Forest Policy and Economics, v. 24, no. 29, p. 84.

Jones, H. P., Hole, D.G. and Zavaleta, E.S. (2012): Harnessing nature to help people adapt to climate change; Nature Climate Change, v. 2, p. 504-509.

Jost, G., Moore, R. D., Menounos, B., and Wheate, R. (2012): Quantifying the contribution of glacier runoff to streamflow in the upper Columbia river basin, Canada; Hydrology and Earth System Sciences, v. 16, no. 3, p. 849-860.

Kasischke, E. S. and Turetsky, M. R. (2006): Recent changes in the fire regime across the North American boreal region - spatial and temporal patterns of burning across Canada and Alaska; Geophysical Research Letters, v. 33, no. 9.

Kienzle, S. W., Nemeth, M. W., Byrne, J. M., and MacDonald, R. J. (2012): Simulating the hydrological impacts of climate change in the upper north Saskatchewan river basin, Alberta, Canada; Journal of Hydrology, v. 412-413, p. 76-89.

Klein, R.J.T., Huq, S., Denton F., Downing T.E., Richels, R.G., Robinson J.B., and Toth, F.L., (2007): Inter-relationships between adaptation and mitigation; Climate Change 2007: Impacts, adaptation and vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson; Cambridge University Press, Cambridge, United Kingdom, p. 745-777.

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., and Safranyik, L. (2008): Mountain pine beetle and forest carbon feedback to climate change; Nature, v. 452, no. 7190, p. 987-990.

Lapointe-Garant, M., Huang, J., Gea-Izquierdo, G., Raulier, F., Bernier, P. and Berninger, F. (2010): Use of tree rings to study the effect of climate change on trembling aspen in Québec; Global Change Biology, v. 16, no. 7, p. 2039-2051.

Lebel, M., Kerkhoven, E., Bothe, R., Hornung, J., and Ohlson, D. (2009): Climate Change Sensitivity Analysis; Report prepared for the Phase 2 Framework Committee, v. 2, Technical Annex, Cumulative Environmental Management Association; <http://cemaonline.ca/index.php/administration/cat_view/2-communications/44-p2wmf>.

Le Goff, H., Flannigan, M. D., Bergeron, Y., and Girardin, M. P. (2007): Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. International Journal of Wildland Fire, v. 16, no. 5, p. 607-618.

Le Goff, H., Flannigan, M. D., and Bergeron, Y. (2009): Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change; Canadian Journal of Forest Research, v. 39, no. 12, p. 2369-2380.

Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E., editors (2008a): From Impacts to adaptation: Canada in a changing climate 2007; Government of Canada, Ottawa, ON, 448 p.

Lemmen, D., Warren, F., and Lacroix, J. (2008b): Synthesis; in From Impacts to adaptation: Canada in a changing climate 2007; edited by D. Lemmen, F. Warren, J. Lacroix, and E. Bush, E.; Government of Canada, Ottawa, ON, p. 1-20.

Lemprière, T.C., Bernier, P.Y., Carroll, A.L., Flannigan, M.D., Gilsenan, R.P., McKenney, D.W., Hogg, E.H., Pedlar, J.H., and Blain, D. (2008): The importance of forest sector adaptation to climate change; Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Information Report NOR-X-416E. 78 p.

Leong. H. (2005): Marine systems (chapter 9); in Arctic Climate Impact Assessment; Cambridge University Press, Cambridge, United Kingdom.

Levine, M., Ürge-Vorsatz, D., K. Blok, L. Geng, D. Harvey, S. Lang, G., Levermore, A., Mongameli Mehlwana, S., Mirasgedis, A., Novikova, J., Rilling, and Yoshino, H. (2007): Residential and commercial buildings, in Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer; Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lilley, W., Hayward, J., and Reedman, L. (2012): Chapter 7 – realizing the potential of renewable and distributed generation (p. 161-183); in Smart Grid, (ed.) F.P. Sioshansi, Boston: Academic Press.

Lin, Q. G., Huang, G. H., and Bass, B. (2011): Impacts from climate change and adaptation responses on energy economy and greenhouse gas emissions in the Toronto-Niagara region, Canada; Energy Sources, Part A: Recovery, Utilization and Environmental Effects, v. 33, no. 17, p. 1581-1597.

Ma, Z., Peng, C., Zhu, Q., Chen, H., Yu, G., Li, W., Zhou, X., Wang, W., and Zhang, W. (2012): Regional drought-induced reduction in the biomass carbon sink of Canada's boreal forests; Proceedings of the National Academy of Sciences, v. 109, p. 2423-2427.

Marshall, B. (2012): Facts and Figures of the Canadian mining industry; The Mining Association of Canada; <http://www.mining.ca/www/media_lib/MAC_Documents/Publications/2013/Facts%20and%20Figures/FactsandFigures2012Eng.pdf>.

McColl, L., Angelini, A. and Betts, R. (2012): Climate Change Risk Assessment for the Energy Sector; UK Climate Change Risk Assessment; <http://randd.defra.gov.uk/Document.aspx?Document=10074_CCRAfortheEnergySector16July2012.pdf>.

McGrath, T., and Ellingsen, J. (2009): The effects of hurricane Juan on managed stands commercially thinned in central Nova Scotia; Forest Research Report FOR 2009-4, no. 89, Halifax, Nova Scotia: Nova Scotia Department of Natural Resources.

McKenney, D. W., Pedlar, J. H., Lawrence, K., Campbell, K., and Hutchinson, M. F. (2007): Potential impacts of climate change on the distribution of North American trees. Bioscience, v. 57, no. 11, p. 939-948.

McKenney, D. W., Pedlar, J. H., Rood, R. B. and Price, D. (2011): Revisiting projected shifts in the climate envelopes of North American trees using updated general circulation models; Global Change Biology, v. 17, no. 8, p. 2720-2730.

Michaelian, M., Hogg, E. H., Hall, R. J., and Arsenault, E. (2011): Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest; Global Change Biology, v. 17, no. 6, p. 2084-2094.

Mideksa, T. K. and Kallbekken, S. (2010): The impact of climate change on the electricity market: A review; Energy Policy, v. 38, no. 7, p. 3579-3585.

Millar, C. I., Stephenson, N. L., and Stephens, S. L. (2007): Climate change and forests of the future: Managing in the face of uncertainty; Ecological Applications, v. 17, no. 8, p. 2145-2151.

Mills, E. (2007): Synergisms between climate change mitigation and adaptation: An insurance perspective; Mitigation and Adaptation Strategies for Global Change, v. 12, no. 5, p. 809-842.

Minville, M., Brissette, F., Krau, S., and Leconte, R. (2009): Adaptation to climate change in the management of a Canadian water-resources system exploited for hydropower; Water Resources Management, v. 23, no. 14, p. 2965-2986.

Minville, M., Brissette, F., and Leconte, R. (2008): Uncertainty of the impact of climate change on the hydrology of a Nordic watershed; Journal of Hydrology, v. 358, no. 1-2, p. 70-83.

Minville, M., Brissette, F., and Leconte, R. (2010a): Impacts and uncertainty of climate change on water resource management of the Peribonka River System (Canada); ASCE Journal of Water Resources Planning and Management, v. 136, no. 3, p. 376-385.

Minville, M., Brissette, F., Krau, S., and Leconte, R. (2012): Adaptation to Climate Change in the Management of a Canadian Water-Resources System Exploited for Hydropower; Water Resources Management; v. 23, no. 14, p. 2965-2986.

Minville, M., Krau, S., Brissette, F., and Leconte, R. (2010b): Behaviour and performance of a water resource system in Québec (Canada) under adapted operating policies in a climate change context; Water Resources Management, v. 24, no. 7, p. 1333-1352.

Mohan, J. E., Cox, R. M., and Iverson, L. R. (2009): Composition and carbon dynamics of forests in northeastern North America in a future, warmer world; Revue Canadienne De Recherche Forestière, v. 39, no. 2, p. 213-230.

Music, B. and Sykes, C. (2011): CRCM diagnostics for future water resources in OPG priority watersheds; Consortium Ouranos sur la climatologie régionale et l'adaptation aux changements climatiques.

Natural Resources Canada (2000): Forest regions of Canada; <http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/25628.pdf>.

Natural Resources Canada (2009): All resource-reliant communities, 2001; Natural Resources Canada, Atlas of Canada; < http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/d2f00430-8893-11e0-a7f4-6cf049291510.html >.

Natural Resources Canada (2010): Freshwater: The Role and Contribution of Natural Resources Canada; <http://www.nrcan.gc.ca/sustainable-development/freshwater/2543?destination=node%2F2543>.

Natural Resources Canada (2011a): The state of Canada's forests: Annual report 2011; Ottawa: Natural Resources Canada, Canadian Forest Service.

Natural Resources Canada (2011b): Energy Efficiency Trends in Canada 1990-2009; 15th edition.

Natural Resources Canada (2012a): Defining the opportunity: assessing the economic impact of the energy and mining sectors in Canada; Energy and Mines Ministers' Conference, September 2010, Charlottetown, PEI; <http://www.scics.gc.ca/english/conferences.asp?a=viewdocument&id=1907>.

Natural Resources Canada. (2012b): The State of Canada's Forests; Annual Report 2012, Natural Resources Canada, Canadian Forest Service, Headquarters, Ottawa; <http://cfs.nrcan.gc.ca/publications?id=34055>.

Natural Resources Canada (2012c): The threat of mountain pine beetle to Canada's boreal forest; <http://www.nrcan.gc.ca/forests/insects-diseases/13381>.

Natural Resources Canada (2012d): Principal mineral areas of Canada; Geological Survey of Canada Map 900A, 61st edition, 2011, Mineral and Metals Sector and National Energy Board, scale 1:6 000 000.

Natural Resources Canada (2012e): Energy; <http://www.nrcan.gc.ca/publications/statistics-facts/1239>.

Natural Resources Canada (2012f ): About Renewable Energy; <http://www.nrcan.gc.ca/energy/renewable-electricity/7295>.

Natural Resources Canada (2012g): The Atlas of Canada – Energy; <http://atlas.gc.ca/site/english/maps/energy.html>.

Natural Resources Canada (2013a): Key Facts and Figures of Canada's Natural Resources Sector; Natural Resources Canada data hub.

Natural Resources Canada (2013b): Energy Markets Fact Book 2013-2014; <http://nrcan.gc.ca/energymarketsfacts>.

NEB [National Energy Board] (2004): A Compendium of Electric Reliability Frameworks Across Canada, Calgary.

NEB [National Energy Board] (2011): Review of offshore drilling in the Canadian Arctic; Calgary; <http://www.neb-one.gc.ca/clf-nsi/rthnb/pplctnsbfrthnb/rctcffshrdrllngrvw/fnlrprt2011/fnlrprt2011-eng.pdf>.

NERC [North American Electric Reliability Corporation] (2012): Long Term Reliability Assessment, Atlanta; <http://www.nerc.com/files/2012_LTRA_FINAL.pdf>.

Newsham, G. R., Birt, B. J., and Rowlands, I. H. (2011): A comparison of four methods to evaluate the effect of a utility residential air-conditioner load control program on peak electricity use; Energy Policy, v. 39, no. 10, p. 6376-6389.

NRTEE [National Round Table on the Environment and the Economy] (2011): Paying the Price: The Economic Impacts of Climate Change for Canada; Ottawa, ON, 162 p.

NRTEE [National Round Table on the Environment and the Economy] (2012a): Facing the elements: Building business resilience in a changing climate (case studies); Ottawa, Ontario.

NRTEE [National Round Table on the Environment and the Economy] (2012b): Facing the elements: Building business resilience in a changing climate (advisory report); Ottawa, Ontario.

Ochuodho, T., Lantz, V., Loyd-Smith, P., and Benitez, P. (2012): Regional economic impacts of climate change and adaptation in Canadian forests: a CGE modeling analysis; Forest Policy and Economics, v. 25, p. 100-112.

OECD [Organisation for Economic Co-operation and Development] (2012): Glossary of Statistical Terms; <http://stats.oecd.org/glossary>.

Ogden, A. E., and Innes, J. (2007): Incorporating climate change adaptation considerations into forest management planning in the boreal forest; International Forestry Review, v. 9, no. 3, p. 713-733.

Ogden, A. E., and Innes, J. L. (2009): Application of structured decision making to an assessment of climate change vulnerabilities and adaptation options for sustainable forest management; Ecology and Society, v. 14, no. 1.

Ohlson, D., Long, G., and Hatfield, T. (2010): Phase 2 Framework Committee Report; Cumulative Environmental Management Association; <http://cemaonline.ca/index.php/administration/cat_view/2-communications/44-p2wmf>.

Ouranos (2010): Savoir s'adapter aux changements climatiques; Montréal: Ouranos.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., and Hayes, H. (2011): A large and persistent carbon sink in the world's forests; Science, v. 333, no. 6045, p. 988-993.

PCO [Privy Council Office] (2010): The Constitutional Distribution of Legislative Powers; <http://www.pco-bcp.gc.ca/aia/index.asp?lang=eng&page=federal&sub=legis&doc=legis-eng.htm>.

Pearce, T., Ford, J., Prno, J., Duerden, F., Berrang-Ford, L., Smith, T., and Marshall, M. (2009): Climate change impacts and adaptations in the Canadian mining sector.

Pearce, T. D., Ford, J. D., Prno, J., Duerden, F., Pittman, J., Beaumier, M., and Smit, B. (2011): Climate change and mining in Canada. Mitigation and Adaptation Strategies for Global Change, v. 16, no. 3, p. 347-368.

Pedlar, J. H., McKenney, D. W., Aubin, I., Beardmore, T., Beaulieu, J., Iverson, L., O'Neill, G.A., Winder, R.S., and Ste-Marie, C. (2012): Placing forestry in the assisted migration debate. Bioscience, v. 62, no. 10, p. 835-842.

Peng, C., Ma, Z., Lei, X., Zhu, O., Chen, H., Wang, W., Liu, S., Li, W., Fang, X., and Zhou, X. (2011): A drought-induced pervasive increase in tree mortality across Canada's boreal forests; Nature Climate Change, v. 1, no. 9, p. 467-471.

PRI [Policy Research Initiative] (2009): Climate Change Adaptation in the Canadian Energy Sector: workshop report; <http://www.horizons.gc.ca/sites/default/files/Publication-alt-format/2009-0004-eng.pdf >.

Price, D. T., Alfaro, R. I., Brown, K. J., Flannigan, M., Fleming, R. A., Hogg, E. H., Girardin, M.P., Lakusta, T., Johnston, M., McKenney, D.W., Pedlar, T., Stratton, R.N., Sturrock, R., Thompson, I.D., Trofymow, J.A., Venier, L.A. (in review): Anticipating the consequences of climate change for Canada's boreal forest ecosystems; Environmental Reviews.

Prowse, T.D., Furgal, C., Chouinard, R., Melling, H., Milburn, D., and Smith, S.L. (2009): Implications of Climate Change for Economic Development in Northern Canada: Energy, Resource, and Transportation Sectors ; AMBIO: A Journal of the Human Environment, v. 38, no. 5, p. 272-281.

Raje, D., and Mujumdar, P. P. (2010): Reservoir performance under uncertainty in hydrologic impacts of climate change; Advances in Water Resources, v. 33, no. 3, p. 312-326.

Rodenhuis, D., Music, B., Braun, M., and Caya, D. (2011): Climate Diagnostics of Future Water Resources in BC Watersheds; Pacific Climate Impacts Consortium, University of Victoria, 74 p.

RSC [Royal Society of Canada] (2010): Environmental and health impacts of Canada's oil sands industry; The Royal Society of Canada Expert Panel, Ottawa ON, 440 p.

Rübbelke, D., and Vögele, S. (2011): Distributional Consequences of Climate Change Impacts on the Power Sector: Who gains and who loses?; CEPS Working Document No. 349, Centre for European Policy Studies, 18 p.

Sathaye, J., Najam, A., Cocklin, C., Heller, T., Lecocq, F., Llanes-Regueiro, J., Pan, J., Petschel-Held, G., Rayner, S., Robinson J., Schaeffer, R., Sokona,Y., Swart, R. and Winkler, H. (2007): Sustainable development and mitigation, in Climate Change 2007: Mitigation; Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer; Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sauchyn, D. and Kulshreshtha, S. (2008): Prairies; in From Impacts to Adaptation: Canada in a Changing Climate 2007; (ed.) D. Lemmen, F. Warren, J. Lacroix, and E. Bush, Government of Canada, Ottawa, ON, p. 275-328.

Schaeffer, R., Szklo, A. S., Pereira de Lucena, A. F., Moreira Cesar Borba, B. S., Pupo Nogueira, L. P., Fleming, F. P., Trocolli, A., Harrison, M., and Boulahya, M. S. (2012): Energy sector vulnerability to climate change: A review; Energy, v. 38, no. 1, p. 1-12.

Schindler, D.W., Donahue, W.F., and Thompson, J.P. (2007): Future Water Flows and Human Withdrawals in the Athabasca River, in Running Out of Steam? Oil Sands Development and Water Use in the Athabasca River-Watershed: Science and Market Based Solutions; University of Alberta Environmental Research and Studies Centre and University of Toronto Munk Centre for International Studies.

Scott, M. J., and Huang, Y. J. (2007): Effects of climate change on energy use in the United States, in Effects of Climate Change on Energy Production and Use in the United States.

Scott, M. J., Dirks, J. A., and Cort, K. A. (2008): The value of energy efficiency programs for US residential and commercial buildings in a warmer world; Mitigation and Adaptation Strategies for Global Change, v. 13, no. 4, p. 307-339.

Shrestha, R. R., Berland, A. J., Schnorbus, M. A., and Werner, A. T. (2011): Climate change impacts on hydro-climatic regimes in the Peace and Columbia watersheds, British Columbia Canada; University of Victoria, Victoria, British Columbia.

Shrestha, R. R., Schnorbus, M. A., Werner, A. T., and Berland, A. J. (2012): Modelling spatial and temporal variability of hydrologic impacts of climate change in the Fraser River basin, British Columbia, Canada; Hydrological Processes, v. 26, no. 12, p. 1841-1861.

Smith, C. and Levermore, G. (2008): Designing urban spaces and buildings to improve sustainability and quality of life in a warmer world; Energy Policy, v. 36, no. 12, 4558-4562.

Soito, J. L.S. and Freitas, M.A.V. (2011): Amazon and the expansion of hydropower in brazil: Vulnerability, impacts and possibilities for adaptation to global climate change; Renewable and Sustainable Energy Reviews, v. 15, no. 6, p. 3165-3177.

Soulé, P.T., Knapp, P.A. (2006): Radial growth rate increases in naturally occurring ponderosa pine trees: a late-20th century CO2 fertilization effect?; The New Phytologist, v. 171, no. 2, p. 379-390.

St. George, S.S. (2007): Streamflow in the Winnipeg River basin, Canada: Trends, extremes and climate linkages; Journal of Hydrology, v. 332, no. 3-4, p. 396-411.

Stantec Consulting Ltd. (2012): Preliminary assessment report, Canadian Beaufort Sea Region; Report prepared for Aboriginal Affairs and Northern Development Canada, Ottawa, ON.

Statistics Canada (2013): Electricity generated from fossil fuels, CANSIM Table 128-0014; <http://www5.statcan.gc.ca/cansim/pick-choisir?lang=eng&p2=33&id=1280014>.

Steenberg, R. N., Duinker, P., Van Damme, L., and Zielke, K. (2012): Indicators of sustainable forest management in a changing climate; Canadian Council of Forest Ministers, Climate Change Task Force, Technical Analysis Group.

Ste-Marie, C., Nelson, E. A., Dabros, A., and Bonneau, M. E. (2011): Assisted migration: Introduction to a multifaceted concept; Forestry Chronicle, v. 87, no. 6, p. 724-730.

Stothart, P. (2011): F&F 2011: Facts and figures of the Canadian mining industry; The Mining Industry of Canada (MAC).

Stratos (2009): Climate Change Impacts on Mining Operations and Infrastructure; report submitted to the Centre for Excellence in Mining Innovation; <http://www.miningexcellence.ca>.

Stratos (2011): Climate change and acid rock drainage - risks for the Canadian mining sector; no. 1.61.7.

Stroeve, J.C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., and Meier, W.N. (2012): Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations; Geophysical Research Letters, v. 39, no. 16, 7 p.

Sturrock, R. N., Frankel, S. J., Brown, A. V., Hennon, P. E., Kliejunas, J. T., Lewis, K. J. and Woods, A. J. (2011): Climate change and forest diseases; Plant Pathology, v. 60, no. 1, p 133-149.

Trenberth, K. (2010): More knowledge, less certainty; Nature Reports Climate Change, v. 4, p. 20-21.

Ürge-Vorsatz, D. and Tirado Herrero, S. (2012): Building synergies between climate change mitigation and energy poverty alleviation; Energy Policy, v. 49, p. 83-90.

Vale (2013): Voisey's Bay Development; <http://www.vbnc.com>.

Van Mantgem, P. J., Stephenson, N. L., Byrne, J. C., Daniels, L. D., Franklin, J. F., Fulé, P. Z., Harmon, M.E., Larson, A.J., Smith, J.M., Taylor, A.H., and Veblen, T. T. (2009): Widespread increase of tree mortality rates in the western United States; Science, v. 323, no. 5913, p. 521-524.

Wang, G.G., Chhin, S., and Bauerle, W.L. (2006): Effect of natural atmospheric CO2 fertilization suggested by open-grown white spruce in a dry environment; Global Change Biology, v. 12, no. 3, p. 601-610.

Webster, A., Gagnon-Lebrun, F., DesJarlais, C., Nolet, J., Sauvé, C., and Uhde, S. (2008): L'évaluation des avantages et des coûts de l'adaptation aux changements climatiques; Ouranos.

Wilbanks, T.J., Romero Lankao, P., Bao, M., Berkhout, F., Cairncross, S., Ceron, J.-P., Kapshe, M., Muir-Wood, R., and Zapata-Marti, R. (2007): Industry, settlement and society; Climate Change 2007: Impacts, Adaptation and Vulnerability; Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson; Cambridge University Press, Cambridge, United Kingdom, p. 357-390.

Wilbanks, T.J., Bhatt, V., Bilello, D.E., Bull, S.R., Ekmann, J., Horak, W.C., Huang, Y.J., Levine, M.D., Sale, M.J., Schmalzer, D.K., and Scott, M.J. (2008): Effects of Climate Change on Energy Production and Use in the United States; A report by the U.S. Climate Change Science Program (CCSP) and the subcommittee on Global Change Research, Department of Energy, Office of Biological and Environmental Research, Washington, DC., USA.

Williamson, T. B., Colombo, S. J., Duinker, P. N., Gray, P. A., Hennessey, R. J., Houle, D., Johnston, M., Ogden, A. and Spittlehouse, D. L. (2009): Climate change and Canada's forests: From impacts to adaptation. Sustainable Forest Management Network and Natural Resources Canada, Canadian Forest Service, Northern Forest Center, Edmonton, Alberta.

WISE Uranium Project [World Information Service on Energy Uranium Project] (2006): Chronology of major tailings dam failures; <http://www.wise-uranium.org/mdaf.html>.

Wotton, B.M., Nock, C.A., and Flannigan, M.D. (2010): Forest fire occurrence and climate change in Canada; International Journal of Wildland Fire, v. 19, no. 3, p. 253–271.

Xu, T., Sathaye, J., Akbari, H., Garg, V., and Tetali, S. (2012): Quantifying the direct benefits of cool roofs in an urban setting: Reduced cooling energy use and lowered greenhouse gas emissions; Building and Environment, v. 48, no. 1, p. 1-6.

Yao, Y., Huang, G.H. and Lin, Q. (2012): Climate change impacts on Ontario wind power resource; Environmental Systems Research 2012, v. 1, no. 2.; <http://www.environmentalsystemsresearch.com/content/1/1/2>.

Zaturecky, I. and Chiu, I. (2005): Alternative wood products from blue-stained mountain pine beetle lumber: non-structural laminated products; Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Mountain Pine Beetle Initiative Working Paper 2005-07; 20 p.

Zmeureanu, R., and Renaud, G. (2008): Estimation of potential impact of climate change on the heating energy use of existing houses; Energy Policy, v. 36, no. 1, p. 303-310.

Zwiers, F. W., Schnorbus, M. A., and Maruszeczka, G. D. (2011): Hydrologic impacts of climate change on BC water resources; Pacific Climate Impacts Consortium and University of Victoria.

# CHAPTER 4:
# FOOD PRODUCTION

Lead Authors:

**Ian D. Campbell** and **Dolores G. Durant** *(Agriculture and Agri-Food Canada)*, **Karen L. Hunter** and **Kim D. Hyatt** *(Fisheries and Oceans Canada*)

Contributing Authors:

**Darren Cook** and **Darrell R. Corkal** *(Agriculture and Agri-Food Canada)*, **Harry (Polo) Diaz** *(University of Regina)*, **Allan Howard** *(Agriculture and Agri-Food Canada)*, **Margot Hurlbert** *(University of Regina)*, **Ahmed Khan** and **Kristen Lowitt** *(Memorial University)*, **Gregory P. Marchildon** *(Johnson-Shoyama Graduate School of Public Policy)*, **David J. Sauchyn** *(Prairie Adaptation Research Collaborative)*

Recommended citation:

Campbell, I.D., Durant D.G., Hunter, K.L. and Hyatt, K.D. (2014): Food Production; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 99-134.

# TABLE OF CONTENTS

# KEY FINDINGS

A changing climate presents Canadian food producers with a number of opportunities as well as risks that will challenge the food supply industry, particularly in the short term. Key findings include:

- Impacts of climate change differ significantly among the sectors discussed (agriculture, fisheries and non-commercial food supply), but common challenges did emerge, including threats to food supply from increased losses from invasive pests and diseases, and risks to the transportation systems upon which the sectors rely.

- The net medium-term outlook is for a likely modest increase in agricultural food production. Longer and warmer growing seasons would allow higher-value warmer-weather crops to be grown further north (where soil conditions permit), lengthen outdoor feeding seasons for livestock, and allow the maple syrup industry to expand northward. However, there will likely be new pests and diseases, as well as more severe outbreaks of current ones, increased growth of weeds, and other challenges that could negatively affect production and require timely adaptation (e.g. improved water efficiencies and changes in crop management practices).

- Northern and remote communities are likely to see great changes in their environment – some will ease food security concerns while others could exacerbate already decreasing country food stocks and difficulties in delivering supplies into isolated areas.

- Canada is expected to remain a net exporter of aquatic foods at the aggregate level, with total biomass of production from wild-capture fisheries in Canada expected to increase due to climate-induced shifts in fish distributions. Regional impacts from invading species, physical habitat changes and societal responses to shifts in availability and access to aquatic food resources will gradually determine future patterns of use and overall economic implications.

- Aquaculture has a greater scope for adaptation to climate change than other fisheries, making it less vulnerable and better positioned to take advantage of opportunities than capture fisheries, and subsistence fisheries in particular.

# 1. INTRODUCTION

Food production is a major economic driver in Canada, with the agriculture sector contributing $98 billion to our GDP in 2009 (AAFC, 2011) and exports of fisheries products valued at over $4.1 billion in 2012 (DFO, 2013a). The importance of reliable access to healthy and affordable food for Canadians also cannot be overstated. While food production is affected by many factors, including technological advancements, market forces, and food demand and preferences (e.g. for organic products), climate is also a key consideration. Food production on land and in water is inherently sensitive to climate.

Canada's food system is as varied as its geography. Food is produced and sourced through industry-based production of agricultural and fisheries products, as well as important country-food chains that involve non-commercial elements, including fishing, hunting, gardening and gathering. Food systems rely on responses by social mechanisms to manage environmental changes that affect food production and food security (Godfray et al., 2010; Ziervogel and Ericksen, 2010; Perry et al., 2010; 2012). This chapter focuses on the food production elements of Canada's food system.

Food production from agriculture relies mostly upon intensive culture and harvest practices at relatively fixed sites, where selectively cultured crops account for the bulk of food produced, making production highly dependent upon market conditions. In contrast, fisheries depend principally on highly mobile, wild harvest systems that are subject to environmental conditions that influence distribution and abundance of products. However, aquaculture, which has been increasing in Canada, does offer a system of producing aquatic foods that allows more predictable production schedules. These different contributors to the food systems face diverse impacts and challenges related to a changing climate (Figure 1).

This chapter discusses the implications of climate change for food production from agriculture, fisheries and other non-commercial sources (including hunting and gathering), focusing on observed and potential impacts. Adaptation is discussed, with additional details provided through case studies that highlight the challenges and vulnerabilities of food production in Canada's changing climate.

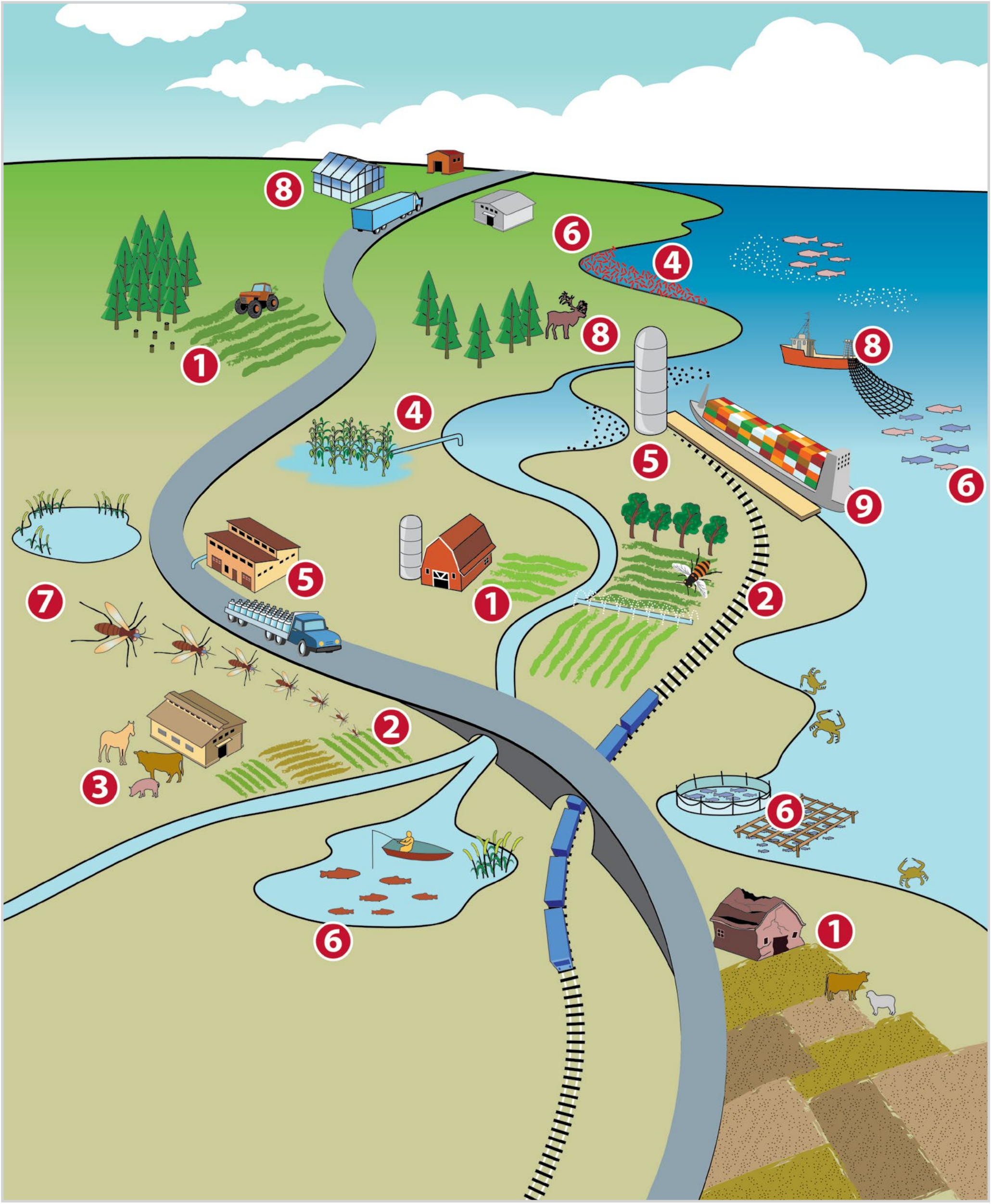


**FIGURE 1:** A summary of potential climate change effects on food production in Canada. **1)** Crop productivity depends strongly and directly on seasonal weather for heat, light and water. Locations for particular crops will also change. **2)** Pollinators would face shorter, less harsh winters but may be affected by increased pest and disease activity, different food sources and changes in the timing of flowering. **3)** Animal production will be affected by changes in crop production, water availability and heating and cooling requirements. **4)** Changes in water supply and precipitation patterns will affect farm operations (e.g. need for drainage or irrigation). Water quality will also be affected (e.g. increased flushing of contaminants into waterways due to heavy rainfall). **5)** Food processing may be challenged by reduced or variable water availability. Food and feed storage will need to deal with increased heat, and in some places, increased storage capacity may be required to allow for increased frequency and duration of transportation interruptions. **6)** Fish stocks will respond to changes in water temperatures, water chemistry, food supply, algal blooms, runoff and ocean currents. Reorganizations of lake/ocean ecosystems are likely, with resultant impacts on all types of fisheries. **7)** Pests, diseases and invasive species could become more virulent and diverse. **8)** Northern/remote communities may be able to increase local food production with adaptation (e.g. greenhouses, cold-tolerant field crops and forages). Access to country foods will be affected as vegetation is directly impacted by changing climate, and species distributions will shift in response to warming. Decreased ocean ice could increase the length of the shipping season, allowing more items to be brought to northern coastal ports. **9)** International trade will be affected by the change in the global geography of food production with countries shipping new types of goods as well as by the potential opening of the Northwest Passage.

# 2. AGRICULTURE

## 2.1 INTRODUCTION

Canada, which has about 650 000 km$^2$ of farm area (~7.2 % of Canada's total land area, Figure 2; Statistics Canada 2012), was the fifth largest agricultural food exporting nation in 2010 (AAFC, 2011) and produces 70% of the food purchased in Canadian stores (Statistics Canada, 2009a). Canada has a wide diversity of agricultural landscapes capable of growing and supporting a large assortment of crops and livestock. The capacity for any area to sustain agriculture is dependent on several factors, including soil composition, water and land availability, temperature, pollinators, sunshine and snow cover.

Climate affects crop productivity, animal production, virility of pests and diseases, pollinator health and water availability and quality. Climate changes will necessitate changes in human activities (e.g. cropping systems, use of irrigation) and lead to flora and fauna reactions (e.g. northward movement). Plants, animals and humans need to adapt to changing conditions. This portion of the chapter outlines recent research findings relevant to climate change impacts and adaptation in the Canadian agriculture and agri-food sector.

## 2.2 ECONOMIC TRENDS AND CONTEXT

The agriculture and agri-food system accounted for 8.2% of Canada's GDP in 2009 (AAFC, 2011). Primary agriculture and food processing play a particularly key role in the economies of certain provinces, such as Saskatchewan and Prince Edward Island (PEI), contributing 12.8% and 10% to their provincial GDPs, respectively (Figure 3), while Ontario, Quebec and Alberta together accounted for almost 70% of the total Canadian agriculture and food processing

**FIGURE 2:** Map showing the agricultural extent of Canada *(Source: AAFC, 2013).*

GDP (Figure 4; AAFC, 2012e). This sector employs over 2 million people and accounts for the largest share of employment in both PEI and Saskatchewan (AAFC, 2011).

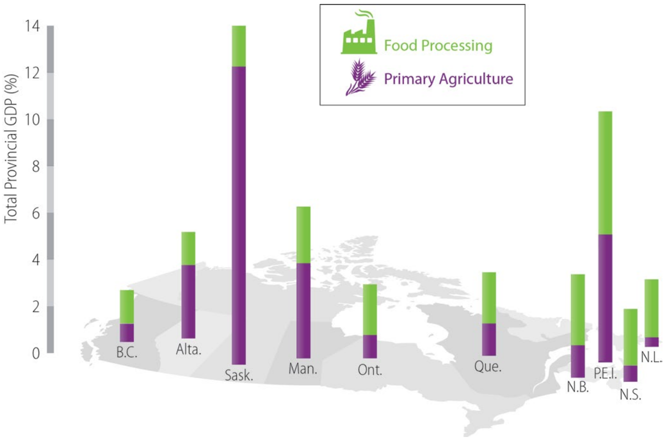


**FIGURE 3:** Contribution of food processing plus primary agriculture to provincial GDPs in 2011 *(modified from AAFC (2012e)*, chart B1.5). 2011 data is preliminary. Excludes beverage and tobacco processing.

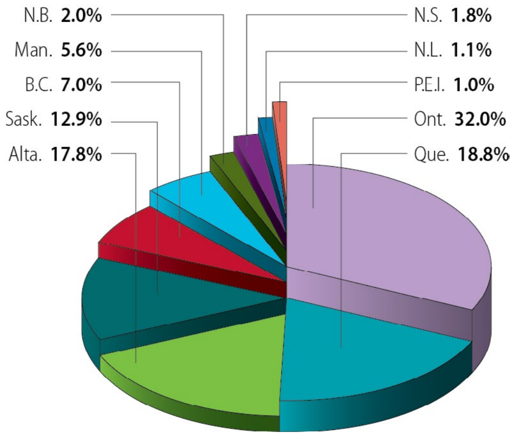


**FIGURE 4:** Distribution of agriculture and food processing contribution to the Canadian agricultural GDP *(modified from AAFC (2012e), chart B1.6).*

Over the last 70 years, there has been consolidation in the sector with 732 800 farms in 1941 decreasing to 205 700 in 2011. While about 62% of farms currently gross under $100 000, the number of farms with gross receipts over $500 000 increased from 19 817 in 2006 to 23 579 in 2011 (Statistics Canada, 2012). Farms with revenues greater than $1 000 000 accounted for 20% of total operating revenues in 1994 rising to 50% in 2009 (AAFC, 2011). At the same time, farm debt has been steadily increasing (NFU, 2011). The data suggest that farmers are continuing to invest in land and equipment, as well as paying more into operating loans and input suppliers (NFU, 2011). The average age of farmers has also risen (Statistics Canada, 2012).

The types of commodities produced across Canada depend on many edaphic (e.g. soils, topography), climatic (e.g. length of frost-free season, precipitation patterns), socio-economic (e.g. consumer preferences, regulatory environments) and historic factors (*see*, for example, Clark, 2010). Figure 5 shows the distribution of commodities amongst farms, while Figure 6 shows the distribution across regions. The largest crops by total field crop area in 2011 were canola at ~22.5 % and spring wheat at ~20% of total farm area respectively (Statistics Canada, 2012). Crop-based farms accounted for 58.4% of farms while livestock-based farms comprised 41.6 % in 2011 (Statistics Canada, 2012).

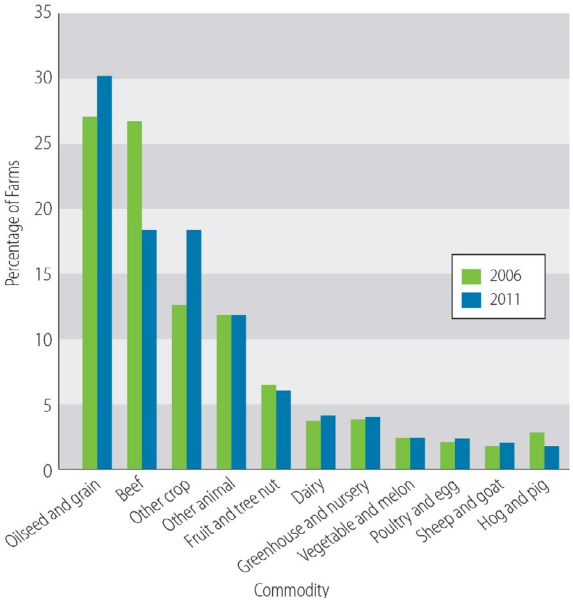


**FIGURE 5:** Percentage of farms by commodity for 2006 and 2011 *(modified from Statistics Canada, 2012).*

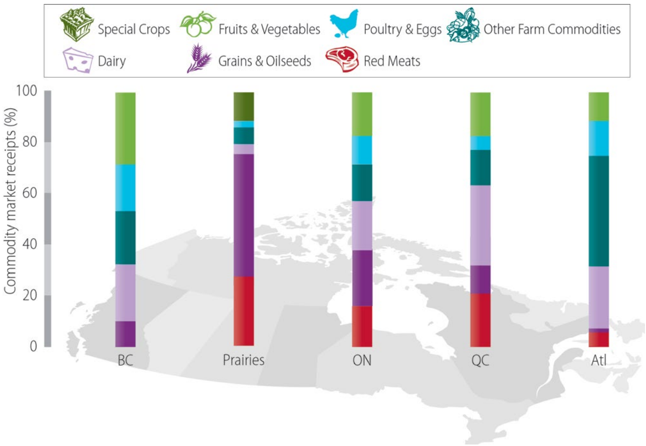


**FIGURE 6:** Commodity market receipts by region for 2009 *(modified from AAFC, 2011, Chart C4.6).*

Another trend in agriculture is the increasing awareness of the importance of sustainable farming. Operations with completed environmental farm plans increased from 13% in 2001 to 35% in 2011 (AAFC, 2014). No-till farming, which can enhance soil health by reducing compaction and increasing carbon storage, water and nutrient infiltration, increased from less than 10% in 1991 to almost 50% of cropped land in 2006 (AAFC, 2011). Water quality is better protected by the increasing use of riparian buffer zones, controlled tile drainage and controlling livestock access to natural surface waters (AAFC, 2011). Greenhouse gas emissions from agriculture decreased by 2.6% between 1990 and 2007, largely due to changes in land use (AAFC, 2011). New or modified technologies and processes are creating more efficient machinery and practices that aim to decrease both on-farm costs and the impact of operations on the landscape.

The livestock sector has shown a downward trend in numbers of animals (e.g. hogs and beef cattle) due to a number of events, including restrictions in cattle exports, high feed prices and a strong Canadian dollar for hog exports (AAFC, 2013). Dairy cattle numbers decreased from nearly 1 800 000 in 1981 to 961 726 in 2011, even as total milk production has remained stable at around 7.5 million kilolitres (Statistics Canada, 2012) due to gains in efficiency (AAFC, 2013) through animal genetics, feed management and other practices (AAFC, 2011).

## 2.3 KEY FINDINGS FROM PAST ASSESSMENTS

Agriculture was addressed in most of the regional chapters of '*From Impacts to Adaptation: Canada in a Changing Climate 2007*' (Lemmen et al., 2008), generally as stand-alone sections describing a wide range of impacts (positive and negative), examples of current adaptation initiatives, and discussion of future adaptation options. Those chapters demonstrated that changes in temperature and precipitation regimes will have important effects on agriculture in Canada, intensifying existing risks, as well as presenting new challenges and opportunities. While all of Canada will be affected, the impacts will not be uniform across the different agricultural landscapes, with distinct issues for four regions: 1) Eastern and Central Canada; 2) Northern Canada; 3) Prairies; and 4) British Columbia.

### EASTERN AND CENTRAL CANADA

*(from Bourque and Simonet, 2008; Chiotti and Lavender, 2008; and Vasseur and Catto, 2008)*

Increasing spring runoff will be a key challenge for this region, presenting concerns regarding flooding (potentially increasing field nutrient losses and surface water pollution) which could make it more difficult to complete spring seeding and other field operations. Increasing spring precipitation and higher intensity storms will also impact manure storage, increase runoff of livestock manure and soil nutrients from fields into riparian zones, and increase soil erosion. Adaptation could involve revising management practices and, in some cases, building runoff retention structures (including wetlands).

Increasing summer temperatures are expected to increase growing season length and allow some crops to be grown farther north, with some crops benefiting and others being negatively affected. Increased evaporation could cause water stress and potentially decrease productivity. Reduced water availability might be partially offset by increased water use efficiency by crops under higher $CO_2$ conditions. An increased likelihood of winter bud kill (especially fruit trees and vines) and the occurrence of more variable, late killing frosts could result in heavy crop losses, as could potential increases in agricultural pests, diseases and weeds.

Livestock operations can expect reduced heating and increased air conditioning needs, as well as more heat waves that will require adaptations such as adding more shade trees to pasture lands. While dry heat waves can decrease animal weight gain, reduce milk production, and reduce conception rates, warmer and wetter conditions can also negatively impact animal health as a result of increased numbers of ticks, mosquitoes, parasites and bacteria. However, livestock may benefit from warmer winters since they can be fattened longer outdoors.

### NORTHERN AND REMOTE COMMUNITIES

*(from Furgal and Prowse, 2008)*

Climate change is affecting the availability and quality of wild foods such as berries, wild rice and game animals, all of which are key elements of country food systems. Food shipments to the north will be affected by a shorter ice-road season (a cheaper way to ship large bulk items to some northern communities). Reduced sea ice cover will result in a longer marine transport season that may benefit coastal communities with port facilities, although the effects of more intense storms and changing ice conditions need to be taken into account.

### PRAIRIES

*(from Sauchyn and Kulshreshtha, 2008)*

Water issues present the greatest concerns for the Prairies. Reduced summer rainfall affects both groundwater quality and availability. Increased drought frequency and intensity, increasing demand to plant more high-value crops, greater demand from non-agricultural users (e.g. oil, gas and potash extraction) and the need to maintain river flows for aquatic ecosystems, may limit the ability to expand irrigated agriculture and livestock. Increased spring floods could increase soil nutrient losses and algae blooms in catchment basins.

While a warmer climate will likely lengthen the growing season, it will also reduce snow cover during winter, leading to less cover protection against soil erosion by winter winds. Increasing pests and diseases are also likely in a warmer climate, as southern organisms move north and northern organisms are less impacted by winter die-offs. Integrated plans and policies for holistic water management at the regional and watershed levels (e.g. capturing excess water for use during droughts) may need to be revised or developed.

### BRITISH COLUMBIA

*(from Walker and Sydneysmith, 2008)*

Reduced summer stream flows, reduced groundwater recharge and increasing demands for water from other sectors will challenge water resource management for agriculture. Agriculture in the Okanagan Valley is already heavily dependent on irrigation, and increasing temperatures and longer growing seasons will mean higher crop-water demands that existing infrastructure may be unable to meet. In coastal regions, sea level rise could cause saltwater intrusion into aquifers as well as coastal inundation of farmland, resulting in a loss of farmland and decreased quality of drinking and irrigation waters.

Increased heat could bring a higher risk of pests, fires and summer drought, which can impact fragile wineries and orchards and affect agri-tourism. Shifts in climate could permit the growth of cereals and potatoes in the interior, along with corn and tomatoes, as far north as Prince George. Adaptations currently in use, such as wind machines to offset late frosts in orchards and wineries, evaporative cooling by irrigation to offset crop heat stress, water licensing for water use to reduce waste, and processes for pest management will need to be adjusted to deal with changing conditions.

## 2.4 RISKS, OPPORTUNITIES AND ADAPTATION

This section discusses the many different risks and opportunities that the Canadian agriculture sector faces from a changing climate, focusing on new findings.

### 2.4.1 LAND SUITABILITY FOR CROPS

The Land Suitability Rating System (LSRS) assesses the climate, soil and landscape characteristics of an area to derive a suitability class rating for the production of a specific crop (AAFC, 2012a). The final land suitability class is based on the most limiting of these factors (climate, soil or landscape). Suitability is expressed in a 1 to 7 rating system where Class 1 has no significant limitations for production of a specific crop and Class 7 is unsuitable for agriculture (Agronomic Interpretations Working Group, 1995). Table 1 describes the severity of limitations associated with each suitability class and groupings of classes for the assessment of potential differences due to climate, soil or landscape.

| Suitability Class | Description | Groupings of suitability classes |
|---|---|---|
| Class 1 | Land in this class has no significant limitations for production of the specified crops | None to Moderate Limitations |
| Class 2 | Land in this class has slight limitations that may restrict the growth of the specified crops or require modified management practices | |
| Class 3 | Land in this class has moderate limitations that restrict the growth of the specified crops or require special management practices | |
| Class 4 | Land in this class has severe limitations that restrict the growth of the specified crops or require special management practices, or both. This class is marginal for sustained production of the specified crops | Severe Limitations |
| Class 5 | Land in this class has very severe limitations for sustained production of the specified crops. Annual cultivation using common cropping practices is not recommended | |
| Class 6 | Land in this class has extremely severe limitations for sustained production of the specified crops. Annual cultivation is not recommended, even on an occasional basis | Not Suitable |
| Class 7 | Land in this class is not suitable for the production of the specified crops | |

**TABLE 1:** Land suitability classes for spring seeded small grain (SSSG) crops *(Source: AAFC, 2012a)*.

Hewitt et al. (2008) used the LSRS system to present current (1971-2000) and projected agricultural land suitability (2010-2039 based on the A2 and A1B SRES scenarios) for spring seeded small grain (SSSG) crops on the Canadian Prairies (Figure 7). The significant changes in LSRS ratings between 1971-2000 and 2010-2039 were then calculated and mapped for the current (2011) agricultural regions of Western and Eastern Canada (Figures 8 and 9, respectively), using the assumption that climate was the only factor that changed through time.

The analysis suggests that the greatest potential improvement for SSSG crops is in western Alberta and northeastern BC, where 5.3% of the land shown could improve. Only a very small amount of land (0.4%), shows decreased potential, primarily on the eastern Prairies and in southern Ontario.

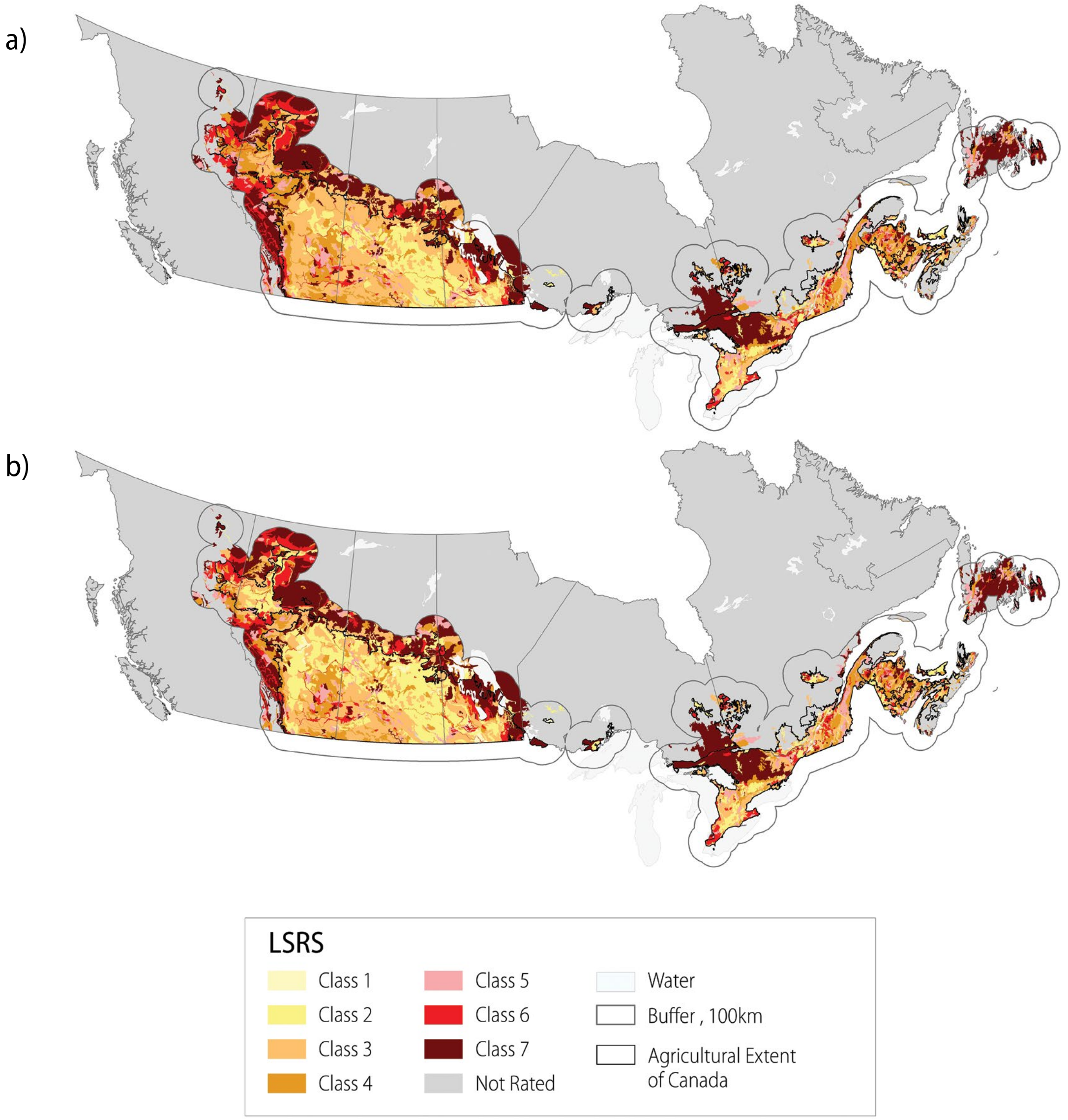


**FIGURE 7 (a, b):** Map of land suitability for spring seeded small grain (SSSG) crops based on climate data for **a)** 1971-2000 and **b)** a scenario of projected land suitability based on modeled climate data for 2010-2039, as prepared by AAFC (2012a) using Hewitt et al. (2008) methodology and updated Soil Landscapes of Canada (SLC) spatial data (Schut et al., 2011). Note: the southern and central areas of British Columbia were not included in the figures because the modelled climate data was at too coarse a resolution to accurately represent the climate in the valleys where agricultural production could occur.

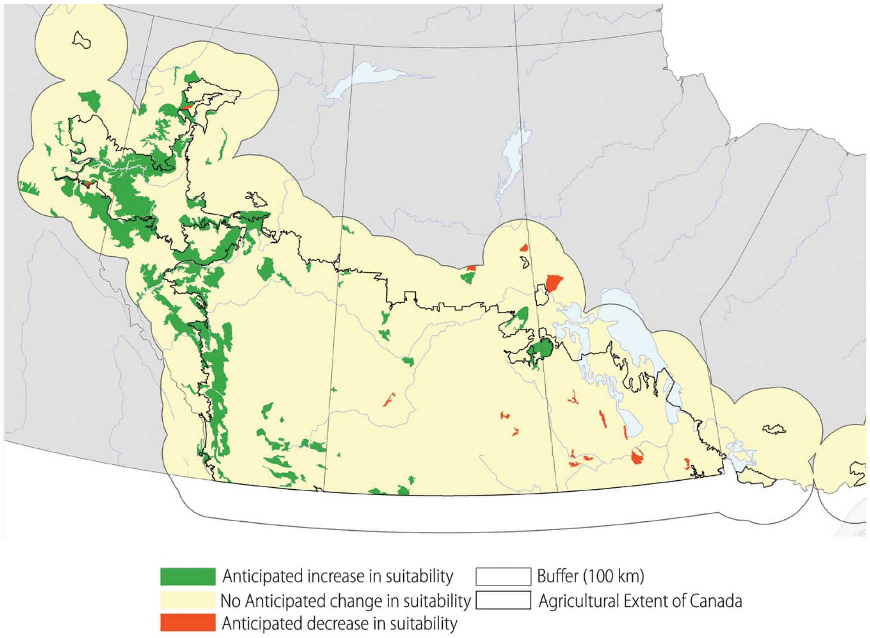


**FIGURE 8:** Map of Western Canada showing projected significant improvement and decline in land suitability for spring seeded small grain crops *(Source: AAFC, 2012a)*.

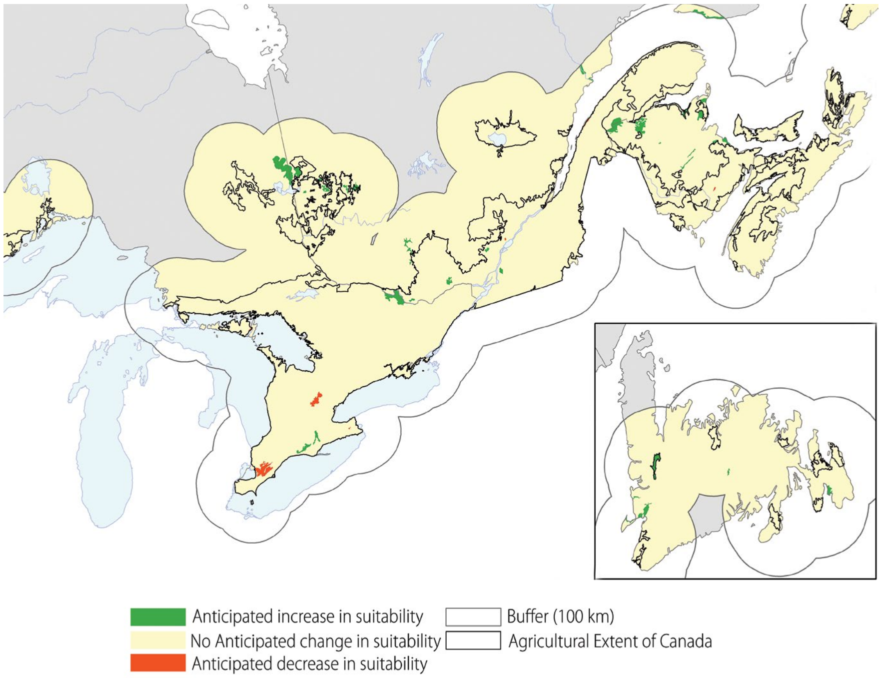


**FIGURE 9:** Map of Eastern Canada showing projected significant improvement and decline in land suitability for spring seeded small grain crops *(Source: AAFC, 2012a)*.

The modelling supports other analyses that indicate a likely increase in potential land for SSSG crops into some areas that are further north, and into areas that are now primarily hay and forage. The modelling also shows that potential for SSSG crops in dry areas could remain the same or increase slightly, assuming that producers seed earlier in order to decrease exposure to drier late summer conditions (AAFC, 2012a).

### 2.4.2 CROPS/CROPPING SYSTEMS

A literature review by Kulshreshtha et al. (2010) identified uncertainties in yield predictions, implying that crop productivity could either increase or decrease in a changing climate. Some of the uncertainty was attributed to studies not considering indirect effects of climate change on pests, diseases and weeds and other factors that influence crop production, such as soils (Wheaton and Kulshreshtha, 2009). Uncertainties in yield projections also include gaps in our current understanding of climatic variability, including how various teleconnections such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) currently interact and how these interactions could be impacted by future climate change (Reuten et al., 2012; *see also* Box 1).

While production of new crops may be agronomically feasible, there are uncertainties as to whether producers would be able to adapt their operations in a timely manner, due to factors such as financial constraints (Kulshreshtha et al., 2010), uncertainties in government policy and programs (Pittman et al., 2011) and increased variability in climate (*see* Box 1). Producers will also need to balance changes to a number of shifting variables. For example, early July temperature and precipitation conditions are critical for canola yield; higher maximum temperatures negatively affect yield, and higher than average precipitation positively affects yield (Kutcher et al., 2010).

Future climate scenarios for the Canadian prairies may favour increased use of pulse crops in rotations, including the increased use of fall seeded pulse crops (Cutforth et al., 2007). Chickpea and lentil cultivars are suited to climatic extremes of frost and drought, for example, as they require physiological stress (e.g. by drought) to terminate flowering and induce seed set (Saskatchewan Pulse Growers, 2000). In response to warmer and longer growing seasons, soybean production may shift northward into Saskatchewan and other parts of the Prairie region (Kulshreshtha, 2011) and conditions may become more suitable for corn production on the prairies. Sorghum could be well suited to new climate conditions since it produces an extensive root system early in its development and closes its stomata quickly when faced with increasing water deficit (Almaraz et al., 2009). Adaptation practices that protect crops from wind damage and high evaporative loss, such as stubble contouring and reduced tillage, will become even more important tools in prairie crop management (Cutforth et al., 2007).

In British Columbia, seasonal and spatial patterns of projected warming and increases in precipitation (*see* Crawford and McNair, 2012; Zwiers et al., 2011; and Chapter 2 – An Overview of Canada's Changing Climate) would allow more options for cropping, and potential benefits for grazing and livestock operations. However, warmer, drier summers can increase susceptibility to drought, and wetter autumns can pose an increased risk to harvesting success. A projected increase in growing degree days in the valley areas surrounding Prince George by the 2050s would make the climate conducive to growing canola and other crops that previously could not have been grown in this area (Picketts et al., 2009).

**BOX 1**

#### CLIMATE VARIABILITY – A KEY CHALLENGE FOR PRODUCERS

Farming as an annual undertaking depends heavily on seasonal weather, but as an industry and business, it depends more on the inter-annual predictability of seasonal weather. A farmer who knows the range of conditions that will be faced over a period of years can select crops, practices, and infrastructure investments that will allow profit to be drawn from those conditions. It is the unpredictability of conditions that causes farm losses. A major difficulty in assessing agroclimate under climate change scenarios is therefore our incomplete understanding of current climate variability (Reuten et al., 2012), and the expectation that future climate will be not just warmer, but more variable. Recent progress in understanding multi-decadal cyclic patterns in atmospheric pressure–ocean current relationships such as the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), the Atlantic Multi-decadal Oscillation (AMO), and the sub-decadal El Niño-Southern Oscillation (ENSO) has helped explain some of the climate variability in Canadian agricultural areas (Perez-Valdivia et al., 2012, Reuten et al., 2012). However, to better project the future variability of agroclimate, a better understanding of how and to what degree climate change will interact with these short and long cycle teleconnections is needed.

Over the past three decades, Quebec's Montérégie region has seen a general trend of increasing temperature, with the greatest change in the growing season occurring in September when mean temperatures have increased by 0.8°C (Almaraz et al., 2008). The warmer and longer growing season will benefit corn, soybean and forage productions (Ouranos, 2010). The cultivation of corn and soybeans might extend into new regions with the appropriate soil and topography, such as Saguenay-Lac-Saint-Jean, Abitibi and Bas-Saint-Laurent–Gaspésie (Ouranos, 2010). Maple syrup production in the region will also be affected (*see* Case Study 1).

### 2.4.3 PESTS, DISEASES AND INVASIVE ALIEN SPECIES

Many agricultural pests and diseases are climate-sensitive, and are expected to respond to climate change with changes in the frequency, severity and distribution of outbreaks (Aurambout et al., 2006; Gagnon et al., 2011; Gagnon et al., 2013; Luck et al., 2014). The impact on food production is difficult to predict, in part because the climatic ecology of many of these pests and diseases is poorly understood, and in part because the severity of losses due to these pests and diseases will be a function not just of their ecology, but also of decisions made around pest and disease control, crops and agricultural practices, and other management decisions

#### CASE STUDY 1

### MAPLE SYRUP AND CLIMATE CHANGE

Maple syrup is a quintessential Canadian product – thanks to a warming climate. A century ago, some 80% of the world's maple syrup was produced in the United States (USA) and 20% in Canada. Today Canada produces about 85% of the world production of maple syrup (AAFC, 2007), with Quebec accounting for 90% (7.7 million gallons) of Canadian production in 2011 (Statistics Canada, 2011).

Northern USA tree species such as the sugar maple are moving north at nearly 100 km per century, with significant movement since 1971 (Woodall et al., 2009). Projections to 2100 for sugar maple range movement in Quebec (Duchesne et al., 2009) and in Ontario (Lamhonwah et al., 2011) show continuing northward movement, although the movement into northern Ontario will be slowed by poorer Canadian Shield soils (Lamhonwah et al., 2011). Many US states have reported that syrup seasons are starting and finishing earlier, that temperature can be too warm to get full production and that the syrup collected is of lower grade with less sugar (USDA, 2012).

Optimal temperatures for the maple sugaring season are -5 °C at night and +5 °C by day for the sap to flow in economically viable amounts (AAFC, 2007; Figure 10). With this temperature range moving north, Canada has gained a much larger part of the industry. With sap flow days moving forward, possibly by as much as 30 days by 2100 (Skiner et al., 2010), start times for tapping trees will need to be adjusted, assuming that the trees are able to adjust to earlier flow times (Duchesne et al., 2009). Planned adaptation could involve investing and installing new, more efficient collection systems that have been shown to increase yield, and increasing quotas in order to allow more new taps to make up for shortfalls (Duchesne et al., 2009).

**FIGURE 10:** Maple sap collection is moving northward as temperatures warm *(Photo © 2007, Her Majesty the Queen in Right of Canada, as represented by the Minister of Agriculture and Agri-Food).*

(Luck et al., 2014). Examples of adaptation measures include earlier detection of pests to better target dates for intervention, the provision of cultivars and integrated pest management tools adapted to the new climate conditions and the development of a sensing network for emergence of new pests (Comité de suivi et de concertation de la stratégie phytosanitaire québécoise en agriculture, 2011; Gagnon et al., 2013). Arguably, the impact on agriculture of new invasive alien species presents greater risks, as there is ongoing research and/or mechanisms in place to manage pests and diseases that are currently present. However, many of the new pests and diseases that could enter Canada due to climate change are already present elsewhere (particularly in the United States) where there may be knowledge to draw from, and control processes in place, that could be adapted and used in Canada (*see*, for example, Case Study 2).

Potential ranges of some climate-sensitive pests and diseases of significance to agriculture have been estimated (e.g. Baker et al., 2000; Aurambout et al., 2009), particularly for invasive alien species, the presence of which can affect international trade through the sanitary and phytosanitary provisions of the WTO. Several countries including Canada are considering how biosecurity policies may need to adapt to climate change and are studying climate change impacts on invasive alien species (Luck et al., 2014). The pest risk assessment process, as currently practiced, involves mapping an organism's current known range against basic climate parameters, which are then used to project the potential range in case of establishment in a new country. Canada and several other countries are using climate scenarios to examine potential future weed and pest distributions (Luck et al., 2014).

In Canada, entry of invasive alien species will increase with increased trade globalisation associated with climate change and other economic and political factors (IPCC, 2007). Potential changes in trade routes, for example the opening of the Northwest Passage, may also alter the risk of introductions (Luck et al., 2014).

The effects of increasing atmospheric $CO_2$ on plant pests and diseases are uncertain; in some cases pest activity may increase or plant hosts may become less resistant, while in others, plant hosts may become more pest resistant and pathogenic (e.g. Chakraborty and Datta, 2003; Fuhrer, 2003; Chakraborty, 2005; Coll and Hughes, 2008).

CASE STUDY 2

### BLUETONGUE: PRIVATE SECTOR AND GOVERNMENT ADAPTATION TO THE POTENTIAL CLIMATE-CHANGE DRIVEN SPREAD OF AN ANIMAL DISEASE

Bluetongue is a viral disease of ruminants, sometimes fatal to sheep but rarely fatal in other animals and not contagious to humans. It is carried by a number of species of midges and could result in closure of export markets. It is not yet believed to have become established in Canada; a handful of Canadian cases are believed to have been due to mites accidentally imported from the United States (Lysyk and Danyk, 2007).

In North America, bluetongue is carried mainly by a species of midge whose Canadian range extends into British Columbia, but not into other provinces at this time. The Canadian Food Inspection Agency (CFIA), the government agency responsible for monitoring such animal diseases, has pre-emptively established five ecologically based regions in Canada for bluetongue control, in the hope that should bluetongue occur in one of those regions, our trading partners will recognize that not all Canadian ruminants are potentially exposed, and trade in animals and products from the other regions will not be affected (CFIA, 2011).

Another pre-emptive adaptation for possible future bluetongue incursions has been implemented by the Canadian Sheep Federation: bluetongue insurance. This voluntary insurance program will compensate insured sheep farmers for loss of animals, business interruption and other consequential losses in the event one of their animals is found to have bluetongue (www.cansheep.ca/cms/en/programs/bluetongueprogram/bluetongueprogram.aspx).

This example highlights several aspects of climate change adaptation for agriculture in Canada, including the proactive response by a government agency and the pre-emptive response by the industry.

## 2.4.4 ANIMAL ISSUES

Livestock management will need to adjust to higher temperatures, shifts in precipitation patterns and adaptation in the cropping sector (Pullar et al., 2011). Livestock producers are keenly aware of the need to increase efficiencies in their operations and reduce their environmental footprint. For example, higher quality feed means less emissions (less gas and manure), higher productivity (more offspring, dairy, eggs) and healthier animals (less susceptible to stress events) (Pullar et al., 2011).

For the dairy industry, great strides have been made in increasing the efficiency of operations. The number of dairy cattle has decreased some 47% while total milk production has remained stable (milk production per cow has increased by 48% from 1981 to 2011; Statistics Canada, 2012). While much of the increased productivity is attributed to genetic selection (Oltenacu and Broom, 2010), the ability of the sector to remain profitable with half the number of cattle suggests producers have strong adaptability capacity, and will be able to adapt farm infrastructure to changing climate conditions.

With the likely increase in crop-growing season length, McCartney et al. (2009) examined the potential in Canada for using warm-season, late-standing crops as feed for cattle. They found that while it could be possible to use residues of corn, sorghum, millet, rape, and turnips and other root crops, there are many caveats, such as the health of the plants, pesticides that were used on the crops, toxins in soils from droughts or floods and nutritional value of the stalks (McCartney et al., 2009). Furthermore, higher annual temperatures would allow producers to consider planting previously unsuitable perennial pastures and winter annual crops. Annual cereals have more flexibility than perennials with respect to planting dates. If planted later, they will produce later seasonal peak yields that can be used to supplement winter pastures (McCartney et al., 2008).

Provincial strategies for climate change adaptation are being implemented that require producers, as well as governments, to consider the effects of climate change on livestock. For example, the Government of Ontario formed a formal partnership with the Animal Health Laboratory at the University of Guelph to support the detection and surveillance of animal diseases, including those that are emerging and evolving as a result of climate change (MOE, 2011).

British Columbia's *Climate Change Adaptation Risk and Opportunity Assessment* (British Columbia, 2012) outlines potential climate change impacts on livestock from climate change, including: changes to livestock grazing management due to too little or too much soil moisture; loss or relocation of livestock due to flooding and other extreme events; reduced water quality and quantity for livestock during dry conditions; warmer winters that could allow diversification of livestock; increased survival of diseases and pests; increasing energy costs due to increased ventilation needs; higher land costs due to increasing pressure on land value as population rises in southern BC; and power outages due to increased frequency of storms and blizzards that affect operations (British Columbia, 2012). Work to date includes a series of regional reports highlighting actions to be undertaken, as well as decision-support tools, such as new irrigation calculators (IIABC, 2009).

In a warmer climate, grassland productivity is expected to increase not only from the longer, warmer growing periods but also because of enriched $CO_2$ environments. Responses of forage crops to climate change are species-specific and there are complex interactions between atmospheric $CO_2$ concentration, temperature, and species (Bertrand et al., 2012). In addition to affecting the yield, future climatic conditions are likely to impact the nutritive value of forages (Bertrand et al., 2012). Increased pasture productivity would increase pasture carrying capacity and reduce cost per animal (Kulshreshtha, 2011). Grassland management, feed management, and use of agroforestry (shelterbelts) have been recommended as possible adaptations to climate change on livestock farms (Climate Change Connection, 2009).

## 2.4.5 EXPORT/GLOBAL MARKET ISSUES

The effects of climate change will vary across Canada and around the world. Risks for some will mean opportunities for others; higher food prices will promote greater investment to produce more food and could result in more spin-off industries such as local seed enterprises (FAO, 2009) and possibly further aquaculture development. However, higher prices mean less choice and reduced access for those with lower incomes. In international trade, agri-food excluding seafood accounted for more than $36 billion of Canadian exports in 2011, more than 8% of Canada's total merchandise exports (AAFC, 2012b). Wheat, canola, canola oil, and pork together accounted for more than $14 billion in exports (AAFC, 2012c). In all, agri-foods contributed more than $9 billion to Canada's trade balance (AAFC, 2012b). While increasing temperatures and $CO_2$ are likely to increase productivity, the effects of negative factors such as reduced water availability, weeds, pests, diseases, invasive species, and extreme weather events are unclear. Furthermore, the effects of climate change on many of our trading partners and competitors are also uncertain. The IPCC estimates that most developing countries will become increasingly dependent on food imports (IPCC, 2007). Given that Canada is one of the world's largest net exporters of agricultural products (WTO, 2000), this likely means increased opportunities for Canadian exporters.

Climate change will affect international trade in foodstuffs in other ways as well. The possible opening of the Northwest Passage may significantly reduce shipping times between North Atlantic and North Pacific nations, increasing trade in fresh produce within the northern hemisphere (Luck et al., 2014). Changes in locations of food production and consumption will also affect international trade, as will the risk of invasive alien species introductions (*see* section 2.4.3).

### 2.4.6 INSTITUTIONAL ADAPTATION

Agricultural practices are continually adapted to cope with climatic variability. Successful agricultural adaptations have historically been achieved with the collaborative efforts of numerous institutions (*see* Case Study 3; Marchildon et al., 2008; Diaz et al., 2009; Hurlbert et al., 2009a; Wheaton and Kulshreshtha, 2010; Corkal et al., 2011). Successful future adaptation for agriculture is likely to require similar multi-disciplinary and inter-disciplinary approaches with the active engagement of stakeholders and institutions that can help coordinate action (e.g. boundary organizations) (Diaz and Rojas, 2006; Batie, 2008; Marchildon, et al., 2008; Hurlbert et al., 2009b).

Institutional arrangements, involving all orders of government working in collaboration with producers, ranchers and other local stakeholders, and using multi-disciplinary and participatory planning approaches to integrate local and scientific knowledge, can assist in addressing current and future climate risks (Nelson et al., 2008; Hurlbert et al., 2009a, b; Corkal et al., 2011). Such adaptive governance can facilitate new technologies, strategies and collaboration, as well as test solutions to local problems, as long as institutions, farmers and local communities can be flexible enough to make the changes necessary to jointly define and solve a shared problem (Nelson et al., 2008; Hurlbert et al., 2009a, b).

Academic and government institutions are undertaking research to better understand climate variability and risk related to agriculture. These include studies that link scientific and local knowledge and inform water management decisions (Marchildon, 2009b; Sauchyn et al., 2010). In turn, watershed groups are encouraging the adoption of improved management practices, such as improved cropping and water management, including irrigation (Diaz et al., 2009).

At the international scale, Canada participates in the Global Research Alliance on Agricultural Greenhouse Gases (GRA), a multinational effort to stimulate and share research in the area of greenhouse gases and agriculture, with an emphasis on technologies and practices that give rise to reductions in greenhouse gas emissions along with increases in climatic resilience and profitability (Shafer et al., 2011).

Examples of federal government policies and regulations which could enhance climate resilience in the agricultural sector include the Livestock Tax Deferral provision which is invoked for areas affected by droughts or floods where producers have been required to sell at least 15% of their breeding herd. Percentages of proceeds from the sale can be deferred as income to the next tax year and may be used to partially compensate for the cost of replacing livestock (CRA, 2011). The Growing Forward 2 (www.agr.gc.ca/growingforward2) policy framework includes business risk management programs and tools, along with three new cost-shared programs to help increase economic sustainability for the agricultural sector. These regional and industry-led programs are designed to address needs in the sector through research, development and knowledge/technology transfer to ensure that innovative solutions are developed for producers in changing market and environmental conditions.

## 2.5 SUMMARY

The agriculture, agri-food, and agri-processing sectors will be affected by climate change in different ways and a diverse range of adaptation techniques will be needed. Innovative research and development, new and updated policies, and adaptive management of farm resources would help to promote an economically sustainable sector in the future..

CASE STUDY 3

## HISTORICAL EXAMPLE OF INSTITUTIONAL CAPACITY FOR ADAPTATION IN THE AGRICULTURAL SECTOR – THE PRAIRIES

In his 1860 report, Captain John Palliser mapped what is now known as Palliser's Triangle after he observed the Prairies during a sustained drought period (Encyclopedia of Saskatchewan, 2007; Axelson et al., 2009). The population in Palliser's Triangle grew rapidly through to the early 1900s, during a wet period – as inferred from proxy tree-ring data during the last 1000 years (Sauchyn et al., 2011). These primarily European settlers did not understand the natural characteristics of the prairie region and were ill-prepared for climate risks from extreme temperatures, strong winds, drought and flooding in this region (Gray, 1996; Marchildon et al., 2008; Toth et al., 2009).

Multi-year droughts during 1914-17 and the 1920s-30s (Figure 11) were devastating to the region's people and ecology, the agricultural sector, rural communities and provincial and federal economies. During the "Dirty Thirties" great tracts of land were lost to soil drifting from wind erosion. De-population of the most affected areas occurred when farmers decided they could no longer survive on their land and began abandoning their farmsteads.

**FIGURE 11:** Drifting soil along fence lines meant loss of top soil in Prairie fields *(Photo is from the Library and Archives Canada collection R194-117-1-E PA-139647).*

Local, provincial and federal governments faced a social, economic and ecological crisis of national significance (Gray, 1996; Marchildon et al., 2008; Marchildon, 2009 a, b; Toth et al., 2009). Citizens and governments were forced to establish new institutional arrangements to better understand the problem, seek solutions for agricultural economic viability, and to strengthen rural community resilience and regional capacity to deal with soil conservation, water management, and sustainable farming practices.

In 1935 (just after the most damaging drought years), the federal government established the *Prairie Farm Rehabilitation Act*, and eventually created the Prairie Farm Rehabilitation Administration (PFRA) with a mandate to "secure the rehabilitation of the drought and soil drifting areas in the Provinces of Manitoba, Saskatchewan and Alberta, and to develop and promote [. . .] systems of farm practice, tree culture, water supply, land utilization and land settlement that will afford greater economic security" (Marchildon, 2009a; Justice Canada, 2012). Farmers and the farm industry worked together to develop innovative new farm implements. Research on farm methods and equipment design was undertaken by Agriculture Canada's Dominion Experimental Farms, universities, and industry. Drought-tolerant crops and new farming methods were researched and field-tested. The province of Alberta created the Alberta Special Areas Board to administer land in a region known as the Alberta Dry Belt, a particularly climate-sensitive area (Gray, 1996; Marchildon et al., 2008).

From the 1930s to 1980s, institutions and farmers worked hard to improve agricultural resilience. Sensitive lands were taken out of production by converting farmland to permanent grass cover or government-managed community pastures. Tillage practices were modified to involve less ground disturbance in an effort to conserve soil and soil moisture. These "minimum tillage" and "direct seeding" practices required new equipment designs which were developed and refined by industry and academia. This adaptation has now become common practice worldwide. Significant institutional efforts were deployed to develop water supplies with the construction of dams, reservoirs, extensive irrigation projects, and water distribution systems (Gray, 1996; Bruneau et al., 2009). The federal and provincial governments of Alberta, Saskatchewan and Manitoba created the Prairie Provinces Water Board to administer and monitor inter-provincial waters (Hurlbert et al., 2009a).

These collaborative institutional efforts are an example of past "institutional adaptations" that not only reacted to an initial situation but were also able to anticipate changes and develop solutions for the future. Today's prairie provinces, once considered as unsuitable for agriculture by Palliser, produce the majority of Canada's $7 billion production of cereal crops (Environment Canada, 2004; Corkal and Adkins, 2008).

# 3. FISHERIES

## 3.1 INTRODUCTION

Fisheries are an important contributor to food production that will be increasingly impacted by a changing climate (Barange and Perry, 2009; Rice and Garcia, 2011). Statistics Canada (2009b) reports that an average of 8 kg of fish (edible weight) per year is consumed by Canadians from retail sources, which translates to approximately 2.2% of national food expenditures (Statistics Canada, 2001). Food trends in Canada suggest that there has been a steady increase in demand for fish and shellfish since the mid-1990s and this increase is expected to rise by over 30% by 2020 (AAFC, 2012d). Changing tastes, healthier eating, availability of culture-fishery products and the appearance of new species at the fish counter are noted as important changes that relate to dietary trends (Statistics Canada, 2005).

Canada's fisheries reflect a diversity of area-specific interactions among climate, hydrology, oceanography, species assemblages, fisheries infrastructure and history of resource use (Figure 12). Climate change impacts on species and ecosystems have cascading effects on fisheries and interrelated human systems (i.e. food systems, cultural and social systems) that rely on aquatic food supplies. The degree of impact will depend on the magnitude of local climate change, the vulnerability of fish and fisheries, and adaptive responses.

This section discusses climate impacts on present and future aquatic food production systems in four major ecoregions (Figure 13, *see* Box 2). Climate change impacts on land-based elements of the aquatic food system (i.e. transport, processing, marketing) are addressed in a detailed case study from the Atlantic ecoregion (*see* Case Study 5). Cumulative effects resulting from multiple stressors on fisheries (i.e. climate and fishing; *see* Frank et al., 2005; Planque et al., 2010); non-renewable resource exploitation, cultural and social change; (*see* Meltofte, 2013); and contaminants (*see* Chapter 7 – Human Health) are not addressed in this chapter.

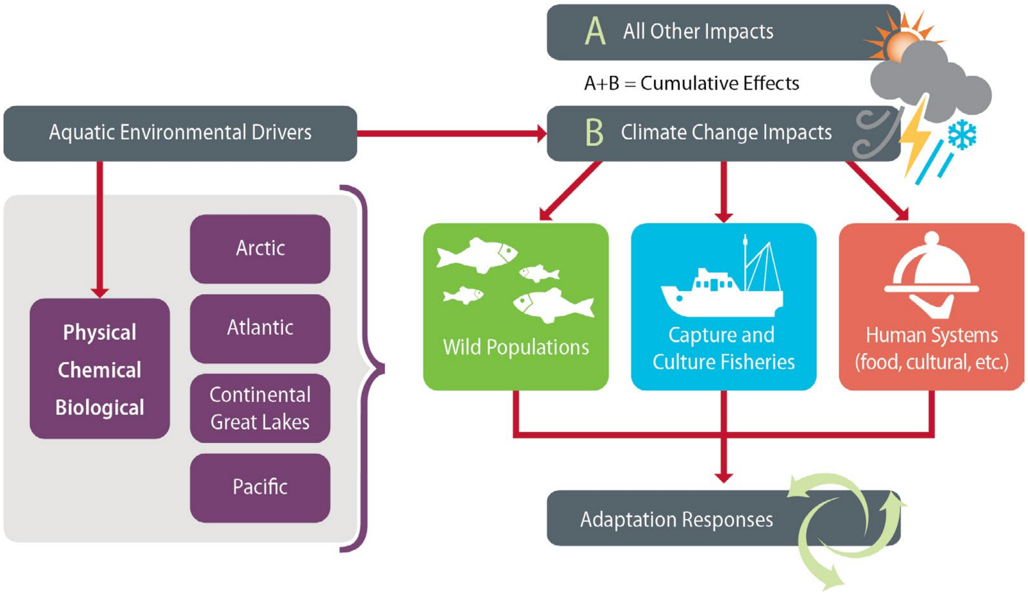


**FIGURE 12:** Pathway of climate change impacts on aquatic food production applied to Canadian aquatic ecoregions.

BOX 2

## CANADA'S AQUATIC ECOREGIONS

**ATLANTIC** – The Atlantic ecoregion is characterized by cold winters, moderate-relief topography, a broad continental shelf and freshwater inputs. Atmospheric forcing affects continuous mixing of the warm, southern Gulf Stream with seasonal inputs of cool and fresh water, as well as sea ice, from the sub-polar Labrador Current and Gulf of St. Lawrence outflows respectively (Loder et al., 1998; DFO, 2012a). Near-surface temperatures are sensitive to seasonal variations in solar insolation, atmospheric temperature, freshwater run-off and strong current systems. Persistent multi-decadal shifts in the ocean climate of the region are influenced by the North Atlantic (NAO) and Atlantic Multidecadal (AMO) Oscillations (Reid and Valdés, 2011). Marine waters exhibit very high secondary production that supports large commercial capture fisheries (Shackell and Loder, 2012). Effects of fishing (Planque et al., 2010) and a cool-phase ocean state (Drinkwater, 2009) have had negative impacts on important groundfish populations.

**ARCTIC** – Defining features are a historically ice-dominated but rapidly changing area (Carmack et al., 2012) that includes an abundance of aquatic habitats which support a specialized assemblage of cold-adapted, late-maturing, resident (e.g. arctic char, walrus) or highly migratory species (e.g. bowhead whale, seabirds). Aquatic ecosystems experience very strong seasonality in sunlight, temperature and freshwater inputs. Ice cover is an important physical feature, affecting heat exchange and light penetration. Areas covered continuously by multi-year ice are generally not productive. However, areas of seasonally-recurrent open water amid sea ice (polynyas) provide critical habitat for a variety of organisms (e.g. under-ice algae, Arctic Cod, seals) and are often described as areas of enhanced productivity (DFO, 2012b). Ice is an important structuring agent influencing both ecosystems (e.g. mammal migrations, foraging locations) and associated human systems (e.g. seasonal travel and access to natural resources). Recent unstable summer ice conditions, ice retreat and altered freshwater input are inducing significant changes in Arctic aquatic ecosystems (Meltofte, 2013).

**CONTINENTAL-GREAT LAKES (CGL)** – This ecoregion forms the largest freshwater system on earth and contains 84% of North America's fresh surface water. CGL ecosystems are driven by continental climate systems that produce warm summers and cold winters during which most rivers and lakes are variably ice-bound. Variations in precipitation lead to annual- to decadal-scale "flood" or "drought" regimes. The latter, combined with strong seasonality, greatly influence river flows, lake surface elevations, nutrient cycling and biological production. Activities associated with more than a century of rapid human population increase have facilitated at least 162 aquatic alien species invasions (Mandrak and Cudmore, 2010) that are associated with many negative changes to CGL ecosystems and fisheries, along with the creation of some new fisheries (e.g. Chinook salmon, rainbow smelt). Modeling exercises suggest future climate change impacts in this ecoregion will result in changes to aquatic thermal regimes with negative consequences for cold- and cool-water species.

**PACIFIC** – The Pacific ecoregion is characterized by a moderate climate, mountainous topography, a narrow continental shelf, many rivers, heavy annual precipitation and a marine transition zone that is variably dominated by conditions associated with either sub-tropical or sub-arctic marine systems (Thomson, 1981). Ocean currents and discharge from major rivers greatly influence circulation, nutrient delivery and primary production of Pacific coastal marine ecosystems. Variability of physical, chemical and biological properties of Pacific coast ecosystems is amplified by the occurrence of sub-decadal El Niño-Southern Oscillation (ENSO) events, as well as decadal-scale shifts between warm and cold-phase states of the Pacific Decadal Oscillation (PDO, Mantua et al., 1997). Biological responses to past climate variability inform much of our understanding of the expected impacts from future climate change on biota in this region (Powell and Xu, 2011).

**FIGURE 13:** Map showing Canada's aquatic ecoregions.

## 3.2 CANADIAN AQUATIC FOOD SUPPLY

Access to the aquatic food supply is achieved through four main supply chains: commercial capture fisheries, culture fisheries, subsistence fisheries and recreational fisheries. Commercial capture fisheries deal with harvest of wild biota; culture fisheries refer to food produced in aquaculture facilities; subsistence fisheries deal mainly with Aboriginal fisheries, plus a component of the subsistence fisheries that overlaps with the broader Canadian recreational fisheries (e.g. food fishery in Newfoundland); and recreational fisheries refer to the licensed harvest of wild biota by individuals and recreational outfitters.

Commercial capture and culture fisheries products are among the most valuable food commodities produced by Canada. Together, harvesters, processors, distributors and retailers comprise Canada's "seafood" industry, which provides a vast array of fisheries products to local, regional, national and global markets (Figure 14). Approximately 85 percent of Canada's commercial fish harvest is distributed via exports to more than 130 countries (AAFC, 2012d). Commercial capture fisheries managed by Fisheries and Oceans Canada (DFO) remain a common property resource, though limited, rights-based mechanisms exist for many fisheries. Subsistence and recreational harvests fall under federal jurisdiction, which may be delegated in such a way that regulatory authorities vary greatly across the country. By contrast, culture fisheries are privately owned investments. Culture fisheries may be licensed and/or regulated by the DFO or provincial bodies on public or private lands. All post-harvest activities related to commercial capture and culture fisheries products are the responsibility of the Canadian Food Inspection Agency and Agriculture and Agri-Food Canada.

Estimates of the quantity and value of commercial capture, culture, recreational and subsistence fisheries for each aquatic ecoregion are shown in Figure 15. Although harvest composition has varied considerably over time, the value of Canada's total unprocessed capture fishery harvest has remained relatively constant (DFO, 2011). However, species contributing to the yield and value of commercial capture fisheries vary greatly among regions (Table 2).

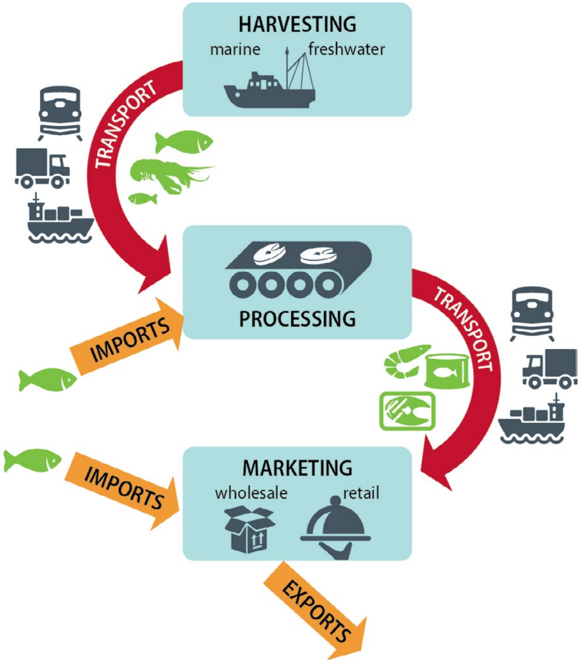


**FIGURE 14:** Diagram depicting the "fish-chain" – incorporating elements of the fisheries food system from ocean to plate.

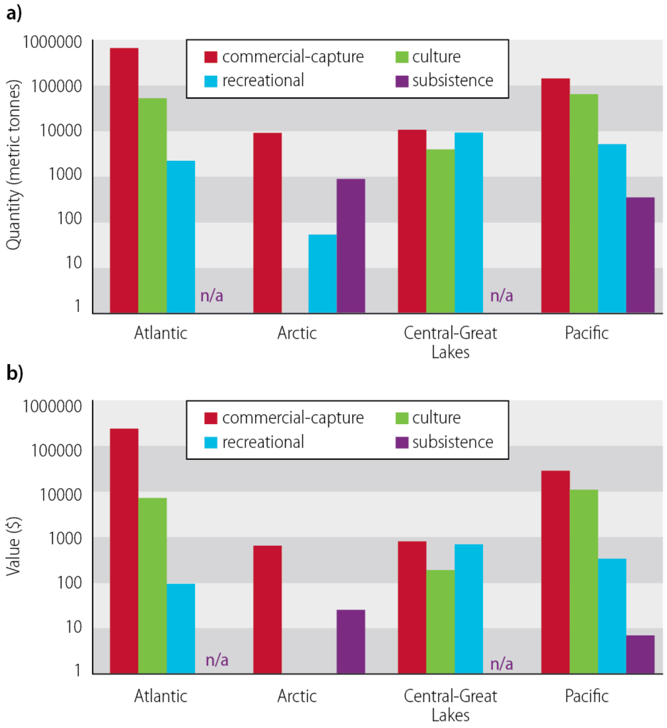


**FIGURE 15:** Estimates (log-scale) of the **a)** quantity and **b)** value of commercial capture, culture, recreational and subsistence fisheries for Canadian aquatic ecoregions (Atlantic, Arctic, Continental-Great-Lakes (CGL) and Pacific). Estimates are provided in log-scale because recreational and subsistence fisheries contributions relative to commercial capture and culture fisheries would not appear if plotted linearly *(Sources: Commercial capture fisheries data (metric tonnes; 2000-2010) retrieved from DFO Fisheries Statistics Branch. Recreational fisheries (number of fish) retrieved from DFO (2012c). Subsistence fisheries quantity (number of fish or metric tonnes) retrieved from DFO Pacific Food, Social and Ceremonial fisheries catch data, Zeller et al. (2011) and Robards and Reeves (2011). Quantity of marine mammal harvest is estimated by using the average weight of the ringed seal (~60kg). Numbers of fish was converted to weight using a conversion factor (Usher, 2000). Value was estimated for all fisheries by applying a mean protein replacement cost of $11.2/kg derived from two sources: Government of Nunavut and Nunavut Tuunggavik Incorporated, 2005 and G.S.Gislason & Associates Ltd and Outcrop Ltd., 2002).*

| Ecoregion | Commercial capture fisheries[1] | Culture-fisheries[1] | Recreational fisheries[2] | Average (+/-SD) percent of population participating in recreational fisheries[3] | Subsistence fisheries[4] |
|---|---|---|---|---|---|
| **Atlantic** | Lobster, shrimp, crab | Atlantic salmon, mussels, oysters | Brook trout, Northern cod, mackerel | 8 +/- 4.2 | Atlantic cod, American lobster |
| **Arctic** | Greenland turbot, shrimp, Whitefish, Arctic char | n/a | Northern pike, Arctic grayling | 10 +/- 8.9 | Arctic char, lake whitefish, marine mammals |
| **Continental-Great Lakes** | Perch, yellow pickerel, lake whitefish | Rainbow trout | Yellow pickerel, perch | 8 +/- 1.4 | Lake whitefish, lake sturgeon |
| **Pacific** | Pacific halibut, Pacific salmon, crab, clams | Atlantic salmon, clams, oysters | Pacific salmon, trout | 9 | Pacific salmon |

**TABLE 2:** Commercially or culturally important species harvested in ecoregions and percent of population participating in the recreational fishery by ecoregion *(Sources: [1]DFO Fisheries Statistics Branch; [2]DFO 2012c: [3]Statistics Canada 2009a. Atlantic is the average of NF, PEI, NB and NS, Arctic is the average of NWT, YK, NUN, CGL is ON, and Pacific is BC. [4]Atlantic: Lowitt (2011); Arctic: Zeller et al. (2011), Robards and Reeves (2011); CGL: Kerr (2010); Pacific: DFO Pacific Food, Social and Ceremonial fisheries catch data).*

Culture fisheries in Canada have only recently appeared as a major supplier of products to Canada's food system. Culture fisheries production has grown by over 130% since the mid 1990s (Statistics Canada 2009a) and was valued at nearly $846 million in 2011 (DFO, 2013b). In 2011, salmon (mainly Atlantic salmon) accounted for about 72% of total cultured-fish value, with shellfish and trout making up most of the balance (DFO, 2013b). While important contributors in the Pacific and Atlantic ecoregions, culture fisheries contributions from the Arctic are virtually non-existent and only minor in the CGL ecoregion.

The rise of culture fisheries is attributable to several factors including:

- lower annual variability in the ratio of costs to yield and increased certainty of year-round product availability to markets compared to wild capture fisheries;
- the capacity to respond to increased future demand from markets for high value products; and
- elevated control over operations, due to the private – rather than common – property nature of the resource (DFO, 2003).

Globally, cultured production of aquatic foods is forecast to continue to increase due to rising demand and improved production methods, and could potentially surpass global consumption of supply generated through commercial capture fisheries in the near future (Figure 16; OECD-FAO, 2011).

Subsistence fisheries, most often accessed by Canada's Aboriginal peoples, represent an economic system that is based on cultural and social networks that support the distribution of goods and food for consumption by the harvesters, their families and the community (Berkes, 1988). Subsistence fisheries are carried out in all four ecoregions. These fisheries contribute directly to food security by

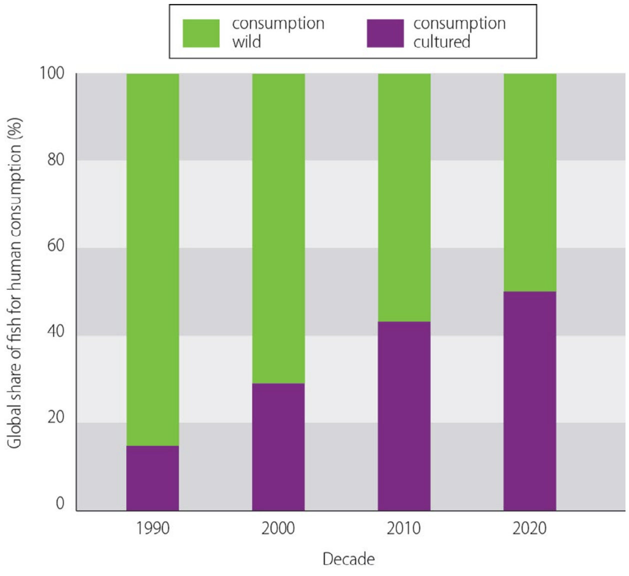


**FIGURE 16:** Global share of fish for human consumption originating from capture and aquaculture by decade *(modified from OECD-FAO Agricultural Outlook 2011 – © OECD 2011).*

supplying fish for consumption, or indirectly by generating earnings for the purchase of other food (i.e. the polar bear hunt) (*see* Box 3 and Chapter 7 – Human Health).

A recent estimate of marine mammal consumption put rates of harvest across the Canadian Arctic among the world's highest (>1000 animals per year), with more than 20 different species being utilized (Robards and Reeves, 2011). The value of the harvest, including several fish species and marine mammals for the Northwest Territories and Nunavut, was $3.4 million, based on a replacement cost of $20 per kg (G.S. Gislason & Associates Ltd and Outcrop Ltd., 2002). The Nunavut Fisheries Strategy (2005) estimated the replacement cost for Arctic char to be $2.3 per kg. We used the average of these estimates to represent the comparative value of subsistence and recreational harvests across ecoregions. Fisheries values presented here do not include any additional market or cultural valuations.

Recreational fishing is conducted for sport by many participants, from which a component of the harvest is kept for consumption. Estimated retained harvest for direct consumption by resident anglers was approximately 57 million fish (DFO, 2012c). These fisheries also generate economic gains for associated industries (lodges, guiding, equipment supply, etc.; Kerr et al., 2009) and are valuable from cultural and social perspectives. The popularity of recreational fishing varies across the country, with spending in Canada of $7-8 billion annually (OMNR, 2013b).

## 3.3 KEY FINDINGS FROM PAST ASSESSMENTS

*'From Impacts to Adaptation: Canada in a Changing Climate 2007'* (Lemmen et al., 2008) found that climate change would have significant impacts on the future integrity of freshwater and marine ecosystems across the country. Findings included:

- Species assemblages were expected to become more southern in character due to impacts of temperature change on the abundance and timing of key life history events.
- Increasing temperature would impact species at the edge of their distributional range, rendering them subject to extirpation or expansion.
- Significant changes in northern hydrologic systems, including reductions in permafrost, reduced sea ice duration and altered snow depth would affect fish and marine mammal distribution and abundance in the Arctic and Atlantic.
- Increased storm intensity and unpredictable weather would impact coastal erosion and sediment flux, thus altering nearshore foraging and spawning areas for aquatic animals.
- Shifting species distributions and abundance could encourage more distant-water and higher-risk activities by harvesters in some areas.

Responses of fish and impacts on fisheries were expected to vary due to differences in the geographic scale and physical boundaries that define freshwater and marine ecosystems. For example, while freshwater fish are relatively immobile in the short-term due to topographic fragmentation of aquatic systems at both small and large scales, Canada's marine fisheries have already exhibited many short-term changes in distribution and abundance of species in response to variations in ocean climate. In addition, evidence from Arctic ecosystems suggested that changes to the timing and success of life history events (e.g. migration, growth, reproduction etc.) for native species of fish and marine mammals – which have strong ties to regional food systems and food security – were already responding to climate-induced change.

Commercial capture fisheries are highly constrained by regulatory regimes in all parts of Canada, reducing the likelihood of rapid adaptation through harvesting of new species, or changes to fishing locations, times or methods of capture. In general, the adaptive capacity of the sector was dependent on governance keeping pace with changes to resources. Given projections of altered resource availability to various commercial capture fisheries, adaptation suggestions centred on developing strategies to identify either new capture fisheries opportunities, or alternately, to accelerate development of culture fishery opportunities that offer greater control over production outcomes. Changes to the design and management of fisheries were suggested as ways to increase the resilience of fisheries-dependent, social and economic systems to climate change.

## 3.4 CLIMATE CHANGE EFFECTS ON AQUATIC SYSTEMS AND FISHERIES

### 3.4.1. IMPACTS ON ECOSYSTEMS

A wealth of empirical observations, as well as modeling of climate-related impacts on freshwater (Chu et al., 2008; Minns, 2009; Sharma et al., 2007; 2009) and marine ecosystems (Beaugrand et al., 2002; 2008; Brander, 2007; Cheung et al., 2009; 2010; Blanchard et al., 2012) suggest that changes to biodiversity and biota supporting fisheries at regional scales can be significant. However, evidence of climate change impacts on aquatic ecosystems is variable and region-dependent (Burrows et al., 2011).

Climate and socioeconomic change in Canada's Arctic ecoregion appear to be interacting at historically unprecedented rates (Carmack et al., 2012; Wang and

Overland, 2012). The loss of Arctic sea ice will have profound effects on habitat states, species distributions and range expansions (e.g. invasive or colonizing species) associated with ecosystem structure and productivity changes (Behrenfeld et al., 2006; Grebmeier et al., 2006; Meltofte, 2013).

In the CGL ecoregion, decadal-scale observations of shorter winters, warmer river and lake temperatures, intensified rain and snow events, and decreased ice cover on lakes (Environment Canada/US EPA, 2009) all reflect changing climate. Climate change appears disadvantageous to CGL cold-water species, but advantageous to expansions of warm-water species at the northern end of their range and to existing or new waves of invasions by alien species. Thus, the history of highly unstable species composition in the CGL is likely to persist or even accelerate under the influence of climate change; affecting ecosystems, fish, fisheries and economies (DFO 2012a, b; 2013c, d; Meltofte, 2013). Although some climate-induced changes in the Arctic and CGL ecoregions are creating prospects for new commercial capture fisheries (MacNeil et al., 2010), they also threaten the security of food supplies from subsistence fisheries maintained for millennia by Aboriginal peoples (Meltofte, 2013).

By contrast, in the Pacific and Atlantic ecoregions, changes in marine ecosystem states and fisheries yields associated with variations in ocean climate have been large enough that clear evidence of long-term climate change impacts, as opposed to climate variation impacts, has yet to emerge (DFO 2012a; DFO 2013d). Subsequently, in Canada's Atlantic and Pacific ecoregions, responses of fish and fisheries to climate change are generally projected from conceptual or simulation models of consequences of persistent state changes, informed by responses to historic variations of climate conditions observed during shorter intervals (Overland et al., 2010).

## 3.4.2 IMPACTS ON AQUATIC BIOTA

Impacts on regional ecosystems, fisheries and associated food systems originate from general processes that include: (1) changes in ecosystem production via 'top-down' (harvest by humans) or 'bottom-up' (predator- and nutrient-driven) impacts that cascade through food webs (Pace et al., 1999; Ware and Thomson, 2005; Frank et al., 2006; Hoekman 2010); (2) life history event disruptions that induce changes in productivity or distribution for key taxa that support fisheries directly (Chavez et al., 2003; Martins et al., 2011); and (3) permanent changes in species presence or absence (Perry et al., 2005) that relate to range shifts (i.e. expansion/contraction) of native and alien invasive species (Hellmann et al., 2008; Minns, 2009).

### CASCADING EFFECTS OF ECOSYSTEM PRODUCTION CHANGES

Fisheries supply from a given ecosystem is regulated naturally by aquatic climate and species interactions within complex food webs. Changes in these interactions can affect fisheries production (Ware and Thomson, 2005; Grebmeier et al., 2006; Mandrak and Cudmore, 2010; Shackell et al. 2012) and provide a basis for predictions of future production changes.

Aquatic ecosystems at high latitudes appear more strongly influenced by climate variation and change than by any other driver (Meltofte, 2013). Freshwater input and heat content of Arctic marine water masses have increased since the 1970s and are related to a two-fold increase in the temperature of their Atlantic-origin water (Proshutinsky et al., 2009), reductions in sea surface salinity (Polyakov et al., 2008) and alterations to the amount and duration of summer sea ice (Deser et al., 2000; Niemi et al., 2010; *see also* Chapter 2). These physical changes support a longer growing season and an observed trend for increased plankton productivity in Arctic waters (Niemi et al., 2010; Meltofte, 2013). In the western Arctic, a change from arctic to subarctic conditions has already resulted in a northward shift of the more productive, pelagic-dominated marine ecosystem, previously limited to the south-eastern Bering Sea, and the displacement of marine mammal and benthic fish populations (Grebmeier et al., 2006).

### DISRUPTED LIFE HISTORY EVENTS

Climate change may broadly induce biophysical impacts at the base of aquatic ecosystems or act, more narrowly, to directly influence key life history stages or events of particular species that support fisheries in Canada's ecoregions (*see* Case Study 4). Modelling studies generally suggest that in a warmer climate, the geographic centres of production and/or harvest of commercially important fish species would shift northward or inshore, thus providing potentially greater access to several species (e.g. tuna, mackerel) in Canadian waters (Ainsworth et al., 2011).

### RANGE SHIFTS AND INVASIONS

Aquatic species in the Arctic are already undergoing range shifts associated with circulation changes in Pacific and Atlantic Ocean water masses (DFO, 2012a). In southern freshwater systems, models examining range expansions of important harvested species suggest variable outcomes that depend on species' thermal preference (Table 3). Climate-induced production losses of cold-water species (walleye and lake trout) that currently support key commercial and recreational fisheries, together with invasions or increased production of less valuable warm-water species (carp, catfish), are likely to drive many future changes in CGL fisheries and associated management systems (e.g. lamprey control).

CASE STUDY 4

## PACIFIC SALMON AND CLIMATE CHANGE

In the Pacific ecoregion, decadal-scale changes in the accessible supply of Pacific salmon driven by climate regime shifts (Mantua et al., 1997; Beamish et al., 1999; Figure 17), treaty negotiations with First Nations (Brown, 2005), and the emergence of aquaculture as a major source of supply (Robson, 2006) have profoundly altered the structure and economic security of commercial capture fisheries in general and the salmon fishery in particular (Meggs, 1991; Glavin, 1996; Brown, 2005). Dramatic declines in the supply available to fisheries subsequent to the 1990s, especially those focused on key salmon species, have been accompanied by elevated cross-cultural tensions (Harris, 2001), and local community instability along with coast-wide reorganization of fishing fleet and fish processing infrastructure (Glavin, 1996; Brown, 2005).

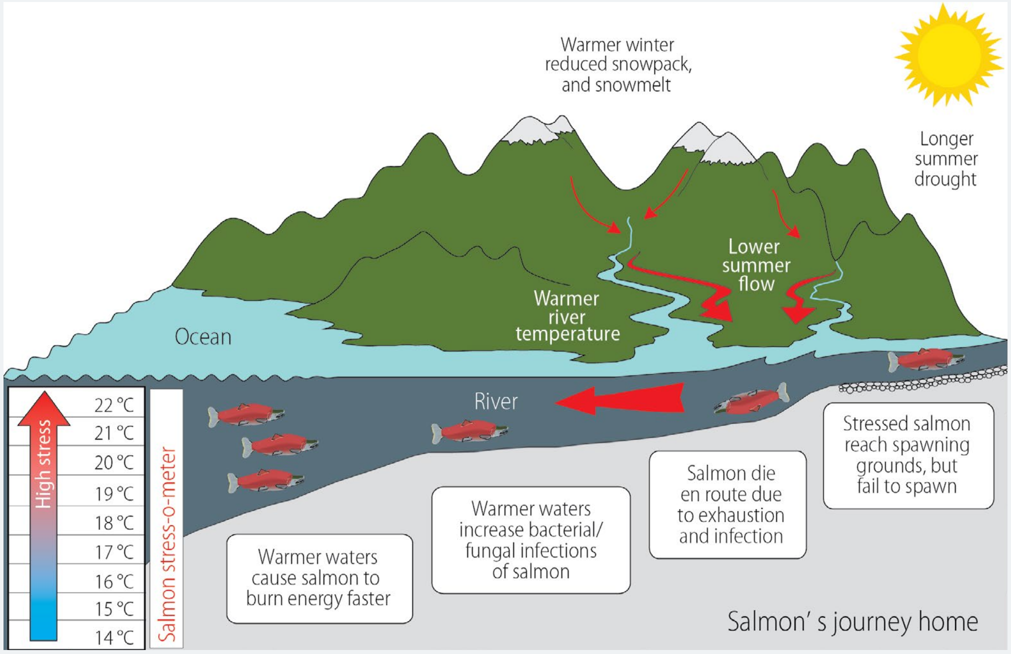


**FIGURE 17:** Climate change effects on waterbodies impact adult Pacific salmon along the journey to their natal streams *(Source: NRCan, 2009)*.

Given the regional, cultural and economic importance of Pacific salmon, these species have been the subject of ongoing research on linkages between climate change and changes in production and/or fisheries yield (e.g. Beamish and Bouillon, 1993; Mantua et al., 1997; Finney et al., 2002; Irvine and Fukuwaka, 2011; Rogers and Schindler, 2011). Sockeye salmon in particular have been the subject of several major reviews, motivated in part by a formal Public Inquiry (Cohen Commission 2010-2012), following record low (2009) and record high (2010) variations in returns and catch of Fraser River fish. Technical reports from the Cohen Inquiry (Hinch and Martins, 2011; McKinnell et al., 2011) allow a reasonably firm conclusion that recent climate change trends in freshwater habitats of the Fraser River were leading to reduced production through influences on adult migration-and-spawning success (e.g. Cooke et al., 2004; Crossin et al., 2008) as well as on juvenile production in freshwater (Peterman and Dorner, 2011). By contrast, although there is strong evidence of a broad regional decline in production of sockeye salmon populations from central to south coastal British Columbia (Hyatt et al., 2008) associated with changes in marine systems (Peterman and Dorner, 2012), the trend is not clearly attributable to long-term climate change as opposed to shorter-term variations that are within the range of historic observations for this area.

These results are consistent with McDaniels et al. (2010) regarding the heightened vulnerability of salmon migration, spawning and incubation success, to climate change effects already apparent in freshwater. Adding to this, longer term climate change impacts in both freshwater and marine environments will accumulate across all life history stages of salmon to produce negative outcomes for southern populations exposed to increasingly unfavourable environments, and either neutral or positive outcomes for northern populations (Healey, 2011).

Information on invasive alien species (IAS) and climate change in aquatic systems in Canada is limited (*reviewed by* Smith et al., 2012). However, in general, responses to climate variation and change will differ between freshwater and marine systems because of differences in constraints on species dispersal (Reist et al., 2006), combined with impacts of invaders on native species already under stress (Pimentel et al., 2005). Overall, climate change will likely exacerbate the impacts of aquatic invasive species on fisheries (Rahel and Olden, 2008), especially in the Great Lakes (USGS, 2012) and Arctic ecoregions (Cheung et al., 2009; Meltofte, 2013).

## 3.5 CLIMATE CHANGE IMPACTS ON AQUATIC FOOD SYSTEMS

### 3.5.1 IMPACTS ON CAPTURE FISHERIES (COMMERCIAL AND RECREATIONAL)

Our understanding of the effects of climate variation and climate change on fish and fisheries is frequently restricted to modelled predictions for both freshwater (*see* Table 3) and marine ecosystems that do not reflect cumulative climate effects and interactions on fisheries yield (with some exceptions, e.g. *see* Crain et al., 2008; Halpern et al., 2008; Ainsworth et al., 2011). However, it is still evident from the models that changes to biodiversity at the regional scale are likely to be significant (Cheung et al., 2009; 2010; Polovina et al., 2011; Meltofte, 2013; *see also* Chapter 6 – Biodiversity and Protected Areas). While effects on biodiversity do not necessarily result in lower biomass or fewer species in aggregate regional catches, the current composition and species-specific yield from regional assemblages are expected to undergo rapid change (Overland et al., 2010; Burrows et al., 2011) resulting in spatial redistribution of global catch potential from southern to more northern waters, that will eventually alter major fisheries in Canada's Atlantic and Pacific regions (Cheung et al., 2009; 2010; Polovina et al., 2011).

In the CGL ecoregion, cumulative impacts of alien invasive species (Mandrak and Cudmore, 2010), climate change, regional human population growth and potential management responses are likely to exacerbate the centennial-scale record of boom-and-bust production observed for both commercial and recreational fisheries (Pimentel et al., 2005; Environment Canada and USEPA, 2009; OMNR, 2013a). Although major commercial and recreational fisheries have never existed in Canada's Arctic, expansion of entirely new suites of subarctic species in response to warming is underway (e.g. salmon; Nielsen et al., *in press*). Thus, major changes to Arctic marine ecosystems, fish and fisheries appear inevitable, and it is also likely that gross production from whatever species assemblage eventually does emerge will support increases in marine fisheries yields (Reist et al., 2006). These resources will contribute to northern food supply and will likely expand in importance under precautionary management (Stram and Evans, 2010; Meltofte, 2013), as needed infrastructure (i.e. small craft harbours) is put in place.

| Species type | Scenario outcome | Reference |
|---|---|---|
| **Cold-water species: lake trout** | Possible 30-40% drop in suitable habitat available for lake trout in Ontario by the end of the century | Minns, 2009 |
| **Cold-water species: cisco** | Warming may extirpate between 25%–75% of cisco populations | Sharma et al., 2011 |
| **Cool-water species: walleye** | Warming may increase available habitat, suggesting a northward shift in the location of the walleye fishery | Hunt and Moore, 2006 |
| **Cold-water species assemblage** | Cold-water species distributions may be reduced to less than 67% of sites within 43 studied watersheds by 2025 (worst case) with the strongest impacts on the most southerly watersheds | Chu et al., 2008 |
| | Warming was a bigger risk factor than an invasive predator (rainbow smelt) for extirpation from cold water lake habitats | Sharma et al., 2011 |
| **Warm-water species: smallmouth bass** | Suitable habitat for smallmouth bass may expand to include most lakes in Canada by 2011 | Sharma et al., 2007 |
| **Species invasion interactions** | A northward gain in suitable habitat by smallmouth bass could increase the number of lakes with vulnerable trout populations to 1612 lakes (20% increase) by 2050 | Sharma et al., 2009 |

**TABLE 3:** Outcomes for freshwater fish species examined under various climate change scenarios (*see also* Dove-Thomson et al., 2011).

Warming of the Arctic will also impact freshwater habitats (Minns, 2009; Sharma et al., 2009) through changes to river and lake ice conditions (Prowse and Brown, 2010), with potential production losses of iconic salmonid species because of their dependency on natural winter ice regimes (e.g. Linnansaari and Cunjak, 2010). Endemic, historically-isolated Arctic species (e.g. char, whales, walrus and polar bear) and fisheries are vulnerable to population decline given expected combinations of climate change, other anthropogenic impacts, and aquatic species invasions (Meltofte, 2013).

Recent assessments (DFO, 2012a, b; 2013c, d) suggest that drastic changes in fisheries yield and value are unlikely to occur in any of Canada's ecoregions within the next ten years. The observations above suggest that, in the longer-term, aggregate fisheries yield in Canada will increase but complex ecosystem and species reorganization outcomes will dictate overall economic value, which remains highly uncertain. Finally, any or all of the changes noted above to commercial capture fisheries yield and related supply chains may influence subsequent distribution patterns among nations (Allison et al., 2009). Changes such as these at either domestic or global scales may translate into shifts in price and value of Canadian harvests, with impacts to gross and net incomes from fishing and fish processing. Changes to operational costs associated with several links in the fisheries food chain could necessitate expansions or contractions of fleet size for countries such as Canada (Sumaila et al., 2011). However, in high latitude areas where harvests do not currently exist, there is potential for financial gain for early participants in new fisheries (Arnason, 2007).

### 3.5.2 IMPACTS ON CULTURE FISHERIES

Climate change has the potential to affect the integrity of aquaculture infrastructure (e.g. net pens, hatcheries), physical habitat settings and species produced. For example, production locations and practices will have different susceptibilities to sea level rise and increases in the severity or frequency of storm events (Moore et al., 2008). In general, from both production and infrastructure perspectives, threats to marine finfish aquaculture appear to be less than for shellfish. Unlike shellfish, cultured finfish do not rely on food sources produced in the culture environment and they do not accumulate biotoxins or coliforms. However, the performance of both finfish and shellfish may be affected by changes in ocean temperature, dissolved oxygen, salinity, acidity (*see* Chapter 2 – An Overview of Canada's Changing Climate) and the occurrence of harmful algal blooms, which may result in lost productivity or direct mortality (Moore et al., 2008). While cultured finfish production is currently dependent on supplies of wild caught forage fish used to produce fish meal, model-based analyses suggest that climate-induced losses of current fish meal sources may be dealt with through innovative development of fish meal substitutes (Merino et al., 2010). Governance and demand-driven costs of alternate sources of fish meal will play strong roles in future production of cultured finfish (Merino et al., 2012). Overall, despite many potential risks, the aquaculture industry should be able to adapt to changing conditions either through technological advances or relocation.

### 3.5.3 IMPACTS ON SUBSISTENCE FISHERIES

Traditional foods provided by the natural environment remain central to Aboriginal health (Hansen et al., 2008, Wheeler et al., 2010). Climate change is likely to induce rapid changes in animal migration patterns, ranges and productivities, which may affect access to a reliable food supply (*see* Box 3; and Chapter 7 – Human Health). These impacts will exacerbate food insecurity for traditional subsistence fisheries in some regions. This will be especially apparent where there are other factors limiting subsistence fisheries, such as fishing allocation policies in the Pacific (Harris, 2001) and where climate variability and change have already resulted in impacts (e.g. in the Arctic; Lemmen et al., 2008).

BOX 3

## NON-COMMERCIAL FOOD SUPPLY

Higher temperatures and changing precipitation patterns are already having an impact on rural and remote environments and communities (Lemmen et al., 2008; A Northern Vision, 2011). Key life-history events for cold-adapted marine mammals at the top of arctic food chains, which are important to regional supply chains, now appear increasingly vulnerable to climate change impacts and potential increases in human activity in the North (Niemi et al., 2010; Meltofte, 2013). Observed impacts of relevance to food systems and security identified by Lemmen et al. (2008) and A Northern Vision (2011) include:

- Winter ice roads have shorter seasons and cost more to maintain, necessitating alternate, more expensive food transport options.
- Permafrost is degrading, affecting the integrity of food delivery infrastructure.
- Arctic sea ice is thinning and threatening ocean mammals and hunting while potentially increasing shipping, tourism, resource exploration and industrial activities.
- Wildlife migration patterns are changing and altering availability of traditional foods (*see* Chapter 6 – Biodiversity and Protected Areas).
- Weather variability and extremes are increasing and changing hunting and transportation routes and increasing the dangers associated with being out on the land or water.
- Traditional food supplies are harder to find as species move or disappear from the region.
- Forests are becoming increasingly vulnerable to pests and forest fires, which is affecting the ecosystems of traditional food supplies (*see* Chapter 3 – Natural Resources).
- Shoreline erosion and storm surges are damaging infrastructure and supply routes.
- Increasing port access, through loss of sea ice, could disrupt traditional lifestyles, bringing new pests, diseases and less healthy foods.
- Melting glaciers are causing short term flooding and may lead to long term drought after they are gone.

The continued effects of climate change on northern and remote communities within Canada could make these communities more vulnerable to food security issues. The homelands, culture, traditional knowledge, and hunting habitats of northern Indigenous peoples could be directly affected. Furthermore, many of these communities depend upon country foods such as wild meat, fish, birds, berries and other plants, all of which are sensitive to changes in climate. Barren-ground caribou in Northern Canada, for example, travel great distances from wintering grounds to calving grounds to insect-relief areas and back again each year. The caribou are now encountering deeper and heavier snow than in the past and appear to be moving away from traditional hunting grounds. Changing climate may also result in reduction or loss of wetlands such as sloughs and marshes, which are important nesting and feeding areas for many migratory birds, and could cause decreasing numbers of birds (Meakin and Kurvits, 2009; *see also* Chapter 6 – Biodiversity and Protected Areas).

Impacts on the Arctic marine food chain will be location-specific. If warmer temperatures affect one part of the chain, they may have ramifications on the entire marine ecosystem. For example, as sea ice melts earlier in the spring and the edge of the icepack gets farther away from land, polar bears have a harder time reaching the seals they require for survival and hunters will require more resources to reach more distant hunting grounds (Ford, 2009).

While northern soils and climate conditions are largely unsuitable for agricultural production, there are some areas that currently have moderate agricultural capability. A longer growing season could allow cultivation of a broader diversity of crops and higher yields, although future precipitation patterns could limit this potential (Ogden and Johnson, 2002). Furthermore, a longer growing season could cause a shift northward in edible plant foods, animals that graze those foods and their predators. While this could increase access to country foods, shifting biomes can also bring or strengthen new diseases and pests that affect humans, flora and fauna (A Northern Vision, 2011).

Climate change planning is an important exercise, and benefits from larger-scale planning activities, such as *The Pan-Territorial Adaptation Strategy: Moving Forward on Climate Change Adaptation in Canada's North* (A Northern Vision, 2011), which proposes approaches for collaborative actions in the three territories, while supporting territory-specific initiatives to meet unique challenges. For example, there is a desire to replace high sugar, high fat, nutrient poor "store-bought" foods that are implicated in rising rates of obesity and diabetes, with healthier traditional and country foods (Kuhnlein and Receveur, 2007) and to consider alternative sources, such as greenhouses and agriculture to supplement the food supply (A Northern Vision, 2011).

## 3.6 ADAPTATION

### 3.6.1 VULNERABILITY AND ADAPTABILITY OF FISHING COMMUNITIES

Continued climate change is expected to induce changes to aquatic ecosystem structure and productivity with resultant changes to the quantity, quality and species composition of fish currently entering food supply chains from Canada's four major fisheries ecoregions. Depending on the resilience of regional supply chains, varying adaptations will be required to minimize vulnerability and maximize opportunity. When ranked at a global scale relative to developing nations with a high dependence on fish in local diets, Canada exhibited low vulnerability to impacts of climate change on its aggregated fisheries supply chain (Allison et al., 2009). However, aggregate statistics often conceal finer-scale differences in food system vulnerability or levels of resilience associated with the full range of culturally and economically important fisheries. In a supply chain with low adaptive capacity, socio-cultural consequences, especially in terms of the food security of the most vulnerable, may result from even small disturbances (Thompson and Scoones, 2009). By contrast, disturbance to more resilient supply chains may bring opportunities, innovation and new pathways of development (Thompson and Scoones, 2009). Consideration of historic responses of fisheries and fishing communities to variations in supply may be used to clarify the origins and nature of vulnerability or resilience exhibited by subsistence, wild-capture and culture fisheries.

### 3.6.2 SUBSISTENCE FISHERIES

Subsistence fisheries, and especially those of Aboriginal peoples in remote communities in Canada's Arctic and Pacific ecoregions, play a defining role for local culture. Subsistence fisheries have repeatedly emerged as a central issue in more than a century of cross-cultural conflict over fisheries in British Columbia (*see* Harris 2001, 2008). Similarly, entitlements to harvest traditional species to meet food, societal and cultural needs of Aboriginal groups scattered from the Yukon to the eastern Arctic are key elements of modern-day treaties with the Government of Canada (*see* Harris and Millerd, 2010, for review). As a result, the maintenance of security of supply of traditional species harvests is extremely important to Aboriginal peoples in Canada. As climate-induced changes to freshwater and marine ecosystems are likely to alter yields and species composition outside of their historic range (*see* Section 3.4), traditional subsistence fisheries harvested at fixed locations or times would appear to be highly vulnerable, with relatively little adaptive scope to maintain customary harvest in cases where the subject species are severely reduced or eliminated by future climate change. This is particularly true in the case of inland and anadromous species.

### 3.6.3 COMMERCIAL CAPTURE FISHERIES

Commercial capture fisheries and the communities that rely on them in the Atlantic, Pacific and CGL ecoregions of Canada have all recently experienced decadal-scale changes in the distribution, abundance and harvest of historically dominant species supporting fisheries. Although these changes cannot be ascribed solely to climate change, they provide useful observations of the relative vulnerability and adaptive capacity of fisheries-dependent communities under stress. For communities with a high degree of economic dependence on fisheries, the magnitude of these changes has been most dramatic in the Atlantic (*see* Case Study 5), but is still significant in the Pacific and CGL ecoregions. Costs and benefits of these changes have been unevenly distributed and economic recovery of communities appears to depend highly on their initial economic well-being (Murray et al., 2005).

Variable climate regimes combined with ongoing waves of exotic species invasions have also had dramatic effects on commercial capture and recreational fisheries in Canada's CGL ecoregion. Although these changes have been accompanied by considerable economic losses (Pimentel et al., 2005), both types of CGL fisheries appear to have at least partially adapted to reductions in harvest of native species (e.g. lake trout, whitefish) through increased harvest of exotic species (e.g. rainbow smelt, Pacific salmon). Moreover, the relatively weaker dependence on fisheries for food-system security in the majority of local communities of the CGL region suggests they have lower vulnerability to climate impacts on fisheries supply chains.

### 3.6.4 CULTURE FISHERIES

The relative absence of control over the basis for wild production that sustains 'wild' fisheries versus increased levels of control associated with intensive culture fisheries is likely to become increasingly important in the face of future climate change. The use of climate change projections to adjust production timing, location of operations and/or identity of cultured species confers an advantage to culture fisheries that is not readily achievable for other supply chains (Barange and Perry, 2009). Thus, although culture fisheries are not without issues (e.g. *see* PFRCC, 2003; Robson, 2006), they clearly display lower levels of vulnerability and greater scope for adaptation to changes in environmental conditions, including future climate change, than either subsistence or commercial capture fisheries. However, the resilience of all types of fisheries will also require that appropriate institutional mechanisms are in place to respond to impacts of future climate change.

### 3.6.5 INSTITUTIONAL ADAPTATION

Technological, behavioural and cultural changes at multiple scales along the fisheries food supply chain are adaptive responses to climate variation and change impacts (*see* Case Study 5). However, all such changes interact, and are interdependent with regulatory and policy frameworks of Fisheries and Oceans Canada (DFO) or their delegates (i.e. provincial agencies, resource management boards). There are several broad categories of activities which together may be viewed as comprising a type of "soft", institutional infrastructure that climate change will influence, and from which general adaptation responses will emerge (Table 4).

The fisheries section of this chapter has principally focused on climate-induced variations in food production and the consequences for harvest as the foundation underlying all subsequent elements of the fisheries food system (e.g. processing, distribution, exchange and marketing, consumption). Although this focus has precluded assessment of climate impact and adaptation responses along the full length of aquatic food supply chains, it is important to recognize their importance. Consequently, a case history of interactions among changes in natural systems and human systems associated with the production and utilization of northern cod is presented to illustrate important and documented interactions among multiple components of a regional food supply chain (*see* Case Study 5).

## 3.7 SUMMARY

Response of fish, as measured by historic trends in climate variation impacts on commercial capture fisheries, suggests that, in aggregate, Canada's fisheries food systems exhibit moderate vulnerability and high adaptive capacity to climate change. In the future, these fisheries will likely continue to harvest a diversity of species that supply food chains at local and global scales. However, this conceals the wide range of vulnerabilities exhibited by traditional, rural subsistence fisheries (high vulnerability), smaller-scale commercial capture and recreational fisheries (moderate vulnerability) and culture fisheries (lower vulnerability) to risks posed by climate change.

| Institutional Infrastructure Element | General Adaptation Response |
|---|---|
| Licensing | Vary licensed time, place and harvest quantity to maintain sustainable fisheries |
| Fisheries Management | Vary investment in monitoring and evaluation of stock status and environmental conditions to ensure effective management of existing fisheries |
| Fisheries Research and Habitat Management | Vary investment in new science supporting existing or new capture and culture fisheries management systems |
| Conservation of Species at Risk | Regulate fisheries and habitat management systems to control risk of extirpation of endangered species |
| Negotiation and Maintenance of Treaties | Modify new or existing treaty provisions to accommodate climate change impacts as climate change risks warrant |

**TABLE 4:** Key institutional adaptation responses by institutional infrastructure element.

CASE STUDY 5

## ENVIRONMENTAL AND ECOSYSTEM CHANGES AND IMPLICATIONS ON NORTHERN GULF SEAFOOD SUPPLY CHAINS AND DIETARY PATTERNS IN NEWFOUNDLAND AND LABRADOR

For nearly three centuries, the cod fishery was the foundation of coastal communities in Newfoundland and Labrador (NL). From the beginning, cod (Figure 18) was a dietary staple and an important export product for the economies of Eastern Canada. Traditional NL foodways changed rapidly with the influx of modern goods and services following confederation with Canada in the late 1940s, and the extended exclusive economic zone jurisdiction over marine resources in the 1970s. Seafood production transformed from traditional small-scale domestic production in the 1950s to industrial production by the 1980s (Sinclair, 1985; Wright, 2001). By the early 1990s, several cod stocks in NL were placed under moratoria because of severe resource decline due to both overfishing and environmental changes (Hutchings and Myers, 1994; Rice et al., 2003). The Northern Gulf cod fishery is a case study for exploring the potential ramifications of environmental and ecosystem changes for seafood production, food security and dietary patterns. The Northern Gulf cod fish stock is migratory in the Gulf of St. Lawrence bordering NL and Quebec.

Both 'potential' and 'realized' fisheries are the product of a three-stage chain: 1) marine ecosystems; 2) harvest activities; and 3) post-harvest activities (processing, marketing and consumption). Potential opportunities along the fish chain can be used to improve institutional linkages for biodiversity conservation, resource sustainability and community well-being, and, in the face of further climate change, the necessary adaptive capacity to deal with these impacts.

**FIGURE 18:** Fisherman filleting cod.

### Marine ecosystems

As typical of large ocean fish stocks, Northern Gulf cod undergo extensive spawning and feeding migrations associated with critical habitats, temperature changes, and food availability (Yvelin et al., 2005). The geography and biophysical complexities of the region, characterized by arctic fjord systems, mean that small environmental changes due to temperature, runoff, water mass, or ocean currents affect the cold intermediate layer and sea surface temperature with ramifications for zooplankton production, larval dispersal, and stock biomass (Frechet, 1990; Quinjon and Snelgrove, 2005; Gailbraith, 2006; Galbraith et al., 2012). Colder temperatures and changes in oceanographic conditions were reported to affect the reproductive rate of cod fish populations leading up to population decline in the mid-1980s (DFO, 2010). Similar temperature impacts were noted for the decline in the years 2003 and 2008 in Northern Gulf fisheries (DFO, 2010). Changes in oceanic circulation between the 1930s and 1980s resulted in a worsening of the hypoxic conditions found in the deep channels (Gilbert et al. 2005), to the point that the deeper estuarine waters became virtually unusable by cod (Plante et al., 1998), which appears to have decreased productivity of the northern Gulf stock (Chabot, 2004). There were also high cod mortality rates due to predation from seals and high exploitation by fisheries (DFO, 2010). These changes in the pre-harvest stage affect ecosystem structure and function, predator-prey relationships, and have ramifications for allocation and catch quotas of recreational food and commercial cod fisheries.

### Harvest activities

In addition to climate variability, the stock collapse has been attributed to many factors including ineffective management strategies, illegal and unreported fishing that affects stock assessment and foreign overfishing (Bavington, 2010). The spawning stock biomass fluctuated from historical highs of 378 000 tonnes in the mid-1980s with a gradual decline to 9000 tonnes in 1993, prompting a complete moratorium on commercial fishing from 1994 to 1996 and in 2003 (DFO, 2010). Consequently, all foreign and most domestic fishing fleet activities were suspended, and total catch in 2010 was just 2% of historical levels.

The collapse of cod fisheries also led to new rules surrounding local seafood access and allocation, as demonstrated by the 1997 Professionalization Act. Limits on subsistence fishing for cod were imposed that affected community access and choice of dietary protein. These policy changes raised concerns about food security and the viability of fishing-dependent communities (Lowitt, 2011).

Twenty years after the moratorium, the cod stock has not rebuilt (Khan, 2011). There are small quotas for commercial and food fisheries. Some households access cod and other seafood through recreational fisheries. For the region as a whole, about 161 tonnes of cod were caught in 2006 for the recreational food fisheries, compared to 1742 tonnes for the commercial capture fisheries (DFO, 2007; 2010). While

*Case Study 5 continued on next page*

wild fisheries declined and remain in collapse, aquaculture has grown 150% since the moratorium (DFO, 2011). At the same time, there has been a shift in ecosystem structure and changes in target species from ground fish to even more lucrative shellfisheries (Savenkoff et al., 2007). Overall, shellfisheries accounted for 60% of the total landings and 84% of the landed value of all capture fisheries in NL in 2010 (DFA, 2011). Recently however, warmer waters have been reported to affect moulting in shellfish such as crab (DFO, 2008; Vasseur and Catto, 2008). Such impacts of climate variability on crab resources have resulted in management measures that restrict fishing to certain geographical grids in order to protect 'soft shells'. These management measures have consequences on harvesting strategies and revenues from shellfish fishing operations, especially if these conditions persist (Schrank, 2005; DFO, 2008).

### Post-harvest activities (processing, marketing and consumption)

Processing and distribution networks have also transformed in reaction to the collapse, to meet certification and consumer needs. The marketing and distribution channels for seafood have changed from a predominantly US market in the pre-collapse period to new global markets in the post-collapse period. These changes along the fisheries food-supply chain, at various spatial scales, have brought substantial social and economic transformation to coastal regions in terms of community survival and livelihood opportunities as well as access to local seafood (Ommer et. al., 2007).

The cascading effect resulting from changes in marine ecosystems that affect livelihoods and food security are very evident along the fisheries food-supply chain from 'ocean to plate'. Findings from two recent surveys indicate that seafood consumption is declining in Newfoundland (Solberg et al., 2007; Lowitt, 2011). Surveys show that consumption of shrimp has increased, and this may be one way local households have adapted their diets following the shift in ecosystem structure. However, indicative of its important place in traditional dietary patterns, cod remains by far the most frequently eaten type of seafood. In the 2011 survey, 81% of households said they eat cod "often", compared to 31% for shrimp, 27% for lobster, and 17% for crab (Lowitt, 2011).

A decline in seafood consumption may be influenced by lower commercial quotas and decreasing subsistence and recreational fishing activities, combined with tighter regulations around local seafood access, resulting in potentially less fish being landed and available for local consumption. The participation rate in the recreational food fishery is also among the lowest in a provincial survey (DFO, 2007), reflecting environmental changes and impacts on cod fish stocks. At the same time, fishing seasons are becoming shorter for many species, with the consequence that local seafood is available for purchase for fewer months of the year.

### Institutional response and adaptation mechanisms

Changes that have taken place in ecosystems, target fisheries, and institutional responses have implications for the food security of coastal communities that have historically depended on seafood as an important part of their diet. Food systems are increasingly integrating other policy areas – including health and environment – to help improve capacity to adapt to environmental and resource challenges (MacRae, 2011).

The adaptive capacity of communities to respond to environmental and ecosystem changes, including changes in food systems, can be strengthened through multi-level governance arrangements that emphasize community empowerment and shared responsibility. By understanding the interactions of social and economic drivers with climate variability and ecosystem changes, effective institutions and adaptive governing capacity can be enhanced to better deal with climate variability and change.

# 4. CONCLUSIONS AND MOVING FORWARD

Food production covers a broad spectrum of activities involving agriculture, fisheries and non-commercial food supply. While further research will continue to enhance adaptation decision-making, adaptation is moving forward with the goal of building resilience against the variability of both short-term weather and long-term climate. The ability of the food sector to grow in market value will depend on its ability to adapt to the new conditions brought about by changing climate and changing geopolitical conditions. The complex, rapidly changing environment requires a flexible and adaptable food sector. Adaptability amongst the sectors discussed in this chapter is evident, with examples of past adaptation (e.g. to drought on the Prairies, cod decline in Atlantic Canada), current initiatives (e.g. shifting types of crops, fishing new species) and planning for the future (e.g. insuring losses from bluetongue outbreaks, the Pan-Territorial Adaptation Strategy).

# REFERENCES

AAFC [Agriculture and Agri-Food Canada] (2007): Canadian maple products, situation and trends 2006-2007; Agriculture and Agri-Food Canada.

AAFC [Agriculture and Agri-Food Canada] (2011): An overview of the Canadian Agriculture and Agri-Food system 2011; Agriculture and Agri-Food Canada, publication 11279E.

AAFC [Agriculture and Agri-Food Canada] (2012a): Climate change scenario maps; Agriculture and Agri-Food Canada; <http://www.agr.gc.ca>.

AAFC [Agriculture and Agri-Food Canada] (2012b): Agri-Food trade service fact sheets; Agriculture and Agri-Food Canada, <www.ats-sea.agr.gc.ca/stats/4679-eng.htm>.

AAFC [Agriculture and Agri-Food Canada] (2012c): Agri-Food trade service, Canadian trade highlights; Agriculture and Agri-Food Canada, <http://www.ats-sea.agr.gc.ca/intro/index-eng.htm >.

AAFC [Agriculture and Agri-Food Canada] (2012d): Fish and seafood industry overview; Agriculture and Agri-Food Canada, <www.ats-sea.agr.gc.ca/sea-mer/ind-eng.htm>.

AAFC [Agriculture and Agri-Food Canada] (2012e): An overview of the Canadian Agriculture and Agri-Food System 2012; Agriculture and Agri-Food Canada, publication 11660E.

AAFC [Agriculture and Agri-Food Canada] (2013): Agri-Environmental Indicators; <http://atlas.agr.gc.ca/agmaf/index_eng.html#context=aei-iae_en>.

AAFC [Agriculture and Agri-Food Canada] (2014): 2012-13 Departmental Performance Report; Agriculture and Agri-Food Canada, <http://www.agr.gc.ca/eng/about-us/planning-and-reporting/departmental-performance-reports/2012-13-departmental-performance-report/?id=1380233567058#s2.1>.

Agronomic Interpretations Working Group (1995): Land suitability rating system for agricultural crops, 1. Spring-seeded small grains, (ed.) W.W. Pettapiece; Technical Bulletin 1995-6E, Centre for Land and Biological Resources Research, Agriculture and Agri-Food, Ottawa, 2 maps, 90 p.

Ainsworth, C.H., Samhouri, J.F., Busch, D.S., Cheung, W.W.L., Dunne, J., and Okey, T.A. (2011): Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries; Ices Journal of Marine Science, v. 68, no. 6, p. 1217-1229.

Allison E.H, Perry AL, Badjeck M-C, Adger , N.W, Brown, K, Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L., and Dulvy, N.K. (2009): Vulnerability of national economies to the impacts of climate change on fisheries; Fish and Fisheries; v.10, no. 2, p.173-96.

Almaraz, J.J., Mabood, F., Zhou, X., Gregorich, E.G., and Smith, D.L. (2008): Climate change, weather variability and corn yield at a higher latitude locale: south-western Quebec; Climatic Change, v. 88, p. 187-197.

Almaraz, J.J., Mabood, F., Zhou, X., Strachan, I., Me, B., and Smith, D.L. (2009): Performance of agricultural systems under contrasting growing season conditions in south-western Quebec; Journal of Agronomy and Crop Science, v. 195, p. 319-327.

A Northern Vision (2011): Pan-Territorial adaptation strategy: moving forward on climate change adaptation in Canada's North, <www.anorthernvision.ca/strategy>.

Arnason, R. (2007): Climate change and fisheries: assessing the economic impact in Iceland and Greenland; Natural Resource Modeling, v. 20, no. 2, p. 163-197.

Aurambout, J.P., Constable, F., Finlay, K., Luck, J., and Sposito, V. (2006): The impacts of climate change on plant biosecurity; Victorian Government Department of Primary Industries, Landscape Systems Science and Primary Industries Research, Victoria, 42 p.

Aurambout, J.P., Finlay, K., Luck, J., and Beattie, G. (2009): A concept model to estimate the potential of the Asiatic citrus psyllid (Diaphorina citri Kuwayama) in Australia under climate change - a means for assessing biosecurity risk; Ecological Modelling, v. 220, p. 2512-2524.

Axelson, J.N., Sauchyn, D.J., and Barichivich, J. (2009): New reconstructions of streamflow variability in the South Saskatchewan River Basin from a network of tree ring chronologies; Water Resources Research, Alberta, Canada, v. 45, WO9422, 10 p.

Baker, R., Sansford, C., Jarvis, C., Cannon, R., MacLeod, A., and Walters, K. (2000): The role of climatic mapping in predicting the potential geographical distribution of non-indigenous pests under current and future climates; Agriculture, Ecosystems & Environment, v. 82, p. 57-71.

Barange, M. and Perry, R.I. (2009): Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture; in Climate change implications for fisheries and aquaculture: overview of current scientific knowledge, (ed.) K. Cochrane, C. De Young, D. Soto and T. Bahri; FAO Fisheries and Aquaculture Technical Paper, no. 530, Rome, FAO, 2009, 212 p.

Batie, S.S. (2008): Wicked problems and applied economics; American Journal of Agricultural Economics, v. 90, no. 5, p. 1176-1191.

Bavington, D. (2010): Managed annihilation: an unnatural history of the Newfoundland cod collapse; UBC Press, Vancouver.

Beamish, R.J. and Bouillon, D.R. (1993): Pacific salmon production trends in relation to climate; Canadian Journal of Fisheries and Aquatic Sciences, v. 50, no. 5, p. 1002-1016.

Beamish, R.J., Noakes, D.J., McFarlane, G.A., Klyashtorin, L., Ivanov, V.V., and Kurashov, V. (1999): The regime concept and natural trends in the production of Pacific salmon; Canadian Journal of Fisheries and Aquatic Sciences, v. 56, no. 3, p. 516-526.

Beaugrand, G., Edwards, M., Brander, K., Luczak, C., and Ibanez, F. (2008): Causes and prediction of abrupt climate-driven ecosystem shifts in the North Atlantic; Ecology Letters, v. 11, p. 1157-1168.

Beaugrand, G., Reid, P.C., Ibanez, F., Lindley, J.A., and Edwards, M. (2002): Reorganization of North Atlantic marine copepod biodiversity and climate; Science, v. 296, no. 5573, p. 1692-1694.

Behrenfeld, M.J. , O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan, A.J., Falkowski, P.G., Letelier, R.M., and Boss, E.S. (2006): Climate-driven trends in contemporary ocean productivity; Nature, v. 444, no. 7120, p. 752-755.

Berkes, F. (1988): Subsistence fishing in Canada: a note on terminology; ARCTIC, v. 41, p. 319-320.

Bertrand, A., Bourassa, J., Bélanger, G., Mongrain, D., Tremblay, G., and Castonguay, Y. (2012): La hausse de températures et du CO2 affecteront-elles la productivité des plantes fourragères?; Demi-journée d'Information Scientifique sur les Fourrages, Victoriaville, Québec, <www.agrireseau.qc.ca/Plantes-Fourrageres/documents/Demi%20journee%202012%20compte-rendu.pdf>.

Blanchard, J.L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J.I., Holt, J., Dulvy, N.K., and Barange, M. (2012): Potential consequences of climate change for primary production and fish production in large marine ecosystems; Philosophical Transactions of the Royal Society B: Biological Sciences, v. 367, no. 1605, p. 2979-2989.

Bourque, A. and Simonet, G. (2008): Quebec; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, p. 171-226.

Brander, K.M. (2007): Global fish production and climate change; Proceedings of the National Academy of Sciences of the United States of America, v. 104, no. 50, p. 19709-19714.

British Columbia (2012): BC agriculture climate change adaptation risk and opportunity assessment provincial report, <www.bcagclimateaction.ca/document-library/>.

Brown, D. (2005): Salmon wars: the battle for the west coast salmon fishery; Harbour Publishing, Madeira Park, British Columbia, 408 p.

Bruneau, J., Darrell R., Corkal, E.P., Toth, B., and Van der Kamp, G. (2009): Human activities and water use in the South Saskatchewan River basin; Prairie Forum, v. 34, no. 1, p. 129-152.

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J., and Richardson, A.J. (2011): The pace of shifting climate in marine and terrestrial ecosystems; Science, v. 334, no. 6056, p. 652-655.

Carmack, E., McLaughlin, F., Whiteman, G., and Homer-Dixon, T. (2012): Detecting and coping with disruptive shocks in Arctic marine systems: a resilience approach to place and people; Ambio, v. 41, no. 1, p. 56-65.

CFIA [Canadian Food Inspection Agency] (2011): Canadian Food Inspection Agency, fact sheet - Bluetongue, <www.inspection.gc.ca/animals/terrestrial-animals/diseases/reportable/bluetongue/factsheet/eng/1306116803992/1306121522520>.

Chabot, D. (2004): Chronic non-lethal levels of hypoxia limit distribution and growth of Atlantic cod (Gadus morhua) in the northern Gulf of St. Lawrence, Canada; in Proceedings of the 7th International Symposium on Fish Physiology, Toxicology and Water Quality, (ed.) G.L. Rupp and M.D. White; EPA U.S. Environmental Protection Agency, Ecosystems Research Division, Athens, Georgia, USA, 600/R-04/049 p. 183-205.

Chakraborty, S. (2005): Potential impact of climate change on plant-pathogen interactions; Australasian Plant Pathology, v. 34, p. 443-448.

Chakraborty, S. and Datta, S. (2003): How will plant pathogens adapt to host plant resistance at elevated CO2 under changing climate?; New Pathologist, v. 159, p. 733-742.

Chavez, F.P., Ryan, J., Lluch-Cota, S.E., and Niquen, M. (2003): From anchovies to sardines and back: multidecadal change in the Pacific Ocean; Science, v. 299, no. 5604, p. 217-221.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., and Pauly, D. (2009): Projecting global marine biodiversity impacts under climate change scenarios; Fish and Fisheries, v. 10, no. 3, p. 235-251.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., and Pauly, D. (2010): Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change; Global Change Biology, v. 16, no. 1, p. 24-35.

Chiotti, Q. and Lavender, B. (2008): Ontario; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON. p. 227-274.

Chu, C., Jones, N.E., Mandrak, N.E., Piggott, A.R., and Minns, C.K. (2008): The influence of air temperature, groundwater discharge, and climate change on the thermal diversity of stream fishes in southern Ontario watersheds; Canadian Journal of Fisheries and Aquatic Sciences, v. 65, no. 2, p. 297-308.

Clark, J. (2010): The ordinary people of Essex: environment, culture, and economy on the frontiers of Upper Canada; McGill-Queen's University Press, 738 p.

Climate Change Connection (2009): A guide to creating climate - friendly farms in Manitoba - livestock edition; MB: Climate Change Connection, Winnipeg, 20 p.

Coll, M. and Hughes, L. (2008): Effects of elevated CO2 on an insect omnivore: a test for nutritional effects mediated by host plants and prey; Agriculture, Ecosystems and Environment, v. 123, p. 271-279.

Comité de suivi et de concertation de la stratégie phytosaniatire québécoise en agriculture (2011): Stratégie phytosanitaire québécoise en agriculture 2011-2021, 23 p. <www.mapaq.gouv.qc.ca/fr/Publications/Strategie_phytosanitaire.pdf>.

Cooke, S.J., Hinch, S.G., Farrell, A.P., Lapointe, M.F., Jones, S.R.M., Macdonald, J.S., Patterson, D.A., Healey, M.C., and Van Der Kraak, G. (2004): Abnormal migration timing and high en route mortality of sockeye salmon in the Fraser River, British Columbia; Fisheries, v. 29, no. 2, p. 22-33.

Corkal, D. and Adkins, P.E. (2008): Canadian agriculture and water; Proceedings of the 13th IWRA World Water Congress, Montpellier, France.

Corkal, D., Diaz, H., and Sauchyn, D. (2011): Changing roles in Canadian water management: a case study of agriculture and water in Canada's South Saskatchewan River Basin; International Journal of Water Resources Development, v. 27, no. 4, p. 647-664.

CRA [Canada Revenue Agency] (2011): Canada Revenue Agency, Guide T4003, Farming Income, <www.cra-arc.gc.ca/tx/bsnss/sgmnts/frmng/menu-eng.html>.

Crawford, E. and McNair, E. (2012): BC Agriculture Climate Change Adaptation Risk + Opportunity Assessment - Provincial Report; British Columbia Agriculture & Food Climate Action Initiative, p. 26-28, <www.BCAgClimateAction.ca>.

Crain, C.M., Kroeker, K., and Halpern, B.S. (2008): Interactive and cumulative effects of multiple human stressors in marine systems; Ecology Letters, v. 11, p. 1304-1315.

Crossin, G.T. , Hinch, S.G., Cooke, S.J., Welch, D.W., Patterson, D.A., Jones, S.R.M., Lotto, A.G., Leggatt, R.A., Mathes, M.T., Shrimpton, J.M., Van Der Kraak, G., and Farrell, A.P. (2008): Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration; Canadian Journal of Zoology, v. 86, p. 127-140.

Cutforth, H.W., McGinn, S.M., McPhee, K.E., and Miller, P.R. (2007): Adaptation of pulse crops to the changing climate of the Northern Great Plains; Agronomy Journal, v. 99, p. 1684-1699.

Deser, C., Walsh, J.E., and Timlin, M.S. (2000): Arctic sea ice variability in the context of recent atmospheric circulation trends; Journal of Climate, v. 13, p. 617-633.

DFA [Department of Fisheries and Aquaculture] (2011): Seafood industry year in review 2010; Newfoundland and Labrador Department of Fisheries and Aquaculture, <www.fishaq.gov.nl.ca/publications/yir_2010.pdf>.

DFO [Fisheries and Oceans Canada] (2003): Achieving the vision: report of the commissioner for aquaculture development; Fisheries and Oceans Canada, Ottawa, Ontario.

DFO [Fisheries and Oceans Canada] (2007): Survey of the recreational cod fishery of Newfoundland Labrador; Department of Fisheries and Oceans Canada, < http://www.dfo-mpo.gc.ca/stats/rec/can/NLCod2007/NLCod2007Report_FINAL.pdf>.

DFO [Fisheries and Oceans Canada] (2008): Assessment of Newfoundland and Labrador snow crab; DFO Canadian Science Advisory Secretariat Response 2008/009.

DFO [Fisheries and Oceans Canada] (2010): Assessment of cod in the Northern Gulf of St. Lawrence. DFO Canadian Science Advisory Secretariat Response.

DFO [Fisheries and Oceans Canada] (2011): Canadian Fisheries Statistics 2008.

DFO [Fisheries and Oceans Canada] (2012a): Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Atlantic Large Aquatic Basin; DFO Canadian Science Advisory Secretariat Response 2012/044.

DFO [Fisheries and Oceans Canada] (2012b): Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Arctic Large Aquatic Basin; DFO Canadian Science Advisory Secretariat Response 2012/042.

DFO [Fisheries and Oceans Canada] (2012c): Fisheries and Oceans Canada Recreational Fishing Survey 2010, no. Fs42-1/2010E.

DFO [Fisheries and Oceans Canada] (2013a): <www.dfo-mpo.gc.ca/stats/trade-commerce/can/export/xprv12-eng.htm>->.

DFO [Fisheries and Oceans Canada] (2013b): <www.dfo-mpo.gc.ca/stats/aqua/aqua11-eng.htm>.

DFO [Fisheries and Oceans Canada] (2013c): Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Freshwater Large Aquatic Basin; DFO Canadian Science Advisory Secretariat Response 2013/011.

DFO [Fisheries and Oceans Canada] (2013d): Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Pacific Large Aquatic Basin; DFO Canadian Science Advisory Secretariat Response 2013/016.

Diaz, H. and A. Rojas (2006): Methodological framework for the assessment of governance institutions; IACC project, <www.parc.ca/mcri/iacc033.php>.

Diaz, H. and IACC Canadian research team (2009): Institutional adaptations to climate change (IACC), integration report: the case of the South Saskatchewan River Basin; IACC project, Canadian Plains Research Center, University of Regina, 36 p., <www.parc.ca/mcri/int01.php>.

Drinkwater, K. (2009): Comparison of the response of Atlantic cod (Gadus morhua) in the high-latitude regions of the North Atlantic during the warm periods of the 1920s-1960s and the 1990s-2000s; Deep-Sea Research Part Ii-Topical Studies in Oceanography, v. 56, no. 21-22, p. 2087-2096.

Duchesne L., Houle, D., Côté, M.A., and Logan, T. (2009): Modelling the effect of climate on maple syrup production in Québec Canada; Forest Ecology and Management, v. 258, p. 2683-2689.

Encyclopedia of Saskatchewan (2007): Canadian Plains Research Center, Regina, <http://esask.uregina.ca/entry/palliser_triangle.html>.

Environment Canada (2004): Threats to water availability in Canada, Burlington, 128 p.

Environment Canada and EPA [United States Environmental Protection Agency] (2009): State of the Great Lakes 2009; United States Environmental Protection Agency, v. 905-R-09-031/En161-3/1-2009E, <http://binational.net/solec/sogl2009/SOGL_2009_en.pdf>.

FAO [Food and Agriculture Organization] (2009): Seed security for food security in the light of climate change and soaring food process: challenges and opportunities; Food and Agriculture Organization of the United Nations, Committee on Agriculture Twenty-first Session, April 2009, Rome, p. 22-25.

Finney, B.P., Gregory-Eaves, I., Douglas, M.S.V., and Smol, J.P. (2002): Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years; Nature, v. 416, no. 6882, p. 729-733.

Ford, J.D. (2009): Dangerous climate change and the importance of adaptation for the Arctic's Inuit population; Environmental Research Letters, v. 4.

Frank, K.T., Petrie, B., Choi, J.S., and Leggett, W.C. (2005): Trophic cascades in a formerly cod-dominated ecosystem; Science, v. 308, no. 5728, p. 1621-1623.

Frank, K.T., Petrie, B., Shackell, N.L., and Choi, J.S. (2006): Reconciling differences in trophic control in mid-latitude marine ecosystems; Ecology Letters, v. 9, no. 10, p. 1096-1105.

Frechet, A. (1990): Catchability variations of cod in the marginal ice zone; Canadian Journal of Fisheries and Aquatic Sciences, v. 47, p. 1678-1683.

Fuhrer J. (2003): Agroecosystem response to combinations of elevated CO2, ozone, and global climate change; Agriculture, Ecosystems and Environment, v. 97, p. 1-20.

Furgal, C. and Prowse, T.D. (2008): Northern Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, Ontario. p. 57-118.

Gagnon, A.E., Roy, M., and Roy, A. (2011): Document de synthèse: impacts directs et indirects des changements climatiques sur les ennemis des cultures, 80 p.

Gagnon, A.E., Arsenault-Labrecque, G., Bourgeois, G., Bourdages, L., Grenier, P., and Roy, M. (2013): Études de cas pour faciliter une gestion efficace des ennemis des cultures dans le contexte de l'augmentation des risques phytosanitaires liés aux changements climatiques, 156 p.

Gailbraith, P.S. (2006): Winter water masses in the Gulf of St. Lawrence. Journal of Geophysical Research, v. 3, C06022.

Galbraith P.S., Chassé J., Gilbert D., Larouche P., Brickman D., Pettigrew B., Devine, L., Gosselin, A., Pettipas, R.G., and Lafleur C. (2012): Physical oceanographic conditions in the Gulf of St. Lawrence in 2011; Canadian Science Advisory Secretariat Research Document, 2012/023, v. 3, 85 p.

Gilbert D., Sundby, B., Gobeil, C., Mucci, A., and Tremblay, G. (2005): A seventy-two year record of diminishing deep-water oxygen in the St. Lawrence estuary: the northwest Atlantic connection; Limnology and Oceanography, v. 50, p. 1654-1666.

Glavin, T. (1996): Dead reckoning: confronting the crisis in Pacific fisheries; Douglas and McIntyre, Vancouver, BC, 181 p.

Godfray, H.C.J., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Nisbett, N., Lawrence, D., Pretty, J., Robinson, S., Toulmin, C., and Whiteley, R. (2010): The future of the global food system; Philosophical Transactions of the Royal Society B-Biological Sciences, v. 365, no. 1554, p/ 2769-2777.

Government of Nunavut and Nunavut Tunngavik Incorporated (2005): Nunavut Fisheries Strategy, 50p.

Gray, J.H. (1996): Men against the desert; Fifth House Ltd, Calgary, 263 p.

Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E.V., Carmack, E.C., Cooper, L.W., Frey, K.E., Helle, J.H., McLaughlin, F.A., and McNutt, S.L. (2006): A major ecosystem shift in the northern Bering Sea; Science, v. 311, no. 5766, p. 1461-1464.

G.S. Gislason & Associates Ltd. and Outcrop Ltd. (2002): The marine-related economy of NWT and Nunavut; Prepared for Canada Fisheries & Oceans, Winnipeg, January 2002.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno. J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., and Watson, R. (2008): A global map of human impact on marine ecosystems; Science, v. 319, p. 948-952.

Hansen, J.C., Deutch, B., and Odland, J.Ø. (2008): Dietary transition and contaminants in the Arctic: emphasis on Greenland; Circumpolar Health Supplements, 2008, v. 2.

Harris, D.C. (2001): Fish, law and colonialism: the legal capture of salmon in British Columbia; University of Toronto Press, Toronto, Ontario, 306 p.

Harris, D.C. (2008): Landing native fisheries: Indian reserves and fishing rights in British Columbia, 1849-1925; University of British Columbia Press, Vancouver, BC, 266 p.

Hellmann J.J., Byers J.E., Bierwagen B.G., and Dukes J.S. (2008): Five potential consequences of climate change for invasive species; Conservation Biology, v. 22, p. 534-543.

Hewitt, J., Chen, K., Brierley, T., and Hill, H. (2008): Assessment of climate change impacts on climate and land suitability ratings for spring seeded small grains on the Canadian Prairies; Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Regina, Saskatchewan.

Hinch, S.G. and Martins, E.G. (2011): A review of potential climate change effects on survival of Fraser River sockeye salmon and an analysis of interannual trends in en route loss and pre-spawn mortality; Cohen Commission, technical report 9.

Hoekman, D. (2010): Turning up the heat: temperature influences the relative importance of top-down and bottom-up effects; Ecology, v. 91, no. 10, p. 2819-2825.

Hunt, L.M. and Moore, J. (2006): The potential impacts of climate change on recreational fishing in Northern Ontario; Ontario Ministry of Natural Resource Climate Change Research Report CCRR-04.

Hurlbert, M., Darrell R., Corkal, and Diaz, H. (2009a): Government and civil society: adaptive water management in the South Saskatchewan River Basin; Prairie Forum, v. 34, no. 1, p. 181-210.

Hurlbert, M., Darrell R., Corkal, Diaz, H., and Warren, J. (2009b): Climate change and water governance in Saskatchewan, Canada; International Journal of Climate Change Strategies and Management, v. 1, no. 2, p. 118-132.

Hutchings, J.A. and Myers, R.A. (1994): What can be learned from the collapse of a renewable resource? Atlantic cod, Gadus Morhua, of Newfoundland and Labrador; Canadian Journal of Fisheries and Aquatic Science, v. 51, p. 2126-2146.

Hyatt, K.D., Hunter, K.L., and Rankin, D.P. (2008): Sockeye salmon index stocks: regional overview of trends and 2006 returns. State of the Pacific Ocean 2006; DFO Canadian Science Advisory Secretariat Report 2007/019.

IIABC [Irrigation Industry Association of BC] (2009): Irrigation Industry Association of British Columbia, landscape irrigation scheduling calculators, <http://landscape-calculator.irrigationbc.com>.

IPCC [Intergovernmental Panel on Climate Change] (2007): Fourth assessment report: climate change; Intergovernmental Panel on Climate Change.

Justice Canada (2012): Prairie farm rehabilitation act. R.S.C. (1985); c. P-17, <http://laws-lois.justice.gc.ca/eng/acts/P-17/ >.

Irvine, J.R. and Fukuwaka, M.A. (2011): Pacific salmon abundance trends and climate change; Ices Journal of Marine Science, v. 68, no. 6, p. 1122-1130.

Kerr, L.A., Connelly, W.J., Martino, E.J., Peer, A.C., Woodland, R.J., and Secor, D.H. (2009): Climate change in the U.S. Atlantic affecting recreational fisheries; Reviews in Fisheries Science, v. 17, no. 2, p. 267-289.

Kerr, S.J. (2010): Fish and fisheries management in Ontario: a chronology of events; Biodiversity Branch, Ontario Ministry of Natural Resources, Peterborough, Ontario, 80 p. + appendices.

Khan, A.S. (2011): Is rebuilding collapsed fisheries a wicked problem? Lessons from a fish chain analysis of Northern Gulf cod fisheries; Doctoral thesis, St John's, NL: Memorial University of Newfoundland.

Kuhnlein, H. and Receveur, O. (2007): Local cultural animal food contributes high levels of nutrients for Arctic Canadian indigenous adults and children; Journal of Nutrition, v. 137, p. 1110-1114.

Kulshreshtha, S.N. (2011): Climate change, prairie agriculture, and prairie economy: the new normal; Canadian Journal of Agricultural Economics, v. 59, p. 19–44, 2011.

Kulshreshtha, S.N., Wheaton, E., and Amiraslany, A. (2010): A literature survey of the potential socio-economic impacts of climate change on Canadian crop production. a report prepared for Agriculture and Agri-Food Canada; Department of Bioresource Policy, Business and Economics, University of Saskatchewan, Saskatoon, Saskatchewan, March 2010.

Kutcher, H.R., Warland, J.S., and Brandt, S.A. (2010): Temperature and precipitation effects on canola yields in Saskatchewan, Canada; Agricultural and Forest Meteorology, v. 150, p. 161-165.

Lamhonwah, D., Murphy, B., and Brown, L. (2011): A GIS-based approach to projecting responses of sugar maples to climate change in Ontario, Canada: final results; Canadian Association of Geographers Annual Conference, University of Calgary, Alberta, June 2.

Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E., (ed.) (2008): From Impacts to Adaptation: Canada in a Changing Climate 2007; Government of Canada, Ottawa, Ontario, 448 p.

Linnansaari, T. and Cunjak, R.A. (2010): Patterns in apparent survival of Atlantic salmon (Salmo salar) parr in relation to variable ice conditions throughout winter; Canadian Journal of Fisheries and Aquatic Sciences, v. 67, no. 11, p. 1744-1754.

Loder, J.W., Petrie, B., and Gawarkiewicz, G. (1998): Ch.5: the coastal ocean off northeastern North America: a large-scale view, p. 105-133; in The Global Coastal Ocean: Regional Studies and Synthesis; The Sea, v. 11, (ed.) A.R. Robinson and K.H. Brink; John Wiley & Sons, Inc.

Lowitt, K. (2011): Examining the foundations for fisheries-tourism synergies and increased local seafood consumption in the Bonne Bay region of Newfoundland; St John's, NL: Community-University Research for Recovery Alliance, Memorial University and Rural Secretariat.

Luck, J., Campbell, I.D., Magarey, R., Isard, S., Aurambout, J.-P., and Finlay, K. (2014): Chapter 21: Climate Change and Plant Biosecurity: Implications for Policy. P. 655-691 in Gordh, G., and McKirdy, S. (eds.), The Handbook of Plant Biosecurity. Springer Science+Business Media, Dordrecht.

Lysyk, T.J. and Danyk, T. (2007): Effect of temperature on life history parameters of adult Culicoides sonorensis (Diptera: Ceratopogonidae) in relation to geographic origin and vectorial capacity for bluetongue virus; Journal of Medical Entomology, v. 44, no. 5, p. 741-751.

MacNeil, M.A., Graham, N.A.J., Cinner, J.E., Dulvy, N.K., Loring, P.A., Jennings, S., Polunin, N.V.C., Fisk, A.T., and McClanahan, T.R. (2010): Transitional states in marine fisheries: adapting to predicted global change; Philosophical Transactions of the Royal Society B-Biological Sciences, v. 365, no. 1558, p. 3753-3763.

MacRae, R. (2011): A joined up food policy for Canada; Journal of Hunger and Environmental Nutrition, v. 6, p. 424-457.

Mandrak, N.E. and Cudmore, B. (2010): The fall of native fishes and the rise of non-native fishes in the Great Lakes Basin; Aquatic Ecosystem Health & Management, v. 13, no. 3, p. 255-268.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. (1997): A Pacific interdecadal climate oscillation with impacts on salmon production; Bulletin of the American Meteorological Society, v. 78, no. 6, p. 1069-1079.

Marchildon, G.P. (2009a): The Prairie Farm Rehabilitation Administration: climate crisis and federal-provincial relations during the Great Depression; The Canadian Historical Review, v. 90, no. 2, p. 275-301.

Marchildon, G.P. (ed.) (2009b): A dry oasis, institutional adaptation to climate on the Canadian Plains; CPRC Press, Regina, 319 p.

Marchildon, G.P., Kulshreshtha, S., Wheaton, E., and Sauchyn, D. (2008): Drought and institutional adaptation in the Great Plains of Alberta and Saskatchewan, p. 1914-1939; Natural Hazards, v. 45, p. 391-411.

Martins, E.G. Hinch, S.G., Patterson, D.A., Hague, M.J., Cooke, S.J., Miller, K.M., Lapointe, M.F., English, K.K., and Farrell, A.P. (2011): Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (Oncorhynchus nerka); Global Change Biology, v. 17, p. 99-114.

McCartney, D., Fraser, J., and Ohama, A. (2008): Annual cool season crops for grazing by beef cattle. a Canadian review; Canadian Journal of Animal Science, v. 88, p. 517-533.

McCartney, D., Fraser, J., and Ohama, A. (2009): Potential of warm-season annual forages and brassica crops for grazing: a Canadian review; Canadian Journal of Animal Science, v. 89, p. 431-440.

McDaniels, T., Wilmot, S., Healey, M., and Hinch, S. (2010): Vulnerability of Fraser River sockeye salmon to climate change: a life-cycle perspective using expert judgments; Journal of Environmental Management, v. 91, p. 2771-2780.

McKinnell, S.M., Curchitser, E., Groot, C., Kaeriyama, M., and Myers, K.W. (2011): The decline of Fraser River sockeye salmon Oncorhynchus nerka (Steller, 1743) in relation to marine ecology; PICES Advisory Report, Cohen Commission Technical Report, v. 4, 195 p., Vancouver, B.C.

Meakin, S. and Kurvits, T. (2009): Assessing the impacts of climate change on food security in the Canadian Arctic; Prepared for Aboriginal Affairs and Northern Development Canada, <www.grida.no/files/publications/foodsec_updt_LA_lo.pdf>.

Meggs, G. (1991): Salmon: the decline of the British Columbia fishery; Douglas and McIntyre, Vancouver, BC, 265 p.

Meltofte, H. (ed.) (2013): Arctic biodiversity assessment. Status and trends in Arctic biodiversity; Conservation of Arctic Flora and Fauna, Akureyri.

Merino, G. , Barange, M., Blanchard, J.L., Harle, J.c, Holmes, R., Allen, I., Allison, E.H., Badjeck, M.C., Dulvy, N.K., Holt, J., Jennings, S., Mullon, C., and Rodwell, L.D. (2012): Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate?; Global Environmental Change, v. 22, p. 795-806.

Merino, G., Barange, M., Mullon, C., and Rodwell, L. (2010): Impacts of global environmental change and aquaculture expansion on marine ecosystems; Global Environmental Change - Human and Policy Dimensions, v. 20, no. 4, p. 586-596.

Minns, C.K. (2009): The potential future impact of climate warming and other human activities on the productive capacity of Canada's lake fisheries: a meta-model; Aquatic Ecosystems Health and Management, v. 12, p. 152-167.

MOE [Ministry of the Environment] (2011): Climate ready: Ontario's Adaptation Strategy and Action Plan 2011-2014; Ministry of the Environment, <www.ene.gov.on.ca/environment/en/resources/STDPROD_081665.html>.

Moore, S.K., Trainer, V.L., Mantua, N.J., Parker, M.S., Laws, E.A., Backer, L.C., and Fleming, L.E. (2008): Impacts of climate variability and future climate change on harmful algal blooms and human health; Environmental Health, v. 7 (Supplement 2): S4.

Murray, G., Bavington, D., and Neis, B. (2005): Local ecological knowledge, science, participation and fisheries governance in Newfoundland and Labrador: a complex, contested and changing relationship; in Participation in Fisheries Governance, (ed.) T.S. Gray; Methods and Technologies in Fish Biology and Fisheries, v. 4, p. 269-290.

Nelson, R., Howden, M., and Stafford Smith, M. (2008): Using adaptive governance to rethink the way science supports Australian drought policy; Environmental Science and Policy II, p. 588-601.

NFU [National Farmers Union] (2011): The state of Canadian agriculture by the numbers; National Farmers Union, April 2011, <www.nfu.ca/policy/nfu-briefs-2011>.

Nielsen, J.L., Ruggerone, G.T., and Zimmerman, C.E. (In Press): Adaptive strategies and life history characteristics in a warming climate: Salmon in the Arctic?; Environmental Biology of Fishes.

Niemi, A., Paulic, J., and Cobb, D. (2010): Ecosystem status and trends report: Arctic marine ecozones; DFO Canadian Science Advisory Secretariat Response Document 2010/066, v. 3 + 66 p.

NRCan [Natural Resources Canada] (2009): Salmon in Hot Water; www.nrcan.gc.ca/earth-sciences/climate-change/community-adaptation/poster/62 .

OECD-FAO [Organisation for Economic Co-operation and Development-Food and Agriculture Organization] (2011): Agricultural Outlook 2011; OECD and FAO Secretariats, <http://dx.doi.org/10.1787/888932427208>.

Ogden, A. and Johnson, P. (2002): Climate change impacts and adaptation in Northern Canada; Northern Climate Change Occasional Paper Series 3, Prepared for the Canadian Senate Standing Committee on Forestry and Agriculture.

Oltenacu, P.A. and Broom, D.M. (2010): The impact of genetic selection for increased milk yield on the welfare of dairy cows; Animal Welfare, v. 19, p. 39-49.

OMNR [Ontario Ministry of Natural Resources] (2013a): Great Lakes Fisheries, <www.mnr.gov.on.ca/en/Business/GreatLakes/2ColumnSubPage/STEL02_173913.html>.

OMNR [Ontario Ministry of Natural Resources] (2013b): Why we need our Great Lakes, <www.ene.gov.on.ca/environment/en/subject/great_lakes/STDPROD_096898.html>.

Ommer, E.R. and The Coasts under Stress Research Project Team (2007): Coasts under stress: restructuring and social-ecological health; Kingston: McGill-Queens University Press.

Ouranos (2010): Learning to adapt to climate change, (ed.) C. DesJarlais, M. Allard, D. Bélanger, A. Blondlot, A. Bouffard, A. Bourque, Chaumont, D., Gosselin, P., Houle, D., Larrivée, C., Lease, N., Pham, A.T., Roy, R., Savard, J.-P., Turcotte, R., and C. Villeneuve; Montreal, 128 p. 2010.

Overland, J.E., Alheit, J., Bakun, A., Hurrell, J.W., Mackas, D.L., and Miller, A.J. (2010): Climate controls on marine ecosystems and fish populations; Journal of Marine Systems, v. 79, no. 3-4, p. 305-315.

Pace, M.L., Cole, J.J., Carpenter, S.R., and Kitchell, J.F. (1999): Trophic cascades revealed in diverse ecosystems; Trends in Ecology & Evolution, v. 14, no. 12, p. 483-488.

Perez-Valdivia, C., Sauchyn, D., and Vanstone, J. (2012): Groundwater levels and teleconnections in the Canadian Prairies; Water Resources Research, v. 48, W07516.

Perry, A.L., Low, P.J., Ellis, J.R., and Reynolds, J.D. (2005): Climate change and distribution shifts in marine fishes; Science, v. 308, no. 5730: 1912-1915.

Perry, R.I., Barange, M., and Ommer, R.E. (2010): Global changes in marine systems: a social-ecological approach; Progress in Oceanography, v. 87, no. 1-4, p. 331-337.

Perry, R.I., Bundy, A., and Hofmann, E.E. (2012): From biogeochemical processes to sustainable human livelihoods: the challenges of understanding and managing changing marine social-ecological systems; Current Opinion in Environmental Sustainability, v. 4, no. 3, p. 253-257.

Peterman, R.M. and Dorner, B. (2011): Fraser River sockeye production dynamics; Cohen Commission Technical Report, v. 10, 134 p. Vancouver, B.C.

Peterman, R.M. and Dorner, B. (2012): A widespread decrease in productivity of sockeye salmon populations in western North America; Canadian Journal of Fisheries and Aquatic Sciences, v. 69, p. 1255-1260.

PFRCC [Pacific Fisheries Resource Conservation Council] (2003): Advisory: wild salmon and aquaculture in British Columbia; Pacific Fisheries Resource Conservation Council, Vancouver, British Columbia.

Picketts, I.M., Werner, A.T., and Murdock, T.Q. (2009): Climate change in Prince George: summary of past trends and future projections; Pacific Climate Impacts Consortium, University of Victoria, Victoria BC, 48 p.

Pimentel, D., Zuniga, R., and Morrison, D. (2005): Update on the environmental and economic costs associated with alien-invasive species in the United States; Ecological Economics, v. 52, no. 3, p. 273-288.

Pittman, J., Wittrock, V., Kulshreshtha, S., and Wheaton, E. (2011): Vulnerability to climate change in rural Saskatchewan: case study of the Rural Municipality of Rudy No. 284; Journal of Rural Studies, v. 27, p. 83-94.

Planque, B., Fromentin, J.M., Cury, P., Drinkwater, K.F., Jennings, S., Perry, R.I., and Kifani, S. (2010): How does fishing alter marine populations and ecosystems sensitivity to climate?; Journal of Marine Systems, v. 79, p. 403-417.

Plante, S., Chabot, D. and Dutil, J.D. (1998): Hypoxia tolerance in Atlantic cod; Journal of Fish Biology, v. 53, p. 1342-1356.

Polovina, J.J., Dunne, J.P., Woodworth, P.A., and Howell, E.A. (2011): Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming; ICES Journal of Marine Science, v. 68, no. 6, p. 986-995.

Polyakov, I.V., Alexeev, V.A., Belchansky, G.I., Dmitrenko, I.A., Ivanov, V.V., Kirillov, S.A., Korablev, A.A., Steele, M., Timokhov, L.A., and Yashayaev, I. (2008): Arctic Ocean freshwater changes over the past 100 years and their causes; Journal of Climate, v. 21, p. 364-384.

Powell A.M. Jr. and Xu, J. (2011): Abrupt climate regime shifts, their potential forcing and fisheries impacts; Atmospheric and Climate Sciences, v. 1, p. 33-47.

Proshutinsky, A., Krishfield, R., Timmermans, M.L., Toole, J., Carmack, E., McLaughlin, F., Williams, W.J., Zimmermann, S., Itoh, M., and Shimada, K. (2009): The Beaufort Gyre freshwater reservoir: state and variability from observations; Journal of Geophysical Research, v. 114, C00A10.

Prowse, T.D. and Brown, K. (2010): Hydro-ecological effects of changing Arctic river and lake ice covers: a review; Hydrology Research, v. 41, no. 6, p. 454-461.

Pullar, D., Allen, N., and Sloyan, M. (2011): Challenges and opportunities for sustainable livestock production in the UK; Nutrition Bulletin, v. 36, p. 432-437.

Quinjon, P.A. and Snelgrove, P. (2005): Differential regulatory roles of crustacean predators in sub-arctic soft sediment systems; Marine Ecology Progressive Series, v. 285, p. 137-149.

Rahel, F.J. and Olden, J.D. (2008): Assessing the effects of climate change on aquatic invasive species; Conservation Biology, v. 22, no. 3, p. 521-533.

Reid, P.C. and Valdés, L. (2011): ICES status report on climate change in the North Atlantic; ICES Cooperative Research Report, v. 310, 262 p.

Reist, J.D., Wrona, F.J. , Prowse, T.D. , Power, M. , Dempson, J.B. , Beamish, R.J. , King, J.R. , Carmichael, T.J., and Sawatzky, C.D. (2006): General effects of climate change on Arctic fishes and fish populations; Ambio, v. 35, no. 7, p. 370-380.

Reuten, C., Saprynka, A., Lundgren, J., Cavanaugh, T., and Boulton, J.W. (2012): Physical and socioeconomic impacts of global atmospheric processes to Canadian agriculture; Literature Survey, RDWI #1201017, Agriculture and Agri-Food Canada, Science and Technology Branch, Regina Saskatchewan, March, 2012.

Rice, J.C. and Garcia, S.M. (2011): Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues; Ices Journal of Marine Science, v. 68, no. 6, p. 1343-1353.

Rice, J.C., Shelton, P.A., Rivard, D., Chouinard, G.A., and Frechet, A. (2003): Recovering Canadian Atlantic cod stocks: the shape of things to come? The scope and effectiveness of stock recovery plans in fishery management; CM 2003/U:06, ICES, Copenhagen.

Robards, M.D. and Reeves, R.R. (2011): The global extent and character of marine mammal consumption by humans: 1970-2009; Biological Conservation, v. 144, p. 2770-2786.

Robson, P.A. (2006): Salmon farming: the whole story; Heritage House Publishing, Surrey, BC, 271 p.

Rogers, L.A. and Schindler, D.E. (2011): Scale and the detection of climatic influences on the productivity of salmon populations; Global Change Biology, v. 17, no. 8, p. 2546-2558.

Saskatchewan Pulse Growers (2000): Pulse Production Manual, 2nd ed., 186 p.; Saskatoon: Saskatchewan Pulse Growers.

Sauchyn, D. and Kulshreshtha, S. (2008): Prairies, in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, Ontario, p. 275-328.

Sauchyn, D., Diaz, H., and Kulshreshtha, S. (ed.) (2010): The new normal - the Canadian Prairies in a changing climate; CPRC Press, Regina. 380 p.

Sauchyn, D., Vanstone, J., and Perez-Valdivia, C. (2011): Modes and forcing of hydroclimatic variability in the upper north Saskatchewan River Basin since 1063; Canadian Water Resources Journal, v. 36, no. 3, p. 205-218.

Savenkoff, C., Castonguay, M., Chabot, D., Hammill, M., Bourdages, H., and Morissette, L. (2007): Changes in the Northern Gulf of St. Lawrence ecosystem estimated by inverse modeling: evidence of a fishery induced regime shift; Estuarine and Coastal Shelf Science, v. 73, no. 4, p. 711-724.

Schrank, W.E. (2005): The Newfoundland fishery: ten years after the moratorium; Marine Policy, v. 29, p. 407-420.

Schut, P., Smith, S., Fraser, W., Geng, X., and Kroetsch, D. (2011): Soil landscapes of Canada: building a national framework for environmental information; Geomatica, v. 65, no. 3, p. 293-309.

Shackell, N.L., Bundy, A., Nye, J.A., and Link, J.S. (2012): Common large-scale responses to climate and fishing across Northwest Atlantic ecosystems; ICES Journal of Marine Science, v. 69, p. 151-152.

Shackell, N. and Loder, J. (ed.) (2012): State of the Scotian Shelf Report, <http://coinatlantic.ca/index.php/state-of-the-scotian-shelf >.

Shafer, S.R., Walthall, C.L., Franzluebbers, A.J., Scholten, M., Meijs, J., Clark, H., Reisinger, A., Yagi, K.e, Roel, A., Slattery, B., Campbell, I.D., McConkey, B.G., Angers, D.A., Soussana, J.-F., and Richard, G. (2011): Emergence of the global research alliance on agricultural greenhouse gases; Carbon Management, v. 2, no. 3, p. 209-214.

Sharma, S., Jackson, D.A., and Minns, C.K. (2009): Quantifying the potential effects of climate change and the invasion of smallmouth bass on native lake trout populations across Canadian lakes; Ecography, v. 32, no. 3, p. 517-525.

Sharma, S., Jackson, D.A., and Minns, C.K. (2007): Will northern fish populations be in hot water because of climate change?; Global Change Biology, v. 12, p. 2052-2064.

Sharma, S., Legendre, P., De Caceres, M., and Boisclair, D. (2011): The role of environmental and spatial processes in structuring native and non-native fish communities across thousands of lakes; Ecography, v. 34, no. 5, p. 762-771.

Skiner, C.B., DeGaetano, A.T., and Chabot, B.F. (2010): Implications of twenty-first century climate change on Northeastern United States maple syrup production: impacts and adaptations; Climate Change, v. 100, p. 685-702.

Smith, A.L., Hewitt, N., Klenk, N., Bazely, D.R., Yan, N., Wood, S., Henriques, I., MacLellan, J.I., and Lipsig-Mumme, C. (2012): Effects of climate change on the distribution of invasive alien species in Canada: a knowledge synthesis of range change projections in a warming world; Environmental Reviews, v. 20, no. 1, p. 1-16.

Sinclair, P. (1985): From traps to draggers: domestic commodity production in Northwest Newfoundland, 1850-1982; NL: ISER Books, St John's.

Solberg, S., Canning, P., and Buehler, S. (2007): Changing patterns of household food consumption in rural communities of Atlantic Canada, in resetting the kitchen table, (ed.) C. Parrish, N. Turner, S. Solberg; Nova Science Publishers, New York, New York, p. 161-175.

Statistics Canada (2001): Food expenditure in Canada 2001; Statistics Canada Service Bulletin, catalogue no. 62-554-XIE.

Statistics Canada (2005): Canada food stats, Canadian food trends to 2020: a long range consumer outlook; prepared for Agriculture and Agri-Food Canada by Serecon Management Consulting Inc, 2005.

Statistics Canada (2009a): Human activity and the environment: annual statistics 2009, catalogue no. 16-201-x.

Statistics Canada (2009b): Food Statistics 2009; Statistics Canada Service Bulletin, catalogue no. 21-020-x.

Statistics Canada (2011): Production and value of honey and maple products 2011; Statistics Canada Service Bulletin, catalogue no. 23-221-x.

Statistics Canada (2012): Snapshot of Canadian agriculture, <www.statcan.gc.ca/pub/95-640-x/2012002/02-eng.htm>.

Stram, D.L. and Evans, D.C.K. (2010): Fishery management responses to climate change in the North Pacific; ICES Journal of Marine Science, v. 66, p. 1633-1639.

Sumaila, U.R., Cheung, W.W.L., Lam, V.W.Y., Pauly, D., and Herrick, S. (2011): Climate change impacts on the biophysics and economics of world fisheries; Nature Climate Change, v. 1, no. 9, p. 449-456.

Thompson, J. and Scoones, I. (2009): Addressing the dynamics of agri-food systems: an emerging agenda for social science research; Environmental Science & Policy, v. 12, no. 4, p. 386-397.

Thomson, R.E. (1981): Oceanography of the British Columbia coast; Canadian Special Publication of Fisheries and Aquatic Sciences, v. 56, 291 p.

Toth, B., Corkal, D.R., Sauchyn, D., Van der Kamp, G., and Pietroniro, E. (2009): The natural characteristics of the South Saskatchewan River Basin: climate, geography and hydrology; Prairie Forum, v. 34, no. 1, p. 95-127.

USDA [U.S. Department of Agriculture] (2012): Maple Syrup 2012; United States Department of Agriculture, National Agricultural Statistics Service, New England Field Office.

USGS [U.S. Geological Survey] (2012): Sea Lamprey fact Sheet 2012; Great Lakes Science Center, Invasive species Program, <http://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=836> >.

Usher, P.J. (2000): Standard edible weights of harvested species in the Inuvialuit settlement region, Ottawa.

Vasseur, L. and Catto, N. (2008): Atlantic Canada; in Impacts to Adaptation: Canada in a Change Climate 2007, (ed.) D.L. Lemmen, F.J. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, Ontario, p. 119-170.

Walker, I. and Sydneysmith, R. (2008): British Columbia; in Impacts to Adaptation: Canada in a Change Climate 2007, (ed.) D.L. Lemmen, F.J. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, Ontario, p. 329-386.

Wang, M.Y. and Overland, J.E. (2012): A sea ice free summer Arctic within 30 years: An update from CMIP5 models; Geophysical Research Letters, v. 39, p. 6.

Ware, D.M. and Thomson, R.E. (2005): Bottom-up ecosystem trophic dynamics determine fish production in the northeast Pacific; Science, v. 308, no. 5726, p. 1280-1284.

Wheaton, E. and Kulshreshtha, S. (2009): The new normal; The Canadian Prairies in a Changing Climate, (ed.) D. Sauchyn, H. Diaz and S. Kulshresththa; University of Regina, CRPRC Press, p. 124-125, 378 p.

Wheaton, E. and Kulshreshtha, S. (2010): Agriculture, in The new normal: the Canadian Prairies in a changing climate, v. 117-139; CPRC Press, Regina, 380 p.

Wheeler, P., Ford, V., Klokov, K., and Syroechkovskiy (2010): Changes in harvest; in Arctic biodiversity trends 2010, selected indicators of change, p. 92-95; CAFF International Secretariat, Akureyri.

Woodall, C.M., Oswalt, C.M., Westfall, J.A., Perry, C.H., Nelson, M.D., and Finley, A.O. (2009): An indicator of tree migration in forests of the eastern United States; Forest Ecology and Management, v. 257, p. 1434-1444.

Wright, M. (2001): A fishery for modern times; Oxford University Press, Don Mills, Ontario.

WTO [World Trade Organization] (2000): World Trade Organization International Trade Statistics 2000, <www.wto.org/english/res_e/statis_e/tradebysector_e.htm>.

Yvelin, J.F., Fréchet, A., and Brêthes, J.C. (2005): Migratory routes and stock structure of cod from the Northern Gulf of St. Lawrence (3Pn, 4RS); CSAS Research Document 2005/055, 50 p.

Ziervogel, G. and Ericksen, P.J. (2010): Adapting to climate change to sustain food security; WIREs Climate Change, v. 1, p. 525-540, doi:10.1002/wcc.56.

Zeller, D.S., Booth, E., Pakhomov, W., and Swartz, D.P. (2011): Arctic fisheries catches in Russia, USA and Canada: baselines for neglected ecosystems; Polar Biology, v. 34, p. 955-973.

Zwiers, F.W., Schnorbus, M.A., and Maruszeczka, G.D. (2011): Hydrologic impacts of climate change on BC water resources; Summary Report for the Campbell, Columbia and Peace River Watersheds, Pacific Climate Impacts Consortium, University of Victoria, Victoria BC, 17 p.

# CHAPTER 5: **INDUSTRY**

Lead Authors:

**Paul Kovacs** and **Jason Thistlethwaite** *(Institute for Catastrophic Loss Reduction)*

Contributing Authors:

**Daniel Scott** *(University of Waterloo)*, **Bob Oliver** *(Pollution Probe)*

Recommended Citation:

Kovacs, P. and Thistlethwaite, J. (2014): Industry; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 135-158.

# TABLE OF CONTENTS

# KEY FINDINGS

There is relatively little published research describing climate impacts on Canadian industry, or assessing industry's response in terms of adaptation, despite some potentially significant economic implications. The impacts of climate change and the adaptive actions taking place are best documented in the more weather-sensitive industries, such as property insurance and tourism. There are potential opportunities through expanded markets and products for these sectors if they successfully implement adaptive actions. For the industry sector as a whole, available information indicates:

- Industrial activity is sensitive to variation in weather and extreme events, with considerable differences in the types and extent of impacts on production, operations, and revenue between and within sectors.
- Changes in industry practices have been predominantly reactive, responding to variation in the weather or extreme events, rather than proactive anticipation of future climate change. Examples of adaptation tend to be isolated rather than representative of a clear trend within the sector.
- Adaptive actions implemented by industry vary widely by sector, and may be under-reported for strategic reasons. Tourism and insurance could take advantage of potential opportunities through adaptive actions.
- There is little published research about indirect impacts of climate change on industry, such as changes associated with consumer demand, supply chains, real estate or other assets, adaptation by other sectors, legal liability or government regulation.
- Barriers towards effective adaptation include limited information on local impacts to businesses, uncertainties about the costs and benefits of different adaptive actions, and limited market demand for the implementation of adaptation.

# 1. INTRODUCTION

This chapter assesses the impact of variation in weather and weather extremes on Canadian industry, and prospects for adaptation to reduce the risk of adverse impacts or realize the potential for gain both currently and under anticipated climate change. It focuses on five industries – property insurance, tourism, residential construction, manufacturing, and trade – and does not address industries discussed elsewhere in the assessment, including power generation, forestry and mining (Chapter 3), agriculture (Chapter 4), health care (Chapter 7), and transportation (Chapter 8).

Available adaptation research tends to focus on sectors with clear relationships with ecosystems or inputs that are sensitive to climate change, such as agriculture, forestry and water management (Willbanks et al., 2007). There is relatively little published research concerning other service or goods producing sectors. This chapter provides a sample of industrial activity in these other sectors in Canada. Some, such as insurance and tourism, have growing bodies of Canadian and international research, while others such as residential construction, manufacturing and trade remain under-analyzed. Proprietary concerns about disclosing information that could hurt competitiveness has been cited as one reason why there is not more information available on adaptation strategies across industry (Agrawala et al., 2011). Of the sectors discussed in this chapter, insurance and tourism are most exposed to climate change impacts, and are the most advanced on developing adaptive actions. Manufacturing and residential construction are less exposed to these impacts, and have only recently started to consider climate change adaptation. Trade markets are arguably the least vulnerable of the sectors discussed, and there is very little evidence that export sectors are developing adaptive actions (Figure 1).

Climate risks for Canadian business include direct impacts, such as damage or costs linked with extreme weather, and indirect impacts, including changes affecting consumer preferences, government regulation, or financial and legal liability associated with ineffective or lacking response to climate change. For the most part, industry has yet to develop effective adaptive approaches to reduce sensitivity to these impacts. There is evidence, however, that industry does respond to existing extreme weather and climate variation through adaptive actions, such as changes in building codes or supply-chain management, which could be used to promote adaptation to climate change. Climate change also offers market opportunities through the provision of new services and products for some sectors, but realizing these opportunities is contingent on effective adaptation.

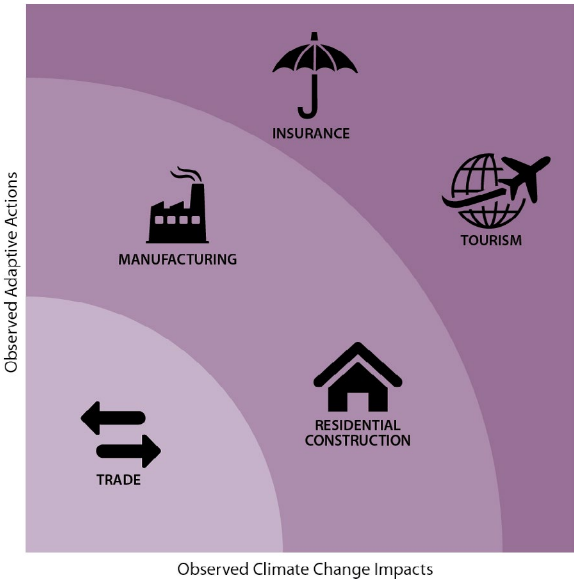


**FIGURE 1:** The exposure of each sector to climate change impacts, compared to their observed adaptive actions.

# 2. ECONOMIC CONTEXT

In 2011, Canada's Gross Domestic Product (GDP) grew to exceed $1.7 trillion (Industry Canada, 2011). About one third of Canadian production is in goods producing industries – including agriculture, oil and gas extraction, mining, forestry, construction and manufacturing. Manufacturing and construction account for the majority of goods production in Canada (75 percent by sales) and are assessed in this chapter. About two thirds of Canadian production and employment is in service industries – including banking and insurance, retail trade, transportation, schools, hospitals, other public services, and tourism. Tourism and insurance account for 5 to 15 percent, respectively, of the service industry in Canada (Industry Canada, 2011).

## 2.1 INSURANCE

Insurance companies had $116.6 billion in income in 2011, the ninth largest of Canada's 22 industries (Statistics Canada, 2012a). Insurance includes a number of different sub-sectors including life and health, and property and casualty insurance companies. Some insurance sectors, such as life insurance, do not currently appear sensitive to variation in the weather (Mills et al., 2001). However, property insurance, and to a lesser extent auto insurance, experience significant swings in costs and earnings with weather variation. In fact, weather damage claims have recently emerged as the largest expense for property insurance companies in Canada (IBC, 2012a; McBean, 2012).

Climate change and the potential increase in the frequency of severe weather has emerged as a significant priority for property insurers (McBean, 2012; Robinson, 2012). The property insurance sector also provides risk-transfer services that generate economic incentives that support adaptation throughout the economy. For these reasons, this chapter focuses on the Canadian property insurance sector. Property insurance companies have been operating in Canada for more than 200 years. Several hundred companies provide property insurance and auto insurance coverage, representing Canada's most competitive financial industry (IBC, 2009). The industry includes a mix of large, mid-sized and smaller companies located across the country.

## 2.2 TOURISM

In 2011, tourism generated $78.8 billion in revenues, representing approximately 2 percent of Canada's gross domestic product, and over 603 000 direct jobs (Government of Canada, 2012a). Many of these jobs are within small businesses and in small communities and rural areas (TIAC, 2012). The contribution of tourism to the Canadian economy is significantly less than other G20 nations, as Canada has fallen from 7th to 18th in international arrivals over the past decade (TIAC, 2012). The World Travel and Tourism Council (2012) forecasts steady growth in Canada's tourism sector between 2012 and 2022 (an average of 2.9 percent per year), and the tourism industry and federal/provincial governments are optimistic that major tourism growth is possible (Canadian Chamber of Commerce, 2012; Government of Canada, 2012a; TIAC, 2012) as international arrivals are projected to increase to 1.8 billion by 2030 (UNWTO, 2011).

While tourism is an important economic driver in every region of Canada (Table 1), it has even greater importance at the community scale, where it is a dominant economic sector in park gateway communities, "cottaging" districts, and many other destinations. It represents a key economic revitalization strategy where traditional resource-based economies have declined (Government of Canada, 2005, 2012b; Scott, 2011).

| Province and Territory | 2011 Gross Domestic Product (2002 Constant $) | 2011 Tourism Employment (Jobs) |
|---|---|---|
| Newfoundland | $316M | 8136 |
| Prince Edward Island | $121M | 2866 |
| Nova Scotia | $683M | 16 636 |
| New Brunswick | $438M | 12 090 |
| Quebec | $5357M | 130 018 |
| Ontario | $9797M | 226 781 |
| Manitoba | $903M | 22 628 |
| Saskatchewan | $677M | 18 063 |
| Alberta | $3063M | 69 308 |
| British Columbia | $4913M | 96 877 |
| Yukon/Northwest Territories/Nunavut | $147M | N/A |
| Total | **$26.415B** | **603 400** |

**TABLE 1:** The economic contribution of tourism across Canada *(Source: TIAC, 2012).*

## 2.3 RESIDENTIAL CONSTRUCTION

The residential construction industry involves spending on both new houses and renovations. The sector accounts for approximately 6 percent of Canada's GDP and was Canada's fastest growing industry over the last decade (TD Economics, 2011; Statistics Canada, 2012b). In 2011, 843 763 Canadians (7.1 percent of working Canadians) were employed by the construction sector (Statistics Canada, 2012b, 2012c).[1] Although the sector suffered a decline in spending and employment after the 2007-2008 financial crisis, conditions improved somewhat in 2011 (CHBA, 2011).

Growth in the residential construction sector in Canada is driven by low levels of unemployment, low interest rates and immigration. The Canadian Home Builder's Association (CHBA) anticipates new home starts will be steady over the next few years, but should increase in response to immigration and demographic pressures (CHBA, 2011).

## 2.4 MANUFACTURING

Manufacturing is Canada's largest and most diverse industrial sector. The annual income of Canada's manufacturers in 2011 was greater than all of the other goods-producing industries combined (Industry Canada, 2011). Several tens of thousands of companies participate in the sector, including large international companies and many mid-sized and smaller firms.

---

[1] These statistics refer to the construction industry as a whole, which includes commercial construction in addition to residential construction. Residential construction is the focus in this chapter, but these statistics provide an indicator of the sector's importance for the Canadian economy.

| | Exports of Goods and Services | | | Imports of Goods and Services | | | G&S Balance |
|---|---|---|---|---|---|---|---|
| | 2011 | 2011 Share | % growth over 2010 | 2011 | 2011 Share | % growth over 2010 | 2011 |
| World | 523 293 | 100.0% | 11.8 | 555 594 | 100.0% | 9.4 | -23 201 |
| U.S. | 370 255 | 69.5% | 10.5 | 337 772 | 60.8% | 7.6 | 32 483 |
| EU | 55 334 | 10.4% | 12.6 | 61 095 | 11.0% | 10.6 | -5761 |
| Japan | 12 612 | 2.4% | 15.3 | 10 816 | 1.9% | -5.9 | 1796 |
| Rest of World | 94 192 | 17.7% | 16.4 | 145 911 | 26.3% | 14.7 | -51 719 |

**TABLE 2:** Canada Goods and Services Trade by Region, 2011 ($ millions and annual % change) *(Source: DFAIT 2012)*.

This sector has experienced significant challenges in recent years due to the global economic crisis, appreciation of the Canadian dollar and weakness in export markets. Most manufacturers have experienced some disruptions from severe weather events, such as delays in securing critical supplies, challenges in making on-time deliveries, and disruptions from power failures (Pegg, 2011; Campbell, 2012).

## 2.5 TRADE

International trade contributes to 35 percent of Canada's GDP (World Bank, 2012). In 2011, Canadian exports were worth over $458 billion and its imports were worth over $455 billion on a balance-of-payments basis (Statistics Canada, 2012d).

Table 2 lists Canada's goods and services trade by region in terms of dollars and percentage change over 2010. Canada's most significant trade partners remain the United States and to a lesser extent the European Union (EU) and Japan.

In 2011, imports from Japan dropped by 5.9% due in large part to the earthquake and tsunami, which devastated that country's economy. This demonstrates how natural disasters can impact Canadian trade markets. Overall, however, Canada's trade markets improved in 2011 and grew by 10.6% over the previous year (DFAIT, 2012). Canada's largest source of exports is industrial goods and materials, followed by energy products, machinery and equipment and automatic parts. Machinery and equipment represent Canada's largest source of imports, followed by industrial goods and materials and automotive products (DFAIT, 2012).

# 3. OVERVIEW OF FINDINGS FROM PAST ASSESSMENTS

Past Canadian assessments (Environment Canada, 1998; Lemmen et al., 2008) tended not to analyze climate change adaptation within Canadian business and the industry sectors addressed in this chapter. Some sectors, specifically tourism and insurance, were discussed because of their high sensitivity to climate impacts such as extreme weather. Other sectors with less observable exposure to climate impacts, such as manufacturing or residential housing, have not received significant attention. Therefore, past assessments provide only a limited perspective on climate change adaptation for Canadian industry outside of tourism and insurance.

Discussions on insurance in past Canadian assessments and those of the Intergovernmental Panel on Climate Change (IPCC) address the industry's role in promoting adaptation and the financial risk linked with climate change. The IPCC discussion suggests that the industry could be sensitive to significant risk through a series of high-cost events taking place over a short period of time. In 2005, hurricanes Katrina, Wilma and Rita all resulted in substantial economic and human losses, and are cited as an example of this type of risk (*see* NRTEE, 2011). Other concerns discussed in past assessments include the prospect that insurance availability could become more limited if the risk of extreme weather increases in some regions (Sauchyn and Kulshreshtha, 2008), and that insurance could become too expensive for many seeking coverage who live in locations exposed to significant climate risks from hurricanes or flooding (Wilbanks et al., 2007). With respect to promoting adaptation, the price of insurance can serve as an economic signal to communicate risk and play an important role in encouraging risk-averse behaviour. Insurers can raise rates for industries or property exposed to climate risks, and lower rates if clients make investments in adaptive capacity (Wilbanks et al., 2007).

Discussions of tourism in the IPCC Fourth Assessment Report and a special report commissioned by the World Tourism Organization and the United Nations Environment Programme recognize the climate sensitivity of the sector and the importance of climate change adaptation, particularly for national and community economies highly dependent on tourism (Wilbanks et al., 2007; Scott et al., 2008). Both assessments document the wide range of direct impacts (e.g. from changes in temperature, precipitation and the frequency of extreme weather), and indirect impacts (e.g. changes in water availability or quality, lost snow cover or beach area, operational and travel costs, and consumer preferences and destination reputation) on global tourism and major tourism destinations. Destination-level impacts are documented in the regional chapters of both assessments. Tourists have tremendous capacity to substitute the place, timing and activities related to travel and an improved understanding of consumer adaptive responses was considered crucial for effective adaptation by tourism businesses and the communities that rely on them. The international assessments conclude that climate change will alter the competitiveness of destinations world-wide and that all destination communities will need to adapt, whether by reducing risks or realizing opportunities (Wilbanks et al., 2007; Scott et al., 2008).

Lemmen et al. (2008) provides a regional assessment of climate change impacts for Canada, including those related to tourism (Table 3). The report indicated that the Canadian tourism sector could experience net gains as a result of climate changes, based largely on a longer warm-weather tourism season and attendant increase in domestic and international tourist activity, as well as a relatively improved competitive position in the international tourism marketplace (Bruce and Haites, 2008). Winter sports tourism is the most exposed to risks as a result of warmer winter temperatures and reduced snowfall.

While past assessments have frequently included a focus on infrastructure, they rarely discuss the implications for residential construction. They generally conclude that climate change will exacerbate existing climate risks faced by home owners. For example, an increase in the intensity and frequency of rainfall will intensify existing issues related to basement flooding for homes with aging sewer systems (Wilbanks et al., 2007). However, there is no direct discussion of adaptation action in the residential housing sector.

Research on climate change adaptation within the Canadian manufacturing sector also remains quite scarce, and is generally addressed in previous assessments in the context of infrastructure and transportation. Direct impacts include

| Region | Key Risks | Opportunities |
|---|---|---|
| **North** | Infrastructure at tourist sites is at risk from degrading permafrost, flooding | Travel season and accessibility will increase as temperatures warm and sea ice declines |
| **Atlantic Canada** | Tourism infrastructure at risk from coastal flooding and erosion linked with extreme weather and sea level rise | Longer warm-weather tourism season will benefit communities |
| **Quebec and Ontario** | Winter sports tourism (skiing, ice-fishing, snowmobiling) will suffer from warmer winter temperatures and more variable snowfall and ice conditions<br>Winter festivals could be negatively impacted<br>Cold water sport fisheries will be reduced<br>Water quality and wild fires could affect tourism in some communities | Summer tourism activities (e.g. golfing, fishing, boating, park visits) will benefit from longer warm-weather season |
| **Prairies** | Water availability for fishing and recreation could decrease<br>Forest fires more likely with warmer temperatures<br>Winter sports tourism will suffer from warmer temperatures and variable snowfall | Summer tourism activities (e.g. golfing, fishing, boating, park visits) will benefit from longer season |
| **British Columbia** | Skiing and other winter recreation activities will suffer from reduced snowfall<br>Forest fires could increase in the interior<br>Sport fishing will be affected as water levels and temperatures change<br>Transportation access to tourist sites will be vulnerable to landslides, flooding and forest fires | Tourist operators will benefit from expanding summer recreation activities |

**TABLE 3:** Regional Climate Impacts for Canadian Tourism *(Sources: Bourque and Simonet, 2008; Chiotti and Lavender, 2008; Sauchyn and Kulshreshtha, 2008; Vasseur and Catto, 2008; Walker and Sydneysmith, 2008).*

those that affect industrial activity in specific locations, in addition to the supply chain that maintains production at these locations (Wilbanks et al., 2007). Indirect impacts include changes in the availability of the inputs (e.g. timber, electricity), consumer preferences for certain products (e.g. more demand for air conditioners, less demand for heaters), or the regulations that govern manufacturing (e.g. stricter cooling standards) (Wilbanks et al., 2007).

Previous research on climate change adaptation and Canadian trade markets is also limited (Bruce and Haites, 2008). The impact of mitigation policies on Canadian and U.S. export markets has been analyzed (e.g. Lister, 2008; Aldy and Pizer, 2011), but research on the sensitivity of Canada's trade networks to climate change and potential adaptive actions was not found in the literature. Previous assessments note the potential sensitivity of Canada's global and continental trade patterns to climate change, with a strong focus on natural resource products (i.e. from forestry, agriculture, fisheries, energy and water) (*see* Bruce and Haites, 2008). Focus was also placed on supply-side issues, while impacts on longer-term demand for Canadian exports were considered speculative (Bruce and Haites, 2008). Climate change impacts on transportation are also important to international trade. Marine and coastal ports on the Atlantic and Pacific coasts that provide important access for trade goods face disruptions linked with the rising sea-level or extreme weather (Vasseur and Catto, 2008; Walker and Sydneysmith, 2008). Damage from freeze-thaw cycles and extreme weather on road networks is another transportation impact that would have implications for international trade (Walker and Sydneysmith, 2008). In terms of adaptation, previous assessments suggest climate change should be considered in the construction of important transportation infrastructure. For example, bridges in coastal regions could be constructed to withstand projected sea-level rise (Vasseur and Catto, 2008).

# 4. RISKS, OPPORTUNITIES AND ADAPTATION

## 4.1 INSURANCE

Damage to homes and businesses caused by severe weather has been increasing for several decades in Canada and elsewhere around the globe. In fact, loss and damage due to intense rainfall, hurricanes, tornadoes, wildfires and winter storms has recently grown to surpass fire and theft and now represents the largest cost for the property insurance industry in Canada (McBean, 2012). In 2011, the Canadian insurance industry paid out a record $1.7 billion for property damage claims linked with weather events, part of an increasing trend in these types of losses (Robinson, 2011; Figure 2). The increase in insured losses primarily involves basement flood damage claims, but there has also been an increase in damage claims paid due to wind and wildfires (McBean, 2012). Figure 3 identifies some of the major extreme weather events that have occurred in Canada over the last 10 years and the costs associated with the damage they caused. For the most part, Canadian insurers have been able to maintain profitable balance sheets, although one-third of the industry reported underwriting losses in 2012 (Dickson, 2012).

Several factors contributed to the increase in severe weather damage to property across Canada – including more people and property at risk, aging infrastructure, and changes in climate (McBean, 2012). There has not yet been a study for Canada to estimate the contribution of climate change to the cost of claims that have been paid by insurers (Kovacs, 2012). Research using international insurance loss data suggests that socio-economic factors, such as increases in wealth, increases in the number and value of properties at risk, and deterioration of the capacity of public infrastructure, explain most of the reported increase in property damage, with little contribution to date resulting from climate change (Choi and Fisher, 2003; Bouwer, 2010). This conclusion is consistent with findings in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012).

There is considerable evidence that climate change will bring more intense rain events (Min et al., 2011) that can overwhelm Canada's aging urban sewer systems and cause

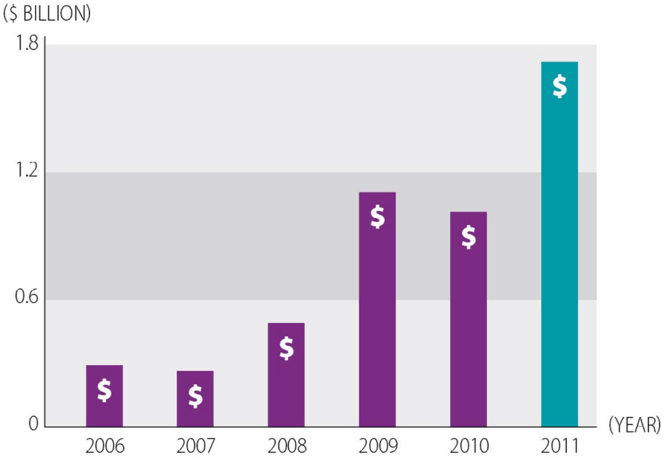


**FIGURE 2:** Catastrophic insurance losses in Canada from 2006-2011 ($ billions). Estimated total losses for full year in constant dollars *(Source: Robinson, 2011).*

significant damage to homes and businesses. This, in turn, is expected to affect the frequency and severity of basement flooding events. There is also evidence that warming will bring about an increase in the severity of Atlantic hurricanes (Kunkel et al., 2008; Senevirate et al., 2012), likely resulting in more insurance claims for damage from wind and heavy rain in eastern Canada. There is concern that climate change will increase the frequency and severity of summer storms across North America, such as tornadoes, hail storms and lightning events (Peterson et al., 2008), potentially increasing damages and losses. There is also considerable evidence that the area burned by wildfire will increase (Wotton et al., 2010; Handmer et al., 2012), adding to the risk of fire damage to homes and businesses located in wildland-urban interface areas. Although there have been important advances in international research on climate extremes, there is a gap in such research in Canada (Kovacs, 2012, *see* Chapter 2 - An Overview of Canada's Changing Climate). Despite this, insurers are convinced that climate change will significantly increase the risk of claims over the next few decades (Mills, 2009a, 2009b; McBean, 2012; Thistlethwaite, 2012).

Some US reports have also suggested that climate change could increase auto insurance and liability insurance claims (Mills and Lecomte, 2006). Extreme weather events such as hail or snow events increase auto insurance claims, as witnessed in Manitoba, for example, when hailstorms generated a significant amount of auto insurance claims during 2012 (MPI, 2011). Some US insurance trade journals have raised the prospect that Directors and Officers Liability insurance claims could increase if courts find these executives negligent for ignoring climate change risks (Mills, 2007). Although liability claims could be a risk for insurers, U.S. and Canadian courts have yet to issue any decision that holds a firm liable for a particular climate change impact (Bobelian, 2012).

While there is a growing consensus in the Canadian insurance industry that the risk of loss and damage will increase in part due to changes in climate, research on opportunities for the Canadian insurance sector is less robust (McBean, 2012). There is evidence from the global insurance market, however, that insurers are starting to explore potential market opportunities linked with climate change (*see* Mills, 2009b). Incentives in property insurance contracts for "rebuilding right" after a damaging weather event are becoming more popular among some U.S. and European insurers. Products that use parametric and index-based coverage for agriculture or livestock weather-related losses are starting to emerge in some developing countries. Insurers are also exploring products to cover risk for new renewable energy technologies. Markets for these products could help insurers adapt to increases in property related losses by generating alternative revenue streams (Mills, 2007; 2012).

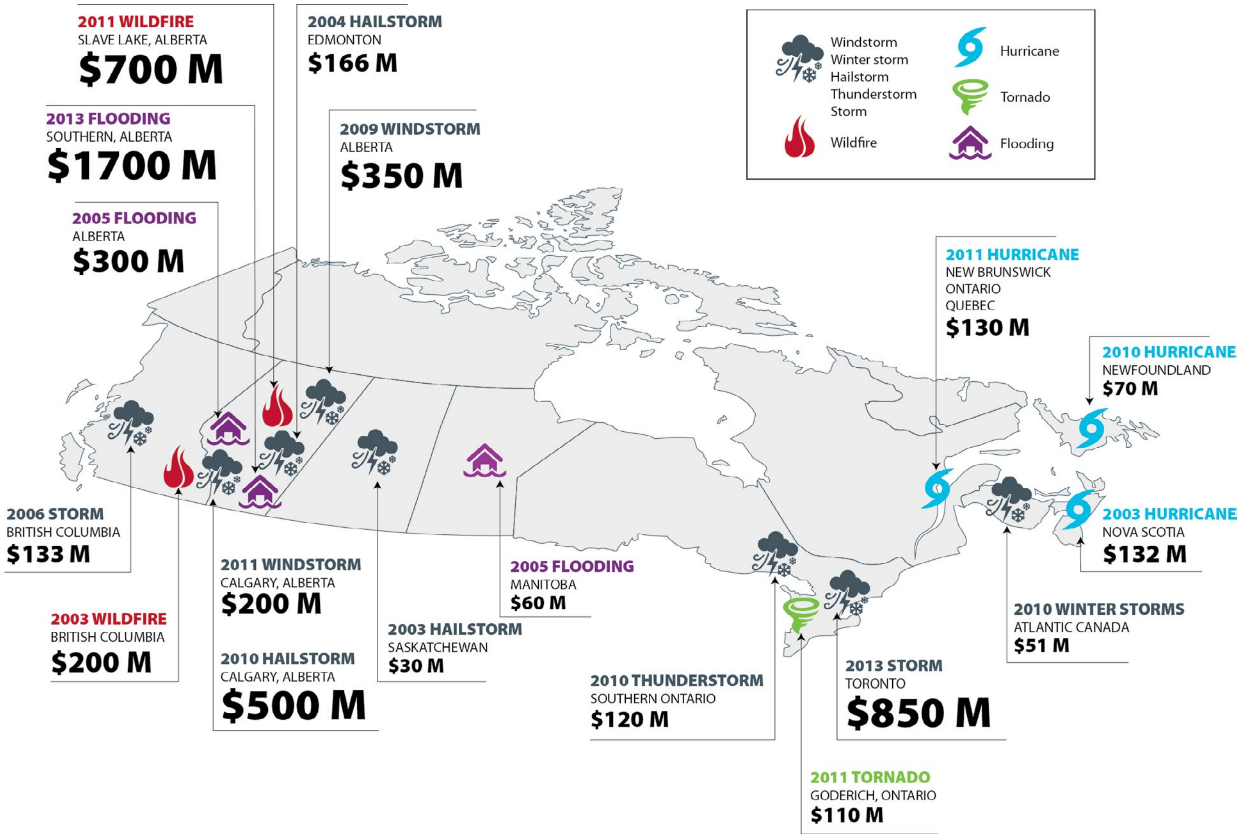


**FIGURE 3:** Insured losses from extreme weather events in Canada *(Sources: IBC, 2008, 2011b, 2013a, b; McBean, 2012).*

## ADAPTATION

Adaptation taking place in the insurance industry is better documented than most other industry sectors in both the international literature (Dlugodecki, 2009; Kunreuther et al., 2009; Mills, 2009a, 2009b; UNEP FI, 2009; Thistlethwaite, 2012) and a number of Canadian studies (Dotto et al., 2010; Kovacs, 2012; McBean, 2012). Coverage adjustments, price increases and purchasing reinsurance contracts represent several important adaptive actions that insurers can use to reduce their exposure to costs generated by extreme weather and climate variability.

Higher costs linked with an increase in damage from extreme weather have led to some adaptation within the insurance sector. While some property insurers have adjusted the coverage they offer in response to extreme weather, such as no longer offering sewer backup insurance in communities with recurring losses, the overall change in coverage offered has been limited relative to some U.S. insurance markets. For example, despite the fact that the 1998 ice storm in eastern Ontario, southern Quebec and parts of Atlantic Canada led to more than 700 000 loss claims by homeowners, there has been almost no reduction in the winter storm coverage property insurers offer to homeowners and businesses over the past decade (Dotto et al., 2010). Similarly, several hundred homes were destroyed by fire in Slave Lake and Kelowna, but there has been no change in the availability and extent of fire coverage (*see* Sandink, 2009). This differs from some coastal U.S. insurance markets, where hurricane loss events have led to a reduction in the extent and availability of insurance (Mills and Lecomte, 2006). It appears that the very competitive nature of the Canadian property insurance industry makes companies willing to provide coverage if they can expect to secure a fair price for assuming the risk.

While changes in the extent and availability of insurance coverage have been minimal, rising loss and damage claims have increased the price homeowners and businesses pay for insurance (Marr, 2011; Mills, 2012). Canada's insurers are starting to use the price of insurance to provide an incentive for adaptation. For example, some insurers establish the price and availability of sewer backup coverage based on the presence of loss prevention actions by the policyholder, like the installation of a backwater valve (Sandink, 2011). Primary insurance companies also actively manage the risk of catastrophic loss and damage events through reinsurance contracts. Reinsurance companies sell contracts to primary insurers that offer to cover a large portion of the costs from rare, but significant loss events. Insurance companies are assessing their potential severe weather costs when they determine, for example, the capital they will hold, the reinsurance protection they buy, pricing, and the coverage offered to consumers. Industry practices have been adapting in this way as companies learn more about the climate risks they face (Mills, 2009a; 2009b).

Although adaptive actions that attempt to address future climate change are emerging, recent surveys of the sector by regulators confirm that such actions remain quite scarce. A U.S. survey conducted by the National Association of Insurance Supervisors revealed that only 11 out of 88 companies surveyed had adopted formal climate change policies (Leurig, 2011). In 2011, a Quebec survey found that a minority of insurers have taken formal adaptive actions. For example, four out of the nine insurers that responded to the survey indicated that they evaluate the link between climatic events and claims by collecting regional weather data (AMF, 2011). It is important to note that these survey results might be influenced by concerns among insurers that information on adaptation is proprietary and sharing it could hurt competitiveness.

The use of climate change risk disclosure surveys by regulators represents a potential tool to promote adaptation within the financial industry. As more information on climate change risk is disclosed, investors, shareholders and regulators will be able to identify firms that are overly exposed to climate change risks. Investors and shareholders concerned about the return on their investments could put pressure on these firms to implement adaptation strategies. The Carbon Disclosure Project (CDP; *see* Case Study 7 in Chapter 3) - a non-profit and voluntary UK initiative - has adopted this disclosure strategy and now hosts the world's largest database on climate change risks. Securities regulators have also responded to efforts like the CDP by increasing their scrutiny of the financial sector's exposure to climate change risks. Several new regulations have emerged in the last few years that target improved disclosure of climate change risks among publicly listed firms (*see* Case Study 1).

Insurers have a range of more robust adaptive actions they could employ to take advantage of their existing expertise and products. These actions include pricing climate change risks into insurance contracts, developing forward-looking models that integrate climate risk information, and promoting adaptation among external stakeholders, to help preserve the availability of insurance. Pricing climate change risks represents a considerable challenge for the industry. Traditional actuarial analysis is not well suited to predicting rare and significant loss events and relies on historical data, which is of limited value to understanding the future impacts of climate change on claims (Olcese, 2010). Actuarial analysis has also been structured to predict fire and theft risk, rather than weather-related risks (AMF, 2011). In the U.S., regulatory risk has been cited as another barrier to integrating climate change risks into pricing (Leurig, 2011). Insurers are concerned that the price increases necessary to cover climate change risks could make rates unaffordable and regulatory interventions could force rate reductions. U.S. regulators have intervened in the past by forcing insurers trying to recoup costs after significant loss events, such as Hurricane Katrina, to reduce their rates (Thistlethwaite, 2012).

Some insurers and industry trade associations have begun to adapt their modeling practices to address limitations in traditional actuarial analysis. For example, U.S. risk modellers have developed "near-term" catastrophe models that place more statistical weight on recent weather and climate variables (e.g. warmer Atlantic ocean temperatures), which are more effective at capturing the climate signal (Eeuwens, 2009). Insurance companies have also begun to research how climate models could be used to inform pricing practices (IBC, 2012a; McBean, 2012). The Association of British Insurers and the UK Met Office recently collaborated in a project that used climate models to understand how water damage will change in response to climate change (Dailey et al., 2009). The Canadian Institute of Actuaries (CIA) is working on the development of an Actuaries Climate Change Index that insurers could use to better qualify climate change risks. The index tracks climate abnormalities by comparing historical information with present weather trends. This information is then combined with socioeconomic data on vulnerability to understand how climate extremes change the risk of a loss event for different markets (Soltera Solutions, 2012). The Insurance Bureau of Canada is also partnering with a number of communities to develop a municipal risk assessment tool (MRAT) to improve data and management of the risk of sewer backup damage (IBC, 2012b). Tools such as the MRAT (*see* Case Study 2) and research on the attribution of climate change to rising insurance losses can help generate financial data on climate change risks (Kovacs, 2012).

CASE STUDY 1

## CLIMATE CHANGE RISK FINANCIAL DISCLOSURE

Financial disclosure of climate change risks is one of the most effective tools for promoting climate change adaptation. Information produced through this disclosure could generate a comparable market signal that investors use to justify investments in firms that promote climate change adaptation as a risk management strategy. In 2012, the UK government announced that any company listed on its London Stock Exchange would be required to disclose their greenhouse gas (GHG) emissions (Secretary of State for Environment, Food and Rural Affairs, 2012). This regulation is the world's first mandatory reporting requirement for GHGs and sets an important precedent among financial regulators. U.S. and Canadian securities regulators have also issued guidance to the effect that climate change impacts are material risks that meet the threshold for disclosure (SEC, 2010; CSA, 2012). Regulations such as this suggest that securities regulators and investors are starting to scrutinize exposure to climate change risks. For the insurance industry and other financial service providers, this scrutiny could incentivize adaptive actions, such as higher risk premiums on financial products exposed to climate change risks

Shareholders are particularly interested in climate change risk information. In recent years, shareholders have filed a number of resolutions asking the companies they invest in to provide information on their ability to manage climate change risks (Ceres, 2013). The U.S. Securities and Exchange Commission (SEC) recently strengthened the power of shareholder resolutions pertaining to climate change risk. Some financial institutions had been able to ignore these resolutions by arguing that it was not a part of 'ordinary business'. In February 2013, the SEC announced that companies would no longer be able to ignore these regulations and climate change impacts are material risks that must be disclosed to investors.

Measurement of climate change risk exposure represents one of the significant challenges that must be addressed to improve disclosure. The Canadian Institute for Chartered Accountants (CICA) is trying to improve the measurement of climate change risks for financial reporting. The CICA has developed guidance that reporting organizations can use to identify information on climate change risk that is material or "decision-useful" to investors (CICA, 2009). Over time, this effort will help generate a market signal through financial disclosures that communicates to investors which firms are most exposed to material climate change risks, and those that have reduced these risks through adaptation.

Despite these advances, more research is needed before climate change models and analysis can be used to better price insurance contracts. Any change in the way insurers price risks will be examined by both policyholders and regulators. The insurance industry must not only generate a technical consensus within the industry on the right practices for pricing climate change risks, but also work with stakeholders to ensure pricing remains affordable (Thistlethwaite, 2012). For this reason, in addition to their own research, insurers are partnering with academia (e.g. CCAP, 2012; ACT, 2013) and engaging external stakeholders to promote adaptive actions. For example, insurers are working with homebuilders, consumers and governments to raise awareness of climate risks and develop tools to assess and manage risks. Examples include building demonstration homes with features beyond those required under the current building code, which can prevent damage from a category 4 hurricane, category 2 tornado, or an intense rainfall event (ICLR, 2007).

Overall, the insurance industry appears to have the capacity and expertise needed to adapt to climate change. Insurers are implementing several adaptive actions, including adjusting coverage and pricing, researching the use of climate models to inform pricing practices, and engaging with stakeholders with influence over infrastructure and building codes. However, the industry needs more information on the financial implications of climate change and adaptation (UNEP-FI and SBI, 2011). While using climate models, increasing premiums for certain kinds of coverage, and assessing the vulnerability of financial reserves to rare weather events constitute important first steps, information on the contribution of climate change to financial risk and the risks involved with implementing adaptive actions remains unclear. A lack of policy and regulations supporting the implementation of adaptation for infrastructure and buildings represents a second barrier for insurers, which is also mentioned in literature on other sectors (Mills, 2012). In the absence of information to help insurers price exposure to climate change risks, and without improvements in the design of existing and future infrastructure, insurers may not price insurance contracts at a level that is affordable to businesses and homeowners (Mills and Lecomte, 2005).

CASE STUDY 2

### THE MUNICIPAL RISK ASSESSMENT TOOL (MRAT)

The Insurance Bureau of Canada has identified climate change as a priority issue for its members (Robinson, 2011; McBean, 2012). One of the most significant challenges facing the insurance industry is a lack of data on the risks related to weather extremes. The Municipal Risk Assessment Tool (MRAT) is designed to help insurers underwrite risk related to extreme rainfall events (IBC, 2011a). Damage from extreme rain is mostly generated by flooded basements when municipal sewers become overwhelmed.

To better understand the risks related to basement flooding, the Insurance Bureau of Canada (IBC) brought together a team of experts including hydrologists, climate scientists, risk managers and infrastructure engineers to develop a tool that identifies risk zones for exposure to basement flooding at the neighbourhood level. Data on existing basement flooding damage trends, hydrology, and existing infrastructure is combined to produce a hazard map that shows a "visual representation of sewer backflow risk zones". These risk zones are based on historical and future climate information, and focus municipal and insurer attention on vulnerabilities that will grow as the climate changes.

For municipalities, the tool will help to calculate costs and benefits for additional investments in infrastructure, provide information on the potential impacts of climate change, and update return periods for extreme rainfall. For insurers, this tool will help make the underwriting process more accurate. Generating this type of information on risk exposure is challenging and invites scrutiny from those who could be paying higher insurance rates. Municipalities, for example, will be hesitant to provide information to insurers that could raise insurance rates for particular neighbourhoods. Insurers, on the other hand, could face reputational risks from consumers if they raise rates to levels that some find unaffordable.

## 4.2 TOURISM

With its close relationships to weather and the natural environment, climate change is anticipated to have extensive impacts on the sustainability and competitiveness of tourism destinations and major tourism market segments around the world. Recent rankings of the impacts of climate change on tourism worldwide have consistently identified Canada as a country with the potential to improve its competitive position as an international destination (Deutsche Bank Research, 2008; Scott et al., 2008). Weather-related shifts in outbound tourism and domestic tourism spending in Canada, a lengthened and improved warm-weather tourism season, and reduced sunshine destination travel in winter would benefit the Canadian tourism sector (Wilton and Wirjanto, 1998; Bigano et al., 2007; Scott et al., 2012a). However, the role that a wide range of non-climatic factors (e.g. fuel prices and transportation costs, border restrictions, currency fluctuations, international reputation, demographic and market trends) play in determining visitation from the U.S. and overseas, and how these will interact with climate change, is not well understood.

As domestic tourism accounts for 80% of tourism spending in Canada (Government of Canada, 2012b), one research priority has been to determine the potential impacts of climate change on major domestic tourism markets (Scott, 2006). Understanding distinctive regional and local-scale impacts, and how the competitiveness and sustainability of major tourism markets could be altered by climate change, are essential for adaptation planning.

### PARK SYSTEMS

National and provincial parks are among Canada's most renowned tourism attractions. Studies of weather and park visitation estimate that under climate change, visitation could increase across the country. If current demand patterns remain, increases will be greatest in Atlantic Canada, Ontario and Quebec, and could be as much as 30% in the national park system by the 2050s (Jones and Scott, 2006). Potentially higher visitation brought about by an extended warm-weather tourism season has several economic, service and ecological implications for park agencies in Canada (Jones and Scott, 2006; Lemieux and Scott, 2011). Changes in the frequency and magnitude of extreme events such as wind storms, floods, and forest fires will also pose a challenge to park agencies, in terms of infrastructure damage, visitor safety, and business interruptions (Lemieux and Scott, 2011; Scott et al., 2012b). For example, in 2011, repairs and cleanup in the aftermath of extreme weather events cost Parks Canada over $14 million (Lindell, 2012).

## WARM-WEATHER RECREATION

With effective adaptation, major warm-weather tourism markets in Canada could benefit from projected climate change. The golf industry and golf tourism destinations across much of the country could see increased season length and demand, with the largest gains of up to 40 days as early as the 2020s in the Great Lakes and Atlantic regions (Scott and Jones, 2007). Adaptation to increase irrigation efficiency will pose a particular challenge in regions with limited or declining water resources.

The projected increase in golf seasons is also a reasonable proxy for the potential extension of other warm-weather tourism seasons, including theme/water parks, zoos, boating, fishing and beach recreation (Jones and Scott, 2006; Dawson and Scott, 2012). For example, in the City of Toronto, which operates 14 public beaches on its waterfront, the climatically suitable swimming season would increase up to 30 days in the 2020s and up to 60 days in the 2050s (Scott and Jones, 2006). Maintaining water quality will be a critical adaptation challenge, because as lake temperature warms, oxygen-carrying capacity is diminished, which can contribute to enhanced algae growth and other water pollution issues that degrade the aesthetics of beaches and pose a health risk to swimmers (Foghaden, 2012; NOAA, 2012). Even larger season extensions are likely for other important water-based tourism activities that require ice-free conditions (e.g. boating, canoeing).

## WINTER RECREATION

In contrast to summer tourism markets, a degraded and shortened winter tourism season represents a risk to tourism in many parts of Canada. The risks posed by climate change to the large ski and snowmobile industries have received considerable attention by researchers, the media, and community leaders (Scott et al., 2012a). Recent record-warm winters with shortened ski seasons in Ontario and Quebec between 2000 and 2010 have resulted in a 10-15% reduction in visitations (Scott et al., 2012a), illustrating the potential impact of future warming trends. The ski tourism industry is at risk of decreased reliability of natural snow cover and increased dependency on snowmaking. In eastern Canada and lower elevations of western Canada, shortened and more variable ski seasons are projected by mid-century, with a contraction in the number of possible ski areas as operation costs increase (Scott et al., 2006; Scott et al., 2007). Despite these adverse impacts on the Canadian ski industry, market opportunities remain as available evidence suggests that impacts would be more pronounced in the New England states and California than in Quebec and British Columbia (Dawson and Scott, 2012; Scott and Steiger, 2012). Investment and real estate markets are already beginning to respond to this differential vulnerability, but comprehensive data still needs to be collected to confirm this conclusion (Ebner, 2008; Butsic et al., 2011; Scott et al., 2012a).

Snowmobiling in Canada is more vulnerable to climate change than the ski industry because the vast expanse of snowmobile trails makes widespread implementation of snowmaking impractical. Snowmobiling seasons in non-mountainous trail regions from Manitoba to Nova Scotia are projected to decline up to 60% over the next 20 years and reliable snowmobile conditions could be largely eliminated under the warmest scenarios for the 2050s (McBoyle et al., 2007). Recent market trends showing a decrease in new snowmobile sales versus all-terrain vehicles (Cycle Country, 2006) may reflect adaptation to ongoing warming trends. Cross-country ski trail networks are also largely reliant on natural snowfall, but are less sensitive than snowmobiling because less snow is required for safe and effective track setting and informal skiing activities (Jones and Scott, 2006). The net destination or regional economic impact of seasonal shifts in tourism activities across Canada remains uncertain, with further analysis needed to determine to what extent losses from winter seasons could be compensated by gains in warm weather seasons.

## NATURE-BASED TOURISM

Growing evidence suggests that nature-based tourism will be influenced at the destination level by climate-induced environmental change. In Canada's north, changing ice conditions are lengthening the Arctic cruise season and providing access to previously inaccessible locations (Hall and Saarinen, 2010; Stewart et al., 2010). The number of planned cruises in Arctic Canada more than doubled between 2005 and 2010, and the market for tourists seeking to experience the Canadian Arctic by sea cruise is expected to grow as it has already in the Antarctic, Norway and Greenland (Stewart et al., 2010). Recent patterns of cruise activity provide insight into the future evolution of this tourism market, with routes near southern Baffin Island and the shores of Hudson Bay declining in recent years, while activity in more northern routes, particularly the Northwest Passage, have increased as these areas become more accessible (Stewart et al., 2010; Stewart et al., 2011). Multi-year sea ice continues to present hazardous travel conditions in the Northwest Passage and elsewhere, emphasizing the role of continued improvements in Canada's search and rescue capacity and our ability to monitor cruise ship traffic in the region to ensure safe development of this emerging tourism market (Stewart et al., 2011). Further consultations between communities and the cruise tourism industry regarding codes of conduct when coming onshore and improved collaboration with willing host communities to accommodate large numbers of tourists is also important to ensure tourism contributes to the sustainable development of these northern communities (Hall and Saarinen, 2010; Stewart et al., 2011).

Elsewhere in the north, the impacts of climate change on tourism are very different. The polar bear tourism market in Churchill, Manitoba will be threatened over the next 20 years by declining sea-ice conditions on Hudson Bay. An onsite survey of tourists revealed that if polar bear populations were to 'appear unhealthy' (very skinny), which is already beginning to occur, only 60% of visitors would still visit the area (Dawson et al., 2010). A large majority of visitors indicated that if they could not view polar bears in Churchill, they would travel elsewhere to see them (Dawson et al., 2010), suggesting that adverse impacts in one northern destination could represent an opportunity for other communities.

Changes in biodiversity and wildlife production will have impacts on other tourism sectors as well, particularly sport fishing and hunting. For example, the recreational fishing effort (days fished) in northern Ontario will likely increase because of increased walleye productivity, while moose hunting opportunities will likely shift northward (Browne and Hunt, 2007). The implications for other economically important tourism industries, such as sport fisheries, hunting, and wildlife viewing (e.g. bird watching) remain uncertain.

The impacts of environmental change on tourism landscapes will also affect destination image and tourist demand. A survey of tourist perceptions of environmental change in Banff and Waterton Lakes national parks found that very substantial change (e.g. large losses in viewable glaciers) was required before a substantial proportion (30% or more) of visitors would choose not to visit these destinations (Scott et al., 2007). This is consistent with results of tourist surveys in diverse environments worldwide (Scott et al., 2012a).

Elsewhere in the country, other climate-related environmental changes, including mountain pine beetle forest destruction in British Columbia, lower water levels in the Great Lakes, eroding beaches and coastlines in the Atlantic provinces, algal blooms and forest fires in Manitoba, and early tulip flowering in Ottawa have been observed to impact tourism, but the impacts under projected climate regimes have not been assessed. Improved understanding of tourist perceptions and responses to environmental change are needed to inform effective adaptation strategies (Gossling et al., 2012).

The impact of environmental changes on tourism at any destination may change over time. Lemelin et al. (2010; 2012) contend that observed and anticipated climate-induced environmental change has given rise to a new market called 'last chance tourism', where tourists visit a destination or attraction before it is 'lost' to climate change. Some Canadian destinations may therefore benefit in the near term as additional tourists visit to see changing landscapes, but then see a subsequent decline in tourism activity as the environmental attraction further degrades (Scott et al., 2012a).

## ADAPTATION

Tourism operators have implemented a wide range of adaptations that allow them to operate in every climatic zone in Canada. Examples include snowmaking, irrigation, air conditioning, fire-smart landscaping, seasonal business diversification, communications through web cams, direct marketing via the internet and social media, and insurance and financial products such as snow or sunshine guarantees (Scott et al., 2012a). While many of these strategies will be useful for coping with future climate change, the motivation for implementing these strategies has been almost exclusively to manage the impacts of current climate variability and extremes (Scott et al., 2012a). There is little evidence that tourism businesses, government tourism operators or marketing organizations, or tourism-dependent communities in Canada have assessed the capacity of current climate adaptations to cope with future climate change or their long-term financial or environmental sustainability (Scott and Jones, 2006; Dodds and Kuenzig, 2009; Lemieux et al., 2011; Scott et al., 2012b).

Assessments of the state of future-oriented climate change adaptation within the Canadian and international tourism sector have consistently found low, but improving, levels of climate change awareness, relatively low perceptions of climate change risk, and substantial optimism about the capacity of adaptation to overcome the challenges of climate change (KPMG, 2010; OECD and UNEP, 2011; Scott et al., 2012b). However, the highly competitive nature of the tourism sector has meant that for strategic business reasons, climate change adaptation strategies are not generally made public, so that the level of adaptation activity in the sector may be underestimated (Scott et al., 2012b)

Some notable examples of proactive adaptation in the Canadian tourism sector include:

- Parks Canada has begun to consider the continued melt of glaciers in Banff and Jasper National Parks as it plans for redevelopment of viewing locations and interpretive centres near these major attractions, and has also begun to accommodate coastal erosion associated with sea level rise in infrastructure planning in PEI National Park (Lemieux et al., 2011).
- The Tourism Industry Association of British Columbia has begun to develop a tourism action plan to respond to ongoing and future mountain pine beetle damage (COTABC, 2009).
- Investors in Revelstoke Mountain Resort (Revelstoke, British Columbia) have considered the potential impact of climate change on the ski industry and related real-estate markets of western North America as part of their major long-range development plan (Ebner, 2008).
- Ontario Parks has identified and evaluated a wide range of adaptation strategies across its six major program areas (Policy, System Planning and Legislation; Management Direction; Operations and Development; Research, Monitoring and Reporting; Corporate Culture and Function; and Education, Interpretation and Outreach), including several related to recreation, tourism and interpretive education (Lemieux et al., 2008).

- Whistler Blackcomb (Whistler, British Columbia) has undertaken a comprehensive assessment of its climate risk and developed a multi-strategy adaptation plan (NRTEE, 2012a) (*see* Case Study 3).

**CASE STUDY 3**

### THE WHISTLER BLACKCOMB ADAPTATION PLAN

In 2009, the Whistler Blackcomb ski resort acknowledged that its success is contingent on a stable climate and that climate change is an issue that affects its entire operation. To address this concern, the resort established a "seven-step strategic framework" to limit the climate change risks facing the resort (Figure 4). The first step in the framework involved a risk assessment using climate change scenarios to generate information on how climate change will affect the resort's operations. This information was used to inform step four of the framework, which involved identifying key actions that can promote adaptation. Doubling snow making capacity, and optimizing snow cover are two key steps the resort has taken under this umbrella to reduce the impacts of warmer weather. The resort has also developed a range of "off-peak" activities, such as hiking and mountain biking, to diversify its business from being solely concentrated on winter activity (NRTEE, 2012a).

| | | |
|---|---|---|
| **ASSESSMENT PHASE** | 1 | What are the financial implications of climate change? (negative, neutral, positive) |
| | 2 | What are our emissions? |
| | 3 | Declared statement of commitment with goals and metrics of reduced emissions |
| **ACTION PHASE** | 4 | Adaption |
| | 5 | Mitigation |
| | 6 | Risk Diversification |
| **ADVOCACY PHASE** | 7 | Inspire others through your actions and education programs |

**FIGURE 4:** Whistler Blackcomb Climate Change Strategy.

Despite these examples, future-oriented adaptation in the tourism sector appears to remain a low priority. Important needs for further action include better information that tourist operators can use to understand the impacts of climate change and the cost-effectiveness of potential adaptation approaches, and the creation of policy and possibly regulations to support adaptation. For example, the paucity of data on the costs and benefits of adaptation is viewed as a significant obstacle to effective adaptation in the tourism sector (Lemieux et al., 2011). In addition, most tourist operations are small or medium-sized enterprises that lack the expertise and capacity to assess the implications of local climate impacts for their business and implement effective adaptation strategies (Scott et al., 2008; Scott et al., 2012a).

The low level of preparedness within the tourism sector (Scott et al., 2008; KPMG, 2010) has been attributed to widespread perception in the sector that climate change adaptation is a government responsibility (Scott et al., 2012a) and that the long timeframes of climate change impacts are incompatible with the shorter timeframes of business planning, thereby restricting adaptation action to low priority status. This conclusion suggests that as in other sectors, there is a role for government to provide information and guidelines to help promote the implementation of adaptive actions. This finding is particularly important for a country like Canada where climate change represents both a risk and an opportunity to the tourism sector. Understanding and preparing for the opportunities that climate change could bring provides incentive for further engagement of the sector.

## 4.3 RESIDENTIAL CONSTRUCTION

Analysis on the impact of climate change on the housing sector largely focuses on the risks linked with direct climate impacts, specifically an increase in property damage caused by more intense and frequent extreme weather. Residential homes are built with the assumption that the climate will remain static. Extreme weather linked with climate change can easily exceed the design threshold of these structures and cause damage (Auld et al., 2008). In Canada, the insurance industry has tracked a significant increase in residential property damage linked with extreme weather in the last 20 years. In fact, weather related damages have now replaced fire and theft as the most significant source of claims (McBean, 2012).

An increase in water damage caused by sewer backups and basement flooding is the biggest contributor to these claims. Water damage claims for Intact Financial Corporation, Canada's largest home property insurer, have risen from 20 to 50 percent of all property related claims in nine years (IFC, 2012). According to the Insurance Bureau of Canada, water damage accounted for almost $1.7 billion in claims in 2011(IBC, 2012c). A recent study combined historical rainfall and insurance claims data to confirm that climate change will increase water-related damage in several Ontario watersheds (Cheng et al., 2012).

The latest Intergovernmental Panel on Climate Change report on extreme weather concludes that "small increases in climate extremes above thresholds or regional infrastructure tipping points have the potential to result in large increases in damages to all forms of existing infrastructure nationally and to increase disaster risks" (Lal et al., 2012 p. 366). Studies in Australia demonstrate that increases in wind speed can dramatically increase damage to various building structures (Coleman, 2002), while other analysis has focused on the damage caused by extreme rain, flooding, and overheating (Graves and Phillipson, 2000; Camilleri, 2001). Gradual increases in temperature and precipitation also pose a risk for residential housing as they are likely to be associated with an increase in the weathering processes that gradually deteriorate the quality of the built environment (Auld, 2008). Soil subsidence and damage to foundations is another climate change risk for residential houses, although there is no research on this topic in Canada (Swiss Re, 2011).

As noted in the discussion of insurance (section 4.1), increases in property damage cannot be wholly linked to climate change. Changes in extreme weather represent just one of several factors driving increasing rates of damage to the housing stock. A more significant factor is that more people and more property are now, more than ever, exposed and sensitive to changes in extreme weather patterns (IPCC, 2012). Aging infrastructure and housing stock, combined with poor land-use planning that allows developers to build in areas already exposed to extreme weather, intensify the effects of climate change (Cutter et al., 2012; Lal et al., 2012; Seneviratne et al., 2012).

Potential indirect impacts from climate change on residential housing include changes in the attitudes of customers (e.g. increased demand for resilient housing), increased regulatory pressure (e.g. changes to building codes), or increased financial liability (e.g. more stringent lending or insurance conditions) (Hertin et al., 2003; *see also* Sanders and Phillipson, 2003; Rousseau, 2004). These indirect impacts could play a significant role in creating the commercial incentives necessary for home builders to engage in adaptation.

There are no public data in Canada tracking climate-related damage to homes, which is why insurance information provides the best available proxy. A recent study found that home builders were not aware of a trend of increased damage, reducing the prospect that they will adapt home designs and construction practices to proactively address climate change (ICLR, 2012).

## ADAPTATION

For most stakeholders within the housing sector, climate change adaptation is a new concern, with research and policy action related to climate change still largely focused on mitigation (improving energy efficiency; e.g. Parker et al., 2000; Scott and Rowlands, 2000; Hertin et al., 2003; Arup Group Limited, 2008; St. Denis and Parker, 2009; Morna and van Vuuren, 2009). An example of recent policy action is new building code provisions in Ontario that require homes to reach a fairly robust energy efficiency standard (Lio & Associates, 2010; Laporte, 2011). The sector does employ a number of tools and practices that to date have been used as reactive measures to address existing climate variability and extreme weather, but could also be used to promote adaptation.

Building codes (Sanders and Phillipson, 2003; Lowe, 2004; Kovacs, 2012), land-use planning (Hertin et al., 2003; Deilmann, 2004; Lowe, 2004), retrofit policy (Arup Group Limited, 2008; Sandink and McGillivray, 2012); and financial planning (Hertin et al., 2003; Milne, 2004) can all be leveraged to promote climate change adaptation in the residential housing industry. The use of these tools to promote adaptation is contingent upon support from multiple stakeholders including homebuilders, regulators, the financial services sector and consumers (Figure 5).

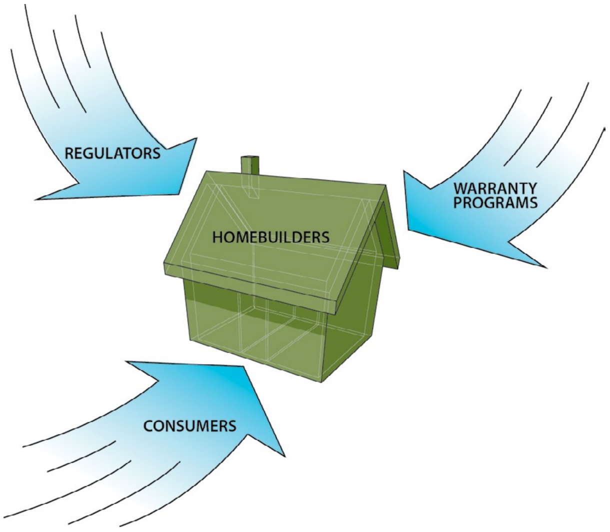


**FIGURE 5:** External stakeholders' role in promoting adaptation in residential housing market.

## THE BUILDING CODE

Most developed countries use a standardized building code as a minimum standard for the design and construction of residential homes. To date, the Canadian building code has used data on existing and historical weather trends to inform the climate load and design values that dictate how homes are built. However, the code is often discussed as one of the most useful tools for promoting adaptation in new homes (Sanders and Phillipson, 2003; Lowe, 2004). Prescriptive guidance on more resilient building practices and updated climate load and design values based on emerging and future weather trends can be integrated into the building code as a strategy for promoting adaptation in new home builds (Auld, 2008; Thistlethwaite et al., 2012). For example, the Northern Infrastructure Standardization Initiative is designed to develop climate change information that can be used to update the codes and standards that inform construction in northern climates (SCC, 2013).

## LAND-USE PLANNING

Land-use planning can be used to encourage the construction of homes in areas protected from hazards associated with existing and future extreme weather events (Richardson and Otero, 2012). Similar to building codes, land-use planning has relied on existing and historical weather to develop rules. However, as demonstrated in international examples, climate models can be used to understand how land-use must change in response to future and gradual changes in weather. In Germany for instance, GIS-based modelling of floodplains will be integrated with hydrological and climate models to inform decision-making on future land-use (Deilmann, 2004). Land-use planning can also substantially reduce damages from storm surge flooding (Mills, 2009b). The Netherlands is currently exploring new land-use planning strategies that preserve natural space in areas where climate change is predicted to increase the risk of overland flooding (Leven met Water, 2007).

## RETROFITS FOR EXISTING HOMES

While the building code and land-use planning can be used to promote adaptation for new homes, existing homes remain the most vulnerable to extreme weather and climate change (Arup Group Limited, 2008). Existing housing stock has been built using older design standards and is linked to older infrastructure. Policies promoting retrofits that improve the resiliency of existing homes to extreme weather represent the most effective adaptation strategy (Steemers, 2003; Sandink and McGillivray, 2012). For example, subsidy programs have been adopted by a number of Canadian municipalities to encourage the installation of backwater valves that can help to reduce flood damage from an increase in the frequency and intensity of rainfall events (Sandink, 2011). Subsidies can also be used to finance rebuilds after extreme weather events, which are designed to improve resilience to future climate change risks (Sandink and McGillivray, 2012). For example, sealing gaps around pipes, cables, windows and door frames can limit damage linked with future flooding events (Arup Group Limited, 2008).

## FINANCING ADAPTATION

Adaptation could also occur by improving financial planning. This could include expanded budgets to cover increased liability for damage to construction sites, or to purchase land that is protected from climate risks. Warranty programs, which insure a home against damage in the first years after construction, are perhaps the most exposed to climate risk (Milne, 2004). Financial reserves for these programs might have to be expanded. Insurance rates may also increase in response to more frequent and extreme weather. To reduce these costs, consumer demand for more resilient building practices is likely to grow (Milne, 2004).

It is important to note that these tools remain underutilized in Canada for the purposes of adaptation as a consequence of several barriers identified by international research. Homebuilders currently lack the information and capacity necessary to implement adaptive actions, and there is insufficient market demand to motivate such action within the sector (Hertin et al., 2003; Liso et al., 2003; *see also* Sanders and Phillipson, 2003; Lowe, 2004; Kovacs, 2012). Information is needed to gain a better understanding of local climate impacts to building design and the cost-benefit of changing designs to improve resilience to climate risks. Capacity is needed to develop the appropriate adaptation solutions, such as new design techniques or technologies (Sanders and Phillipson, 2003; Lowe, 2004). Engaging building design experts in the consideration of climate change is challenged by the spatial resolution of climate projections, which is not well suited to informing design requirements to protect homes from the severe weather likely to accompany climate change (Sanders and Phillipson, 2003; Lowe, 2004). In addition, designs based on future projections represent a substantive paradigm shift from the building code and current design approaches, which currently rely on historical experience (Lowe, 2004; Kovacs, 2012).

Market demands also impact decisions among the key players in the housing sector (Rousseau, 2004). Adaptation can add costs to the construction of a home if new technologies or design practices are incorporated. Builders are unlikely to support more resilient design practices without either: i) customer demand and willingness to pay for improvements; ii) regulations that require adaptation (i.e. building code, land-use planning); or iii) increased exposure to financial scrutiny among their investors and insurers (Hertin et al., 2003; Milne, 2004; Arup Group Limited, 2008). These market pressures also fuel opposition among builders with regard to changes in the building code or land-use planning, as they can add costs to their operations (Liso et al., 2003). Nonetheless, there is recognition that the building code is an important tool for advancing adaptation (e.g. Environment Canada, 2010), along with the need to identify ways that the code can integrate adaptation into new home building (MOE, 2011; ECO, 2012).

This analysis suggests that adaptation advances within the housing sector are largely contingent upon external stakeholders such as consumers or building code officials. Homebuilders are unlikely to implement adaptive actions without more information on local climate change risks, consumer demand, changes in the building code or land-use planning that supports more resilient building practices. Research on the costs and benefits of implementing certain retrofits or building code changes represents a particularly important gap (ICLR, 2012). Collaboration between building scientists, the insurance industry and homebuilders represents an important first step to develop this research (*see* Case Study 4).

CASE STUDY 4

## BUILDING A "BETTER THAN BUILDING CODE" HOME

Climate change may bring an increase in the frequency and intensity of extreme wind events. A number of building practices that can reduce the risk of loss and damage from extreme wind events have been identified, but are rarely implemented in the construction of a new home (ICLR, 2010). As a consequence, important information that could help promote adaptation within the housing sector, such as the costs, expertise and materials needed to build these homes, is rarely generated.

The Institute for Catastrophic Loss Reduction has partnered with The Co-operators General Insurance to address this gap by constructing 'demonstration homes' that address many of the technical concerns among home builders related to building a weather-resilient home. The first house was constructed in West Point, Prince Edward Island after a fire destroyed the initial home. The design and construction incorporated several new technologies and practices that strengthen existing requirements in the building code to ensure a home can withstand extreme wind events. These building design improvements were developed through research at the Boundary Layer Wind Tunnel Laboratory at Ontario's Western University. Features are shown in Table 4.

| Feature | Objective |
|---|---|
| 1" (25mm) thick steel rods that anchor the floors together (between first floor and foundation) | Ensure home is anchored to the ground to mitigate "uplift" wind pressure |
| Braces that connect roof trusses to house frame | Mitigate risk that a roof will lift off home during intense winds |
| Special shingles that can withstand 200 km/h | Reduce shingle damage during high winds, which can allow rain water to penetrate home |
| Heavy roof sheathing connected with "ring-shank" nails | Reduce likelihood sheathing could lift off roof during intense wind |
| Adhesive weather-resistant strips overlaid on every roof joint in roof sheathing | Prevent water from seeping in through joints in roof sheathing |
| Water resistant sealing around windows and doors | Limit rain water penetration |
| Wind-resistant siding, fascia and soffits | Limit rain water penetration |

**TABLE 4:** Design features and objectives of the 'demonstration home' *(Source: ICLR, 2010)*.

While such code and safety features can be built into affordable homes, more research is necessary to confirm the cost-benefit of using these features to mitigate extreme weather risk (Oulehan, 2010). Many could eventually be included in revisions to the building code, so that a future generation of homes are better capable of preventing damage from the severe weather hazards expected with change in the climate (Thistlethwaite et al., 2012).

After the demonstration house was constructed, it was subjected to hurricane winds on several occasions. The house sustained no damage as a consequence of these extreme winds. While this helped demonstrate the benefits of enhanced construction practices, more research is required to better understand whether the benefits of applying these technologies in all homes exceed the costs.

## 4.4 MANUFACTURING

Literature on climate change and the Canadian manufacturing sector almost exclusively addresses mitigation actions, while information on climate impacts, risks, opportunities and strategies used to promote adaptive actions is not well developed.

From international research it is clear that climate change can have a range of physical impacts on the manufacturing sector. Changes in the environment can limit the availability of certain key manufacturing inputs, such as water or timber, thereby increasing costs for manufacturers. For example, forest fires, pests, diseases and changing growth patterns could decrease forest productivity (NRTEE, 2011; *see* Chapter 3), which in turn could increase costs for manufacturing products, such as construction wood products and pulp and paper. Water shortages are a risk for industrial processes that use water for cooling, irrigation, cleaning or refining raw materials (Morrison et al., 2009).

High temperatures could limit production by creating unworkable conditions for employees (Agrawala et al., 2011). For example, international studies have suggested that higher temperatures and humidity can decrease productivity and increase health risks (Hanna et al., 2011; Kjellstrom and Crowe, 2011; Dunne, 2013). Extreme weather can also disrupt operations by damaging infrastructure and interrupting supply chains. For example, an Atlantic hurricane could disrupt vital transportation of materials and shut down supplier plants in southern Ontario (NRTEE, 2012b).

Changes in consumer demands and preferences resulting from climate change (and a growth in environmental awareness among the public and stakeholders) present indirect opportunities and risks for several areas of manufacturing. Generally speaking, milder winters and warmer summers may increase the demand for certain consumer products and decrease it for others (e.g. increase in demand for air conditioners during the summer months; Wilbanks et al., 2007; *see* Chapter 3). Areas of manufacturing that are greenhouse gas-intensive could face risks as consumers start purchasing products that are more energy efficient, thereby helping to mitigate climate change (Ceres, 2010).

### ADAPTATION

While the Canadian manufacturing sector is engaged in some adaptation initiatives (*see* Case Study 5), specific adaptation measures tend not to be reported or documented in available literature. International research does, however, provide some insight into manufacturing strategies for dealing with existing climate variability and extreme weather. These strategies have been identified as "soft measures" that could help integrate climate change adaptation across the firm or sector by integrating considerations of longer-term climate impacts (Agrawala et al., 2011).

Environmental management systems are often employed at a site level to deal with changes in energy, water availability or weather extremes (Agrawala et al., 2011). Supply-chain management is another strategy that manufacturers currently employ to mitigate risks from extreme weather. For example, developing strategies that promote flexibility in the supply chain can reduce damage from extreme weather events. The use of multiple suppliers, locating production across different facilities, and generating surpluses of certain goods that are frequently interrupted can improve the resiliency of supply chains to extreme weather and climate variability (Agrawala et al., 2011). Business continuity planning is another strategy manufacturers use to deal with extreme weather. Proactive planning that develops contingencies for an interruption can play a significant role in mitigating the cost of extreme weather (Forfas, 2011). In addition, most manufacturers buy business interruption insurance which can help to recover lost income in the event that extreme weather causes a disruption in operations (Chasan, 2012).

While the business resilience reports of the National Roundtable on the Environment and the Economy (NRTEE) focus on the broader implications of climate change for the business sector, rather than a specific focus on manufacturing, they do highlight some barriers to effective adaptation relevant to this sector and common to sectors discussed in this chapter. Manufacturers have difficulty translating climate change impacts and risks into information that is decision-useful for key processes. In addition, the sector is unsure of the cost-benefits or effectiveness of adaptation as a business strategy (NRTEE, 2012b). The research also notes that an absence of regulation or policy that encourages manufacturers to reduce their exposure to climate change impacts is an important barrier. For example, regulations that reduce the use of water for manufacturing processes in areas where water scarcity is expected to increase could be an important motivator for adaptation among firms (NRTEE, 2012b).

## 4.5 TRADE

Research on the link between climate change adaptation and trade remains an emerging field. Changes to a country's comparative trade advantage and the supply chains that support global trade networks are the two most significant climate change impacts (Tamiotti et al., 2009). Countries that rely on agricultural production for a comparative advantage are most at risk from climate change (Perez-Garcia et al., 2002; Julia and Duchin, 2007; Tamiotti et al., 2009). Canada's exposure to these trade markets is minimal compared to the U.S., EU or Japan (DFAIT, 2012). There is evidence that supply chains affecting Canadian trade markets are exposed to climate change risks. For example, the 2011 Thailand floods

**CASE STUDY 5**

### RIO TINTO ALCAN

Rio Tinto Alcan is one of the world's largest manufacturers of aluminum (NRTEE, 2012a). The smelting operations that form a large portion of Rio Tinto Alcan's business rely on large capital investments, long lead times for new developments, and lean supply chains. Ensuring that every link in the supply chain is free of delay or disruption is an important aspect of managing facilities and operations. Failing to address possible consequences of events that can disturb supply chain efficiency can result in significant losses for the company. For example, in 2011, the aluminum market suffered production disruptions as a result of flooding along the ports of the Mississippi River (NRTEE, 2012a). To improve business performance and adapt to predicted climate change patterns, Rio Tinto Alcan is developing a climate change framework which will aid them in assessing the sensitivity of the supply chain and other operations, as well as infrastructure, to risks associated with climate change.

This framework is designed to identify a wide variety of risks, including vulnerability of transport systems, potential for downtime of essential operations resulting from extreme weather events, and varied power generation capacities. It acknowledges the importance of considering climate change scenarios, and the company has formed a collaborative research alliance with the Ouranos consortium to improve its understanding of the impacts of climate change on the Lac Saint-Jean basin in Quebec. These initiatives will allow Rio Tinto Alcan to integrate climate change impacts into the risk management and adaptation portion of their business model.

disrupted supply chains to Canadian manufacturing importers (DFAIT, 2012). In-depth analysis of the climate sensitivity of Canada's trade networks with its major partners is needed.

### ADAPTATION

Trade has played an important role in addressing the impact of climate variability or extreme weather on a country's economy. Research suggests this capacity could also play an important role in climate change adaptation. If a country experiences a scarcity of goods as a consequence of climate change impacts, such as a drought that limits agricultural production, other trade partners could step in and fill that demand gap (Tamiotti et al., 2009). For example, a longer growing season in Canada could lead to agricultural surpluses that would offset a scarcity of goods in other parts of the world. Adaptation in this context would involve targeting and promoting growth in sectors that may be able to address scarcity in other countries as a consequence of climate change.

Demand for climate change adaptation expertise and information is also increasing and could represent an export opportunity for some countries (UNEP-FI and SBI, 2011). As a country that experiences highly variable weather, Canadian expertise on risk management and financial risk-transfer tools that offset these risks could take advantage of more global demand.

Adaptive actions that reduce the vulnerability of trade supply chains have been discussed in previous assessments in the context of transportation (*see also* Chapter 8 – Water and Transportation Infrastructure). For example, measures such as dykes and sea walls are important to protect ports from sea-level rise or storm surges (Vasseur and Catto, 2008). These actions have often been employed in response to significant historical events and could be used to improve the resiliency of key transport hubs to climate change. Like other industrial sectors, accurate cost-benefit analysis on the implementation of adaptation to protect supply chains does not exist. The lack of this data represents an important barrier to effective adaptive actions in the trade sector (Tamiotti et al., 2009).

## 5. CONCLUSIONS AND MOVING FORWARD

Research on climate change adaptation and Canadian industry has tended to focus on insurance and tourism, sectors that are most exposed to climate risks. Sectors that are less climate-sensitive but important economic contributors have yet to receive significant attention from the research community. Existing studies make a distinction between "direct" climate impacts, such as extreme weather, and "indirect" impacts, such as changes in consumer demand. Most research to date focuses on direct impacts, with only limited information available on indirect impacts.

This assessment suggests that Canadian businesses are starting to integrate adaptation into business decision making, but that actions that support adaptation within Canadian industry have yet to be implemented on a wide scale. Again, the greatest progress has been documented for insurance and tourism. The case studies in this chapter reveal that industry supports adaptation when climate impacts are prioritized and understood by key stakeholders within the sector. However, documented changes in practices are largely reactive, in response to variation in the weather or extreme events, rather than being proactive in response to projections of future climate. These reactive actions often involve the same tools that industry would use to promote adaptation. Research has identified some important needs to be addressed before such adaptation is likely to occur on a wide scale. These include the development of expertise about the impacts of climate change on business within each sector, and a better understanding of the cost-benefit behind adaptive actions. Weak market demand for adaptive actions, such as changes in consumer preferences or government policies that support adaptation, also represents a barrier.

The lack of research on how to address these barriers represents an important gap. There is little research that helps translate climate data and adaptive actions into language that fits into decision-making frameworks used by Canadian industry. This includes quantification of costs and benefits related to both climate impacts and adaptation actions. Research on the "indirect" impacts of climate change, such as evolving customer preferences, financial liability or government regulations is also an underdeveloped area. Such research would help inform how businesses can be incentivized to implement adaptation. Finally, more case studies on effective business strategies for addressing existing climate risk are needed. Such case studies provide a benchmark for "business-as-usual" approaches to climate risk that can be evaluated against proactive examples of adaptation. This comparison can generate important information, such as the costs, labour, materials or management strategy required for effective adaptation in industry.

# REFERENCES

ACT [Adaptation to Climate Change Team] (2013): Adaptation to Climate Change Team; <http://act-adapt.org/programs/>.

Agrawala, S., Carraro, M., Kingsmill, N., Lanzi, E., Mullan, M., and Prudent-Richard, G. (2011): Private Sector Engagement in Adaptation to Climate Change; OECD Environment Working Papers 39. Paris: OECD.

Aldy, J. E., and Pizer, W.A. (2011): The Competitiveness Impacts of Climate Change Mitigation Policies Regulatory Policy Program, Harvard University, Cambridge, MA; <http://www.hks.harvard.edu/m-rcbg/rpp/Working%20papers/RPP_2011_08_Aldy_Pizer.pdf>.

AMF [Autorité des marchés financiers] (2011): Managing Climate Change Risks; Autorité des marchés financiers; <http://www.lautorite.qc.ca/files//pdf/publications/professionnels/assurance/AMF-climate-change-web.pdf>.

Arup Group Limited (2008): Your Home in a Changing Climate. London, UK: Three Regions Climate Change Group; <http://www.arup.com/Publications/Your_home_in_a_changing_climate.aspx>.

Auld, H. (2008): Adaptation by Design: The Impact of Changing Climate on Infrastructure. Journal of Public Works and Infrastructure, 3: 276–288.

Auld, H., Waller, J., Eng, S., Klaassen, J., Morris, R., Fernandez, S., Cheng, V., and MacIver, D. (2008): The Changing Climate and National Building Codes and Standards; Ottawa, Canada: Environment Canada.

Bigano, A., Hamilton, J., and Tol, R. (2007): The Impact of Climate Change on Domestic and International Tourism: a Simulation Study, in Integrated Assessment Journal 7: 25–49.

Bobelian, M. (2012): An Alaskan Town Threatened by Climate Change Loses in Court; Forbes, September 26; <http://www.forbes.com/sites/michaelbobelian/2012/09/26/an-alaskan-town-threatened-by-climate-change-loses-in-court/>.

Bourque, A. and Simonet, G. (2008): Quebec; in From Impacts to Adaptation: Canada in a Changing Climate 2007, edited by D.S. Lemmen, F.J.Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON, p. 171-226.

Bouwer, L. (2010): Have Disaster Losses Increased Due to Anthropogenic Climate Change? American Meteorological Society; p. 39–46.

Browne, S. and Hunt, L. (2007): Climate Change and Nature-based Tourism, Outdoor Recreation, and Forestry in Ontario: Potential Effects and Adaptation Strategies; Ontario Ministry of Natural Resources.

Bruce, J. P. and Haites, E. (2008): Canada in an International Context in From Impacts to Adaptation: Canada in a Changing Climate, 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix, and E. Bush, p. 387–424. Government of Canada, Ottawa.

Butsic, V., Hanak, E., and Valletta, R. (2011): Climate Change and Housing Prices: Hedonic Estimates for Ski Resort in Western North America; Land Economics, 87: 75–91.

Camilleri, M. (2001): Impacts of Climate Change on Building Performance in New Zealand; Building Research & Information, 29 (6): 440–450.

Campbell, R. J. (2012): Weather-related Power Outages and Electric System Resiliency; CRS Report for Congress. Congressional Research Service; <http://www.fas.org/sgp/crs/misc/R42696.pdf>.

Canadian Chamber of Commerce (2012): Top 10 Barriers to Competitiveness; Canadian Chamber of Commerce, Ottawa; <http://www.chamber.ca/images/uploads/Top10/Top10Barriers.pdf>.

CCAP [Climate Change Adaptation Program] (2012): Climate Change Adaptation: A Priorities Plan for Canada; Waterloo, ON: Climate Change Adaptation Project; <http://adaptnowcanada.ca/report/>.

Ceres (2010): Climate Change Risk Perception & Management: A Survey of Risk Managers; Ceres, Boston; <http://www.ceres.org/resources/reports/risk-manager-survey>.

Ceres (2013): Shareholder Resolutions. Coalition for Environmentally Responsible Economies; <http://www.ceres.org/investor-network/resolutions>.

Chasan, E. (2012): Q&A: An Insurer's Take on Business Interruptions After Hurricane Sandy; Wall Street Journal, November; <http://mobile.blogs.wsj.com/cfo/2012/11/02/qa-an-insurers-take-on-business-interruptions-after-hurricane-sandy/>.

CHBA [Canadian Home Builders Association] (2011): Canadian Housing Industry - Performance and Trends; Canadian Home Builders Association; <http://vancouver.ca/ctyclerk/civicagencies/housing/RPRT_Housing_Industry_Performance_and_Trends_Oct_2011.pdf>.

Cheng, C.S., Li, Q., Li, G., and Auld, H. (2012): Climate Change and Heavy Rainfall-Related Water Damage Insurance Claims and Losses in Ontario, Canada; Journal of Water Resource and Protection, no. 4, p. 49–62.

Chiotti, Q. and Lavender, B. (2008): Ontario; in From Impacts to Adaptation: Canada in a Changing Climate 2007, edited by D.S. Lemmen, F.J.Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON, p. 227-274.

Choi, O. and Fisher, A. (2003): The Impact of Socioeconomic Development and Climate Change on Severe Weather Catastrophe Losses: Mid-Atlantic Region and the U.S.; Climate Change, no. 58, p. 149–170.

CICA [Canadian Institute of Chartered Accountants] (2009): Building a Better MD&A: Climate Change Disclosures; Canadian Performance Reporting Board; <http://www.cica.ca/research-and-guidance/mda-and-business-reporting/mda-publications/item12846.pdf>.

Coleman, T. (2002): The Impact of Climate Change on Insurance Against Catastrophes; Melbourne: Insurance Australia Group.

COTABC [Council of Tourism Associations of British Columbia] (2009): Council of Tourism Associations of British Columbia Tourism Sector Strategy: For the Southern Interior Region in Response to Mountain Pine Beetle; <http://torc.linkbc.ca/torc/downs1/COTA_MPB_Strategy_Executive_Summary.pdf>.

CSA [Canadian Securities Administrators] (2012): Staff Notice 51-333 Environmental Reporting Guidance; Canadian Securities Administrators; <http://www.osc.gov.on.ca/documents/en/Securities-Category5/csa_20101027_51-333_environmental-reporting.pdf>.

Cutter, S., Osman-Elasha, B., Campbell, J., Cheong, S.-M., McCormick, S., Pulwarty R., Supratid, S., and Ziervogel, G. (2012): Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation; in Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, (ed.) C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, et al., p.339–392. A Special Report of the Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC); Cambridge University Press, Cambridge, UK.

Cycle Country (2006): Record All-terrain Vehicle - ATV - Sales in US Deliver Double-digit Growth Again; <www.cyclecountry.com>.

Dailey, P., Huddleston, S., and Fasking, D. (2009): The Financial Risks of Climate Change; ABI Research Paper No. 19.

Dawson, J. and Scott, D. (2012): Managing for Climate Change in the Alpine Ski Sector; Tourism Management.

Dawson, J., Stewart, E.J., Lamelin, H., and Scott, D. (2010): The Carbon Cost of Polar Bear Viewing in Churchill, Canada; Journal of Sustainable Tourism 18: 319–336.

Deilmann, C. (2004): Climate Change: Lessons from Germany; Building Research & Information, v. 32, no. 1, p. 65–66.

Deutsche Bank Research (2008): Climate Change and Tourism: Where Will the Journey Take Us?; Berlin.

DFAIT [Department of Foreign Affairs and International Trade] (2012): Canada's State of Trade: Trade and Investment Update 2012; Ottawa, Canada: Department of Foreign Affairs and International Trade Canada; <http://international.gc.ca/economist-economiste/assets/pdfs/performance/SoT_2012/SoT_2012_Eng.pdf>.

Dickson, J. (2012): Remarks by Superintendent Julie Dickson to the 2012 National Insurance Conference of Canada (presentation); National Insurance Conference of Canada, October 1, Quebec City; <http://www.osfi-bsif.gc.ca/app/DocRepository/1/eng/speeches/jd20121001_e.pdf>.

Dlugodecki, A. (2009): Coping with Climate Change: Risks and Opportunities; London: Chartered Insurance Institute.

Dodds, R. and Kuenzig, G. (2009): Climate Change and Canada's Municipal Destination Marketing Organizations; The Icarus Foundation; <http://www.theicarusfoundation.com/pdf/ExecSummaryDMOandCC_Final.pdf>.

Dotto, L., Duchesne, L., Etkin, D., Elianna, J., Joe, P., Jones, B., Koshida, G., et al. (2010): Canadians at Risk: Our Exposure to Natural Disasters; ICLR Research Paper Series - Number 48. Institute for Catastrophic Loss Reduction; <http://www.iclr.org/images/Canadians_at_Risk_2010.pdf>.

Dunne, J.P., Stouffer, R.J., and John, J.G.(2013): Reductions in Labour Capacity from Heat Stress Under Climate Warming; Climate Change, v. 10.

Ebner, D. (2008): Deep Snow, Deep Pockets: It's a Billon-dollar Bet on Climate Change; The Globe and Mail, January.

ECO [Environmental Commissioner of Ontario] (2012): Ready for Change? An Assessment of Ontario's Climate Change Adaptation Strategy; Toronto: Environmental Commissioner of Ontario.

Eeuwens, K. (2009): Have Near Term CAT Risk Models Failed?; Reactions, June 15.

Environment Canada (1998): The Canada Country Study. <http://publications.gc.ca/site/eng/113767/publication.html>.

Environment Canada (2010): Climate Information to Inform New Codes and Standards; Environment Canada; <http://www.ec.gc.ca/sc-cs/default.asp?lang=En&n=20CD1ADB-1>.

Foghaden, C. (2012): The Blooming Paradise: Algae Blooms, Environmental Change and Tourism Impacts; Scandinavian Journal of Hospitality and Tourism.

Forfas (2011): Business Continuity Planning in Severe Weather; Dublin, Ireland; <http://www.forfas.ie/media/ffs111109-BCP_in_Severe_Weather.pdf>.

Gossling, S., Scott, D., and Hall, C.M. (2012): Consumer Demand and Demand Response of Tourists to Climate Change; Annals of Tourism Research, v. 39, no. 1, p. 36–58.

Government of Canada (2005): A Visit to Canada's Countryside: Rural Tourism; <http://www5.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=21-006-X2005005&lang=eng>.

Government of Canada (2012a): Industry Overview: Tourism; Supporting Tourism, September 25; <http://www.tourism.gc.ca/eic/site/034.nsf/eng/h_00003.html>.

Government of Canada (2012b): Canada's Federal Tourism Strategy; <http://www.ic.gc.ca/eic/site/034.nsf/eng/00216.html>.

Graves, H.M. and Phillipson, M.C. (2000): Potential Implications of Climate Change in the Built Environment; BRE Centre for Environmental Engineering.

Hall, C.M. and Saarinen, J. (2010): Polar Tourism: Definitions and Dimensions; Scandinavian Journal of Hospitality and Tourism, v. 10, no. 4, p. 448–467.

Handmer, J., Honda, Y., Kundzewicz, N., Arnell, N., Benito, G., Hatfield J., Mohamed, I.F., and Peduzzi P. (2012): Changes in Impacts of Climate Extremes: Human Systems and Ecosystems; in Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, (ed.) C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, et al., p. 339–392. A Special Report of the Working GroupsI and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Hanna, E.G., Kjellstrom, T., Bennett C., and Dear, K. (2011): Climate Change and Rising Heat: Population Health Implications for Working People in Austrialia; Pacific Journal of Public Health, v. 23, no. 2, p. 145–265.

Hertin, J., Berkhout, F., Gann, D.M., and Barlow, J. (2003): Climate Change and the UK House Building Sector: Perceptions, Impacts and Adaptive Capacity; Building Research & Information, v. 31, no. 3-4, p. 278–290.

IBC [Insurance Bureau of Canada] (2008): Facts of the General Insurance Industry in Canada; Toronto: Insurance Bureau of Canada.

IBC [Insurance Bureau of Canada] (2009): Facts of the General Insurance Industry in Canada; Toronto: Insurance Bureau of Canada.

IBC [Insurance Bureau of Canada] (2011a): Municipal Storm and Sanitary Infrastructure Risk Assessment Tool Project; Insurance Bureau of Canada.

IBC [Insurance Bureau of Canada] (2011b): Southern Alberta Windstorms Cost $200 Million in Insured Damage; Insurance Bureau of Canada; <http://www.ibc.ca/en/Media_Centre/News_Releases /2011/12-22-2011.asp>.

IBC [Insurance Bureau of Canada] (2012a): Canadian Severe Weather - Events and Insured Damage; Insurance Bureau of Canada; <http://www.ibc.ca/en/Media_Centre/News_Releases/2012/05-31-2012-2.asp>.

IBC [Insurance Bureau of Canada] (2012b): Municipal Risk Assessment Tool; Insurance Bureau of Canada; <http://www.ibc.ca/en/Natural_Disasters/Municipal_Risk_Assessment_Tool.asp>.

IBC [Insurance Bureau of Canada] (2012c): IBC Reminder to Torontonians About Protecting Homes from Water Damage; <http://www.ibc.ca/en/Media_Centre/News_Releases/2012/05-31-2012-2.asp>.

IBC [Insurance Bureau of Canada] (2013a): June Alberta Floods are Costliest Insured Natural Disaster in Canadian History – Estimate of insured losses exceed $1.7 billion; Media Release, September 23, 2013, online, <ibc.ca/en/Media_Centre/News_Releases/2013/June_Alberta_Floods_are_Costliest_Insured_Natural_Disaster_in_Canadian_History.asp>.

IBC [Insurance Bureau of Canada] (2013b): Preliminary insured losses released in the most expensive natural disaster in Ontario history – IBC expects the number to go even higher; Media Release, August 14, 2013, online, <ibc.ca/en/Media_Centre/News_Releases/2013/Preliminary_insured_losses_released_in_the_most_expensive_natural_disaster_in_Ontario_history.asp>.

ICLR [Institute for Catastrophic Loss Reduction] (2007): ICLR and The Co-operators Complete Canada's First Safer Living Home; Cat Tales; <http://www.iclr.org/images/CatTales1_1_.pdf>.

ICLR [Institute for Catastrophic Loss Reduction] (2010): Home Builder's Guide: Designed for Safer Living; Institute for Catastrophic Loss Reduction.

ICLR [Institute for Catastrophic Loss Reduction] (2012): A Plan Forward: Building Practices to Increase the Resilience of Homes to Severe Weather; Toronto: Institute for Catastrophic Loss Reduction.

IFC [Intact Financial Corporation] (2012): Natural Disaster and Intact Insurance; Intact Financial Corporation; <http://library.constantcontact.com/download/get/file/1103201627468-256/Water+Damage+Fact+Sheet.pdf>.

Industry Canada (2011): Canadian Industry Statistics: GDP Canadian Economy; Industry Canada; <http://www.ic.gc.ca/eic/site/cis-sic.nsf/eng/h_00013.html#vla2b>.

IPCC [Intergovernmental Panel on Climate Change] (2012): Summary for Policymakers; in Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, 3–21, (ed.) C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, NY, USA, p. 1-19.

Jones, B. and Scott, D. (2006): Climate Change, Seasonality and Visitation to Canada's National Parks; Journal of Parks and Recreation Administration, v. 24, no. 2, p. 42–62.

Julia, R. and Duchin, F. (2007): World Trade as the Adjustment Mechanism of Agriculture to Climate Change; Climatic Change, v. 83, no. 3-4, p. 393–409.

Kjellstrom, T. and Crowe, J. (2011): Climate Change, Workplace Heat Exposure, and Occupational Health and Productivity in Central America; International Journal of Occupational and Environmental Health, v. 17, no. 3., p. 270–281.

Kovacs, P. (2012): Insurance: Aligning Price of Insurance with Risk of Damage; in Climate Change Adaptation: A Priorities Plan for Canada, (ed.) B. Feltmate and J. Thistlethwaite; Climate Change Adaptation Project, Waterloo, ON.

KPMG (2010): Climate Change and Sustainability Services; KPMG; <http://www.kpmg.com/Global/en/WhatWeDo/Advisory/Risk-Compliance/Internal-Audit/Climate-Change-Sustainability-Services/Pages/default.aspx>.

Kunkel, K.E., Bromirski, P.D., Brooks, H.E., Cavazos, T., Douglas, A.V., Easterling, D.R., Emanuel, K.A., et al. (2008): Observed Changes in Weather and Climate Extremes, in Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean and U.S. Pacific Islands; A Report by the U.S. Climate Change Science Program and the Subcomittee on Global Change Research, Washington D.C..

Kunreuther, H., Michel-Kerjan, E., Doherty, N.A., Grace, M.F., Klein R.W., and Pauly, M.V. (2009): At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes; MIT Press, Cambridge, MA.

Lal, P.N., Mitchell, T., Aldunce, P., Auld, H., Mechler, R., Miyan, A., Romano, L.E., and Zakaria, S. (2012): National Systems for Managing the Risks from Climate Extremes and Disasters; In Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, edited by C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, et al., 339–392. A Special Report of the Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC); Cambridge University Press, Cambridge, UK.

Laporte, D. (2011): Ontario Code Tops in Energy Efficiency; The Toronto Star, August 19. <http://www.yourhome.ca/homes/article/1041046>.

Lemelin, H., Dawson, J., and Stewart, E. (2012): Last Chance Tourism. London: Routledge.

Lemelin, H., Dawson, J., Stewart, E., and Lueck, M. (2010): Last-chance Tourism: The Boom, Doom and Gloom of Visiting Vanishing Destinations; Current Issues in Tourism, v. 13, no. 5, p. 477–493.

Lemieux, C., Beechey, T., and Scott, D. (2011): The State of Climate Change Adaptation in Canada's Protected Areas Sector; Canadian Geographer, v. 55, no. 3, p. 301–317.

Lemieux, C. and Scott, D. (2011): Changing Climate, Challenging Choices: Identifying and Evaluating Adaptation Options for Conservation; v. 48, no. 4, p. 675–690.

Lemieux, C., Scott, D., Davis, R.G., and. Gray, P.A. (2008): Changing Climate Challenging Choices: Ontario Parks and Climate Change Adaptation; Natural Resources Canada, Ottawa.

Lemmen, D.S., Warren, F.J., and Lacroix, J. (2008): Synthesis; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix, and E. Bush, p. 1–20; Government of Canada, Ottawa.

Leurig, S. (2011): Climate Risk Disclosure by Insurers: Evaluating Insurer Responses to the NAIC Climate Disclosure Survey; A Ceres Report. Boston: Ceres.

Leven met Water. (2007): Towards a Climate-proof Netherlands; Amsterdam, Netherlands; <http://www.levenmetwater.nl/static/media/files/Routeplanner_eng.pdf>.

Lindell, R. (2012): Extreme Weather Hit National Parks Hard in 2011; Global News; <http://www.globalnews.ca/force%20of%20nature/6442585028/story.html>.

Lio & Associates (2010): A Study of Prescriptive Requirements for Energuide 80 in Ontario's Building Code; Report for Ontario Ministry of Municipal Affairs and Housing; Toronto; <http://www.mah.gov.on.ca/Asset8297.aspx?method=1>.

Liso, K.R., Aandahl, G., Eriksen, S., and Alfsen, K.H. (2003): Preparing for Climate Change Impacts in Norway's Built Environment; Building Research & Information, v. 31, no. 3-4, p. 200–209.

Lister, M. (2008): Climate Change, Trade and Competitiveness: Risks and Opportunities in a North American Perspective; Public Policy Forum.

Lowe, R. (2004): Lessons from Climate Change: A Response to the Commentaries; Building Research & Information, v. 32, no. 1, p. 75–78.

Marr, G. (2011): Climate Change Blamed for Spike in Home Insurance Premiums; The Financial Post, November; <http://business.financialpost.com/2011/11/17/climate-change-blamed-for-spike-in-home-insurance-premiums/?__lsa=fa67-72a2>.

McBean, G. (2012): Telling the Weather Story; Institute for Catastrophic Loss Reduction and Insurance Bureau of Canada.

McBoyle, G., Scott, D., and Jones, B. (2007): Climate Change and the Future of Snowmobiling in Non-mountainous Regions of Canada; Managing Leisure v. 12, no. 4, p. 237–250.

Mills, E. (2007): From Risk to Opportunity - Insurer Responses to Climate Change; Ceres.

Mills, E. (2009a): A Global Review of Insurance Industry Responses to Climate Change; The Geneva Papers, no. 34, p. 323–359.

Mills, E. (2009b): From Risk to Opportunity: Insurer Responses to Climate Change; Ceres.

Mills, E. (2012): The Greening of Insurance; Science, 338 (December); p. 1424–1425.

Mills, E. and Lecomte, E. (2005): Availability and Affordability of Insurance Under Climate Change: A Growing Threat for the U.S; Ceres.

Mills, E. and Lecomte, E. (2006): From Risk to Opportunity: How Insurers Can Proactively and Profitably Manage Climate Change; Ceres.

Mills, E. Lecomte, E., and Peara, A. (2001): U.S. Insurance Perspectives on Global Climate Change; Lawrence Berkeley National Laboratory, U.S, Department of Energy, University of California; <http://evanmills.lbl.gov/pubs/pdf/climate_report.pdf>.

Milne, J. (2004): Climate Change, Insurance and the Building Sector: Synergisms, Conflicts and Adaptive Capacity; Building Research & Information, v. 32, no. 1, p. 48–54.

Min, S-K., Zhang, X., Zwiers, F.W., and Hergerl, G.C. (2011): Human Contribution to More-intense Precipitation Extremes; Nature, no. 470, p. 378–381.

MOE [Ontario Ministry of Environment] (2011): Climate Ready: Ontario's Adaptation Strategy and Action Plan; Ontario Ministry of Environment, Toronto.

Morna, I. and van Vuuren, D. (2009): Modelling Global Residential Sector Energy Demand for Heating and Air Conditioning in the Context of Climate Change; Energy Policy, v. 37, no. 2, p. 507–521.

Morrison, J., Morikawa, M., Murphy, M. and Schulte, P. (2009): Water Scarcity & Climate Change: Growing Risks for Busiensses and Investors; Boston: Ceres and Pacific Institute; <http://www.thesapientsolution.com/research/20090525_Water_Scarcity_and_Climate_Change_thesapientsolution.pdf>.

MPI [Manitoba Public Insurance] (2011): Manitoba Public Insurance Annual Report; Winnipeg: Manitoba Public Insurance; <http://mpi.mb.ca/AnnualReport/AnnualReport2011/PDFs/Financial.pdf>.

NOAA [National Oceanic and Atmospheric Administration] (2012): Climate Change and Harmful Algal Blooms; <http://www.cop.noaa.gov/stressors/extremeevents/hab/current/CC_habs.aspx>.

NRTEE [National Round Table on the Environment and the Economy] (2011): Paying the Price: The Economic Impacts of Climate Change for Canada; 04, Climate Prosperity. National Round Table on Environment and Energy, Ottawa.

NRTEE [National Round Table on the Environment and the Economy] (2012a): Climate Prosperity: Case Studies; National Round Table on Environment and Energy; <http://nrtee-trnee.ca/wp-content/uploads/2012/03/cp5-case-studies.pdf>.

NRTEE [National Round Table on the Environment and the Economy] (2012b): Facing the Elements: Building Business Resilience in a Changing Climate; 05, Climate Prosperity; National Round Table on Environment and Energy, Ottawa.

OECD [Organisation for Economic Co-operation and Development], and UNEP [United Nations Environment Programme] (2011): Climate Change and Tourism Policy in OECD Countries; Paris: Organisation for Economic Co-operation and Development and United Nations Environment Program.

Olcese, A. (2010): Climate Change: A Wave of Opportunity for Property and Casualty Insurers; Beyond Risk.

Oulehan, G. (2010): Habitat for Resilience; Canadian Underwriter, October; <http://www.canadianunderwriter.ca/news/habitat-for-resilience/1000389796/>.

Parker, P., Scott, D., and Rowlands, I. (2000): Residential Energy Consumption and Greenhouse Gas Emissions: Global Context for Local Action; Environments, v. 28, no. 3, p. 11–28.

Pegg, H. (2011): Thai Floods Capsize North American Production; Autonet.ca, November; <http://www.autonet.ca/auto-news/automotive-industry-news/2011/11/24/thai-floods-capsize-north-american-production/>.

Perez-Garcia, J., Joyce, L.A., Mcguire, D., and Xiao, X. (2002): Impacts of Climate Change on the Global Forest Sector; Climatic Change, v. 54, no. 4, p. 439–461.

Peterson, T.C., Zhang, X., Brunet-India, M., and Vazquez-Aguirre, J.L. (2008): Changes in North American Extremes Derived from Daily Weather Data; Journal of Geophysical Research - Atmospheres, v. 113.

Richardson, G.R.A. and Otero, J. (2012): Land use planning tools for local adaptation to climate change; Natural Resources Canada, Ottawa, ON.: Government of Canada, 38 p. <http://www.nrcan.gc.ca/earth-sciences/sites/www.nrcan.gc.ca.earth-sciences/files/files/landuse-e.pdf>.

Robinson, G. (2011): Extreme Weather and Insurance; November, NRTEE-NBC Climate Change Adaptation Forum.

Robinson, G. (2012): P&C Insurance: State of the Industry (presentation); CIAA Luncheon, April 30.

Rousseau, D. (2004): Adapting to Climate Change: Some Observations; Building Research & Information, v. 32, no. 1.

Sanders, C.H. and Phillipson, M.C. (2003): UK Adaptation Strategy and Technical Measures: The Impacts of Climate Change on Buildings; Building Research & Information, v. 31, no. 3-4, p. 222–230.

Sandink, D. (2009): The Resiliency of the City of Kelowna: Exploring Mitigation Before, During and After the Okanagan Mountain Park Fire; ICLR Research Paper Series - Number 45. Institute for Catastrophic Loss Reduction; <http://www.iclr.org/images/ICLR_Report_Kelowna_D4_2.pdf>.

Sandink, D. (2011): Involving Homeowners in Urban Flood Risk Reduction: A Case Study of the Sherwood Forest Neighbourhood; ICLR Research Paper Series - No. 51. Institute for Catastrophic Loss Reduction.

Sandink, D. and McGillivray, G. (2012): Insurance: Adaptation for Existing Homes; in Climate Change Adaptation: A Priorities Plan for Canada, (ed.) B. Feltmate and J. Thistlethwaite; Climate Change Adaptation Project, Waterloo, ON.

Sauchyn, D. and Kulshreshtha, S. (2008): Prairies; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix, and E. Bush, p. 275–328; Government of Canada, Ottawa.

SCC [Standards Council of Canada] (2013): Northern Infrastructure Standardization Initiative; Standards Council of Canada; <http://www.scc.ca/en/stakeholder-participation/roadmaps-and-standardization-solutions/northern-Infrastructure-standardization-initiative>.

Scott, D. (2006): Climate Change and Sustainable Tourism in the 21st Century; in Tourism Research: Policy, Planning and Prospects, (ed.) J. Cukier. Department of Geography Publication Series; University of Waterloo, Waterloo, ON.

Scott, D. (2011): Climate Change and a Healthy, Sustainable Environment: An Opportunity for Recreation and Parks Leadership; Lake Louise.

Scott, D., Amelung B., Ceron, J-P, Dubois, G., Gossling, S., Peeters P., and Simpson M. (2008): Climate Change and Tourism: Responding to Global Challenges; United Nations World Tourist Organization and United Nations Environment Programme.

Scott, D., Gossling, S., and Hall, C.M. (2012a): Climate Change and Tourism: Impacts, Adaptation and Mitigation; Routledge, London.

Scott, D., Gossling, S., and Hall, C.M. (2012b): International Tourism and Climate Change; Wiley Interdisciplinary Reviews: Climate Change v. 3, no. 3, p. 213–232.

Scott, D. and Jones, B. (2006): Climate Change and Seaonality in Canadian Outdoor Recreation and Tourism-Executive Summary. Waterloo, ON: University of Waterloo.

Scott, D. and Jones, B. (2007): A Regional Comparison of the Implications of Climate Change of the Golf Industry in Canada; The Canadian Geographer, v. 51, no. 2, p. 219–232.

Scott, D., Jones, B., and Konopek, J. (2007): Implications of Climate and Environmental Change for Nature-based Tourism in the Canadian Rocky Mountains: A Case Study of Waterton Lakes National Parks; Tourism Management, v. 28, no. 2, p. 570–579.

Scott, D., McBoyle, G., Mills, B., and Minogue, A. (2006): Climate Change and the Sustainability of Ski-based Tourism in Eastern North America. Journal of Sustainable Tourism, v. 14, no. 4, p. 376–398.

Scott, D. and Rowlands, I. (2000): Integrating Technical and Social Energy Studies: Prospects for Change in the Canadian Residential Sector; Environments, v. 28, no. 3, p. 1–10.

Scott, D. and Steiger, R. (2012): Climate Vulnerability of the Ski Industry; in Climate Vulnerability, (ed.) R Pielke; Elsevier, San Diego.

SEC [U.S. Securities and Exchange Commission] (2010): SEC Issues Interpretive Guidance on Disclosure Related to Business or Legal Developments Regarding Climate Change; <http://www.sec.gov/news/press/2010/2010-15.htm>.

Secretary of State for Environment, Food and Rural Affairs (2012): Company Reporting of Greenhouse Gas Emissions by Quoted Companies; <http://www.parliament.uk/documents/commons-vote-office/June_2012/20-06-12/3.DEFRA-Company-reporting-greenhouse-gas-emissions-by-quoted-companies.pdf>.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., and Marengo, K. (2012): Changes in Climate Extremes and Their Impacts on the Natural Physical Environment; in Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, (ed.) C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, et al., p. 109–230. A Special Report of the Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC); Cambridge University Press, Cambridge, UK.

Solterra Solutions (2012): Determining the Impact of Climate Change on Insurance Risk and the Global Community. Ottawa: Canadian Institute of Actuaries; American Academy of Actuaries; Society of Actuaries; Casualty Actuarial Society.

St. Denis, G. and Parker, P. (2009): Community Energy Planning in Canada: The Role of Renewable Energy; Renewable and Sustainable Energy Reviews, p. 2088–2095. Canada;a26?lang=eng&retrLang=eng&id=1870002&paSer=&pattern=&stByVal=1&p1=1&p2=37&tabMode=dataTable&csid>.

Statistics Canada (2012a): Table 187-0002 – Quarterly statement of changes in financial position, by North American Industry Classification System (NAICS), selected financial ratios and selected seasonally adjusted components; Statistics Canada, CANSIM Database; <http://www5.statcan.gc.ca/cansim/a26?id= 1870002&pattern=&p2=37&tabMode=dataTable&p1=1&stByVal=1&paSer=&csid=&retrLang=eng&lang=eng>

Statistics Canada (2012b): Construction; Statistics Canada; <http://www.statcan.gc.ca/pub/11-402-x/2011000/chap/construction/construction-eng.htm>.

Statistics Canada (2012c): Table 281-0024 - Employment (SEPH), Unadjusted for Seasonal Variation of Employeee for Selected Industries Classified Using the North American Industry Classication Systems (NAICs); Statistics Canada, CANSIM Database; <http://www5.statcan.gc.ca/cansim/a05?lang=eng&id=2810024>.

Statistics Canada (2012d): Exports of Goods on a Balance-of-payments Basis, by Product; <http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/gblec04-eng.htm>.

Steemers, K. (2003): Towards a Research Agenda for Adapting to Climate Change; Building Research & Information, v. 31, no. 3-4, p. 291–301.

Stewart, E.J., Dawson, J., and Draper, D. (2011): Cruise-ship Tourism in Nunavut, Arctic Canada: An Analysis of Resident Perspectives; Journal of Hospitality and Tourism Management.

Stewart, E.J., Tivy, A., Howell, S.E.L., Dawson, J., and Draper, D. (2010): Cruise Tourism and Sea Ice in Canada's Hudson Bay Region; Arctic, v. 63, no. 1, p. 57–66.

Swiss Re. (2011): The Hidden Risks of Climate Change: An Increase in Property Damage from Soil Subsidence in Europe; Swiss Re, Geneva; <http://media.swissre.com/documents/Soil_Subsidence_Publication_en_0718.pdf>.

Tamiotti, L., Teh, R., Kulacoglu, V., Olhoff, A., Simmons, B., and Hussein, A. (2009): Trade and Climate Change; United Nations Environment Programme and the World Trade Organization, Geneva; <http://www.wto.org/english/res_e/booksp_e/trade_climate_change_e.pdf>.

TD Economics (2011): Canada's Construction Sector Flexes Its Economic Muscle; TD Economics.

Thistlethwaite, J. (2012): The ClimateWise Principles: Self-Regulating Climate Change Risks in the Insurance Sector; Business & Society.

Thistlethwaite, J., Kovacs, P., and Kelly, G. (2012): Insurance: Adapting Building Codes for Climate Change; in Climate Change Adaptation: A Priorities Plan for Canada, (ed.) B. Feltmate and J. Thistlethwaite; Climate Change Adaptation Project, Waterloo, ON.

TIAC [Tourism Industry Association of Canada] (2012): The Canadian Tourism Industry - A Special Report; Tourism Industry Association of Canada, Ottawa.

UNEP-FI [United Nations Environment Programme Finance Initiative] (2009): The Global State of Sustainable Insurance; Insurance Working Group United Nations Environment Programme Finance Initiative.

UNEP-FI [United Nations Environment Programme Finance Initiative], and SBI [Sustainable Business Institute] (2011): Advancing Adaptation Through Climate Information Services; Geneva: UNEP-FI and Sustainable Business Institute; <http://www.unepfi.org/fileadmin/documents/advancing_adaptation.pdf>.

UNWTO [United Nations World Tourism Organization] (2011): Tourism Towards 2030 - Global Overview; United Nations World Tourism Organization, Madrid.

Vasseur, L. and Catto, N. (2008): Atlantic Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix, and E. Bush, p. 119–170; Government of Canada, Ottawa.

Walker, I.J. and Sydneysmith, R. (2008): British Columbia; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix, and E. Bush, p. 329–386. Government of Canada, Ottawa.

Wilbanks, T.J., Romero Lankao, P., Bao, M., Berkhout, F., Cairncross, S., Ceron, J.P., Kapshe, M., Muir-Wood, R., and Zapata-Marti, R. (2007): Industry, Settlement and Society; in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziani, P.J. Palutikof, P.J. Van der Linden, and C.E. Hanson, p. 357–390. Cambridge University Press. Cambridge, UK.

Wilton, D. and Wirjanto, T. (1998): An Analysis of the Seasonal Variation in the National Tourism Indicators; Canadian Tourism Commission, Ottawa, Canada.

World Bank (2012): Exports of Goods and Services (% of GDP); <http://data.worldbank.org/indicator/NE.EXP.GNFS.ZS>.

World Travel and Tourism Council (2012): Travel & Tourism: Economic Impact 2012 Canada; London, UK; <http://www.wttc.org/site_media/uploads/downloads/canada2012.pdf>.

Wotton, B.M., C.A. Nock, and M.D. Flannigan. (2010): Forest Fire Occurence and Climate Change in Canada; International Journal of Wildland Fire, v. 19, no. 3, p. 253–271.

# CHAPTER 6:
# BIODIVERSITY AND PROTECTED AREAS

Lead Authors:

**Patrick Nantel**, **Marlow G. Pellatt** and **Karen Keenleyside** *(Parks Canada)*, **Paul A. Gray** *(Ontario Ministry of Natural Resources)*

Contributing Authors:

**Isabelle Côté** *(Simon Fraser University)*, **Philip Dearden** *(University of Victoria)*, **Simon Goring** *(University of Wisconsin)*, **Nancy Kingsbury** *(Environment Canada)*, **Donald McLennan** *(Aboriginal Affairs and Northern Development Canada)*, **Tory Stevens** *(British Columbia Ministry of the Environment)*

Recommended Citation:

Nantel, P., Pellatt, M.G., Keenleyside, K. and Gray, P.A. (2014): Biodiversity and Protected Areas; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 159-190.

# TABLE OF CONTENTS

# KEY FINDINGS

Biodiversity – the variety of species and ecosystems and the ecological processes of which they are a part – has a paramount influence on Canada's natural capital and its ability to deliver services. Those services, in turn, contribute to human health and well-being and support a wide range of economic sectors. Climate change, interacting with other human stressors such as pollution and landscape fragmentation, is already impacting biodiversity in Canada. Future impacts will be affected by the magnitude of continuing climate change and adaptation decisions made to enhance ecosystem resilience. Key findings of this chapter include:

- Climate-related shifts in species distributions have already been documented in Canada. Future range shifts will include expansion, contraction and fragmentation in species-specific patterns. In many locations, differential range shifts among species are likely to result in novel ecosystems.
- Phenological mismatches occur when shifts in the timing of life cycle events differ between dependent species and, as an example, can result in migrating species arriving at a site after the peak prey availability has passed. Phenological mismatches are expected to become more frequent in the future, as is hybridization. The impacts of hybridization can drive rare species to extinction or, in other cases, increase the adaptability of some species by introducing genetic variation.
- For many species, the current and projected rates of environmental change are likely to exceed their natural ability to adapt, increasing stress and threatening biodiversity. As a result, climate change is magnifying the importance of managing ecosystems in a manner that enhances resilience and preserves biodiversity.
- Protected areas, including parks, wildlife reserves and marine protected areas will play an important role in the conservation of biodiversity in a period of rapid change. Many protected areas will provide "refuge" or migration corridors for native species, serving to maintain genetic diversity. Protected areas tend to be more resilient than the intervening landscapes and waterscapes because they contain relatively intact ecosystems and are less impacted by non-climate stressors such as habitat loss and fragmentation.
- Many Canadian jurisdictions are expanding their system of parks and other protected areas as part of their overall management plans and climate change adaptation strategies. Initiatives aimed at maintaining or restoring landscape connectivity serve to increase ecosystem resilience by enhancing the capacity for species to adjust their distribution in response to climate change. Associated research, monitoring, citizen science, public awareness, and visitor experience programs build understanding and help to engage the public in meaningful participatory decision-making.
- The conservation community recognizes the value of ecological restoration in strengthening the resilience of ecosystems to climate change. Integration of climate change adaptation strategies into restoration decision-making in Canada, as elsewhere, is complex.

# 1. INTRODUCTION

Canada is home to major portions of the world's polar regions and tundra, boreal and temperate forests, grasslands and aquatic ecosystems, including the Great Lakes and territorial waters in the Pacific, Arctic and Atlantic oceans. These ecosystems contain about 10% of the world's forests and 20% of the world's freshwater (Environment Canada, 2009). They also provide niche space for more than 70 000 species of mammals, birds, reptiles, amphibians, fish, invertebrates, plants and other organisms (CESC, 2011).

Biodiversity, the variety of species and ecosystems and the ecological processes of which they are a part, is the natural capital that provides the foundation for much of Canada's economic and social well-being. It contributes to cleaner air and water, climate regulation, carbon storage, pollination and flood regulation. Humans directly and indirectly benefit from biodiversity as, for example, a source of food, fibre, materials for clothing, timber, and recreational opportunities. Biodiversity is also vital for the maintenance and enhancement of economic sectors (such as agriculture and tourism) during periods of rapid environmental change (Environment Canada, 2009).

This chapter summarizes the impacts of climate change on Canada's biodiversity and describes some of the tools available to maintain and enhance ecological resilience. Although most work to date has focused on the effects of climate change on individual species, some research on interspecific relationships is underway, which will enhance understanding of the impacts of climate change on ecosystem-level processes and ecosystem services (Walther, 2010).

Technical terms used in this chapter are defined in Box 1.

BOX 1

## TECHNICAL TERMS USED IN THIS CHAPTER

**Aerial insectivores:** Bird species that eat insects while flying. Examples include the Chimney Swift and Barn Swallow.

**Biogeochemical cycles:** Pathways by which chemical elements or molecules move through both living and non-living compartments of an ecosystem.

**Biodiversity:** The variety of species and ecosystems and the ecological processes of which they are a part.

**Biogeographical zones:** Divisions of a land surface based on life form, species distribution, or the adaptation of plants and animals to climatic, soil, and other conditions.

**Climate envelope:** Model that predicts the distribution of a species in geographic space on the basis of a mathematical representation of its known distribution in a space represented by climate data (such as temperature, and precipitation).

**Ecological integrity:** A condition (of a protected area or other ecosystem) that is characteristic of its natural region and likely to persist, including non-living components and the composition and abundance of native species and biological communities, rates of change and supporting processes. Ecological integrity is a measure of ecological resilience (*see below*).

**Ecological niche:** The set of environmental conditions and resources that define the requirements of a species to complete its life cycle.

**Ecological resilience:** The capacity of a system to absorb disturbance and reorganize so as to still retain essentially the same function, structure and feedbacks, and therefore the same identity.

**Ecological (or ecosystem) services:** The multitude of resources and processes that are supplied by ecosystems and benefit human societies. These include products like clean drinking water and processes such as the decomposition of wastes.

**Ecosystem:** A community of living organisms (plants, animals and microbes) in conjunction with the nonliving components of their environment (air, water, soil), interacting as a system.

**Hybridization:** Interbreeding between two animals or plants of different species, subspecies or populations.

**Hybrid vigour:** Quality in hybrids of being stronger than either parent variety or species, a phenomenon most common with plant hybrids. Also called heterosis or heterozygote advantage.

**Hypoxia:** Oxygen depletion, a phenomenon that occurs in aquatic environments as dissolved oxygen becomes reduced in concentration to a point where it becomes detrimental to aquatic organisms living in the system.

**Phenology:** The description (or study) of periodic plant and animal life cycle events and how these are influenced by seasonal and yearly variations in climate, as well as habitat factors (such as elevation).

**Zoonotic disease:** An infectious disease that is transmitted between species (sometimes by a vector) from animals other than humans to humans or from humans to other animals.

**Zooplankton:** Heterotrophic (sometimes detritivorous) organisms drifting in oceans, seas, and bodies of fresh water.

# 2. OVERVIEW OF PREVIOUS ASSESSMENT FINDINGS

The ecological, social and economic effects of climate change were discussed in every regional chapter of '*From Impacts to Adaptation: Canada in a Changing Climate*' (Lemmen et al., 2008). Key conclusions related to biodiversity arising from that assessment include, but are not limited to:

- In Canada, northern ecosystems (e.g. taiga, tundra, and polar deserts) are, and will continue to be, particularly vulnerable to climate change. Impacts on Arctic species will involve habitat loss, competition from northward migrating species, and the arrival of new diseases and parasites from the south (Furgal and Prowse, 2008).
- Climate change impacts on species distribution, abundance, physiology and life cycle timing will alter interspecific relationships and habitats. Earlier onset of spring is changing the timing of growth and reproduction of many plant species that provide food and habitat for a variety of species. For example, the blossoming date of Trembling Aspen (*Populus tremuloides*) in Alberta has advanced by 26 days in the past 100 years (Beaubien and Freeland, 2000). Such timing shifts can cause decoupling of species that have co-evolved (Beaubien and Freeland, 2000 *in* Sauchyn and Kulshreshtha, 2008).
- Coastal and estuary ecosystems are at risk from increased erosion and "coastal squeeze" which could eliminate habitat for some species, such as the Piping Plover (Vasseur and Catto, 2008; Walker and Sydneysmith, 2008). Projected warming of the Gulf Stream and cooling of the Labrador Current could alter habitat and affect species in Atlantic Canada (Vasseur and Catto, 2008).
- Increased moisture stress in prairie ecosystems will likely decrease productivity in natural grasslands, although longer growing seasons and reduced competition from shrubs and trees (because of drier conditions) may partly offset the effects of reduced moisture (Sauchyn and Kulshreshtha, 2008).
- Habitats located in alpine ecosystems, cold steppes, and the Acadian forest could contract or become increasingly fragmented as the climate warms (Vasseur and Catto, 2008). Conversely, some species, including those of the Carolinian zone, may successfully occupy new niche space in more northern habitats as warming continues.
- Although forest productivity could increase with higher atmospheric $CO_2$ concentrations and longer growing seasons, increases in the frequency and intensity of fires, insect outbreaks, droughts, and icing events could offset potential gains. Eastward expansion of the mountain pine beetle epidemic into the boreal forest is also a concern (Bourque and Simonet, 2008).
- In Hudson Bay, observed changes in the distribution and abundance of seal and polar bear populations, as well as in a number of fish species, correlate with a decrease in the length of the sea ice season and higher water temperatures (Furgal and Prowse, 2008).
- Climate change impacts on water quantity and quality is a concern for lakes and rivers across Canada. Higher temperatures are affecting the thermal habitat of many fish species, increasing potential habitat for invasive species and creating favourable conditions for unwanted algal blooms (Chiotti and Lavender, 2008).
- In northern and alpine regions, the rapid melting of glaciers will change flow regimes with effects on downstream aquatic ecosystems and water supplies for many towns and cities (Sauchyn and Kulshreshtha, 2008).

Many examples of adaptation measures and approaches were also discussed in Lemmen et al. (2008). Measures to help protect biodiversity included: increased connectivity and reduced fragmentation between ecosystems; extension of protected area networks to conserve areas representative of each natural region; and implementation of inventory, monitoring and research programs to inform adaptive decision-making.

# 3. CLIMATE AND BIODIVERSITY

Climate is a key driver of ecosystem composition, structure, and function. It also interacts with other factors that influence biodiversity, such as pollution and land use change. As a result, many ecological studies include modeled or observed evaluations of relationships between biodiversity and climate change.

Current evidence indicates that climatically suitable ranges (or climate envelopes) for many species will likely shift northwards in response to warming temperatures (e.g. McKenney et al., 2007; Coristine and Kerr, 2011), with major implications for people who rely on the current configuration of ecosystem types. For example, ecological niche models for 765 species suggest that climate change may increase biodiversity in southern Quebec during this century as species move northward (Berteaux et al., 2010; Chambers et al. 2013). Similarly, many bird species that currently breed in the northern portion of eastern United States are likely to move northward into Canada, increasing bird species richness in Eastern Canada (Desgranges and Morneau, 2010).

Although migratory fronts may expand northward, the rear (southern) edge of species range is likely to contract in response to shifting climate (Hampe and Petit, 2005). Rear edges are often more genetically diverse than the rest of the population as a result of previous changes in species distributions (Jaramillo-Correa et al., 2009), such that the northward shift of southern populations may not only affect regional diversity and ecosystem function, but also the overall genetic diversity of the species involved (Hampe and Jump, 2011).

Biodiversity may also be affected when species shifts are limited by physical conditions (e.g. barriers to movement) and/or biological processes (e.g. reduced access to food at critical times in the life cycle such as breeding and rearing periods). Resulting changes in species composition can have varying consequences, such as disruptions in predator-prey and host-parasite relationships. Therefore, although we know that Canada's biodiversity will change in response to new climate conditions, uncertainties remain regarding how such changes will affect ecosystem composition, structure and function (Varrin et al., 2007). In all likelihood, response will be ecosystem/habitat-specific, resulting in a patchwork of increasing and decreasing species richness and productivity, changing with time across the country.

This section of the chapter addresses current understanding of the impacts of climate change on:

1. life cycle timing (phenology);
2. observed and projected species distribution;
3. fish and wildlife health; and
4. disturbance regimes and other human-induced stresses such as habitat fragmentation.

It also includes brief discussion of uncertainties, knowledge gaps and broader social and economic implications.

## 3.1 CHANGES IN THE TIMING OF LIFE-HISTORY EVENTS (PHENOLOGY)

Increases in winter and spring temperature at mid and high latitudes have led to earlier spring phenologies for some taxa (Schwartz et al., 2006a; Coristine and Kerr, 2011). Canadian examples of ongoing phenological shifts include earlier onset of breeding by amphibians (e.g. Walpole and Bowman, 2011; Walpole et al., 2012), earlier occupation of breeding habitat and emergence of hatchlings by bird species across North America (Waite and Strickland, 2006; Friends of Algonquin Park, 2012; Hurlbert and Liang, 2012; *see also* Case Study 1), and the earlier onset of the growing period for plant species (Schwartz et al., 2006a).

Insect physiology is strongly correlated with temperature. For example, in some insects, metabolism can almost double with an increase of 10°C, making them very responsive to temperature (Gillooly et al., 2001; Clarke and Fraser, 2004). Metabolic responses to increasing temperature influence, and likely amplify, population-level dynamics, including fecundity, survival, generation time and dispersal (Bale et al., 2002). Given that the timing of the spring life-cycle stages of many insect and plant species has already advanced in response to warmer temperatures (Harrington et al., 2001; Logan et al., 2003), a potential consequence for migratory birds is a phenological mismatch. This mismatch is characterized by a lack of synchrony between seasonal peaks in plant or insect biomass and hatchling growth and development (e.g. Rodenhouse et al., 2009; Knudsen et al., 2011; *see* Case study 1).

Changes in ocean climate (*see* Chapter 2 – An Overview of Canada's Changing Climate), particularly sea surface temperature, have a strong influence on the timing of life-history events for marine organisms. For example, in the Strait of Georgia, the period of peak abundance of the dominant species of zooplankton has progressed from occurring in late May fifty years ago to occurring in mid-March in 2004 (DFO, 2010). This change may also be a driver for the progressively earlier hatch dates for several seabirds in the area (Gaston et al., 2009) and is symptomatic of the strong links between recruitment success at higher trophic levels and the timing of temperature-dependent primary production in marine ecosystems (Bertram et al., 2009; Koeller et al., 2009). Species that have different habitat requirements for different life-history stages may be especially vulnerable to temperature changes. For example, juvenile salmon on both Atlantic (Friedland et al., 2003) and Pacific (Crozier et al., 2008) coasts are under increasing stress as a result of warming temperatures that may lead to a mismatch between the timing of smolting (a combination of behavioural, morphological, and physiological responses that stimulate migration and prepares the fish for life in the ocean) and biogeochemical conditions in the marine environment.

### CASE STUDY 1

## CLIMATE WARMING, PHENOLOGY MISMATCH AND POPULATION DECLINE IN MIGRATORY BIRDS

Birds are well studied and closely monitored, with research supported by long-term data sets assembled from many sources (e.g. Christmas Bird Counts, the Breeding Bird Survey). Analyses reveal sharp declines in some migratory bird populations, especially aerial insectivores, shorebirds and grasslands birds (Stuchbury, 2007; Nebel et al. 2010; Sauer et al., 2011; North American Bird Conservation Initiative Canada, 2012). In the last 40 years, 20 common North American bird species suffered declines in population levels of more than 50% (Federal, Provincial and Territorial Governments of Canada, 2010). Most declines are continuing, with thousands of birds lost every year. The rate and magnitude of decline has been high enough to warrant 'Threatened' status under the Species at Risk Act for species such as the Common Nighthawk (*Chordeiles minor*), Chimney Swift (*Chaetura pelagica*), Canada Warbler (*Cardellina canadensis*), Eastern Meadowlark (*Sturnella magna*) (COSEWIC, 2007a & b, 2008, 2011). Similar declines of migratory bird populations in recent decades have been documented in Europe (Møller et al., 2008).

Climate change is likely an important factor in current population declines (Knudsen et al., 2011; North American Bird Conservation Initiative Canada, 2012), contributing to habitat deterioration on wintering grounds of migratory birds due to drought and other climate impacts, and an increasing phenological mismatch – a decoupling of the timing of migration and high food abundance. While there is evidence that phenological mismatches can have significant effects on populations and species (Post et al., 2009; Knudsen et al., 2011; Miller-Rushing et al., 2012), few studies have explicitly addressed the effects of climate change on phenological mismatches for migratory birds.

An index of phenological mismatch, calculated as the difference between temperature trends on wintering grounds compared to breeding grounds, is a good predictor of population declines in North American bird populations (Jones and Cresswell, 2010). In Europe, bird species that did not advance their spring migration declined during 1990 to 2000, whereas species that did advance the timing of migration had stable or increasing populations (Møller et al., 2008). Also, despite earlier arrival dates, birds now arrive on higher degree-days than in the past so that heat-dependent ecological processes, such as insect emergence, have advanced relatively further, creating a 'thermal delay' (Saino et al., 2010, Figure 1). Bird species with greater 'thermal delay' have experienced steeper population declines.

Some European species (including the Blue Tit (*Parus caeruleus*), Great Tit (*Parus major*), Pied Flycatcher (*Ficedula hypoleuca*), Sparrowhawk (*Accipiter brevipes*) demonstrated increased mismatch due to breeding dates advancing either less (Both et al., 2009) or more (Pearce-Higgins et al., 2005) than the advancement of the main food peak available to nestlings. However, the phenological mismatch may not occur in environments with relatively abundant food throughout the breeding season. For instance, in North America, the onset of egg laying by the aerial foraging Tree Swallow is strongly correlated to flying insect biomass during the laying period and not to the timing of the seasonal peak in food supply, which occurs later in the season in most sites and years (Dunn et al., 2011).

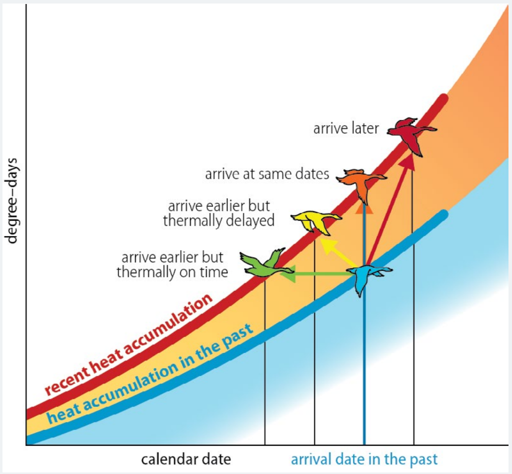


**FIGURE 1:** Climatic and phenological changes can bring about ecological mismatch of migratory birds. Curves represent the progress of spring in two years, as the increase of degree-days (heat accumulation) over time. The curve for the recent year (red line) lies above that for the past (blue line) because of winter and spring warming, which means that degree-days increase more rapidly. Migratory birds show no change, advancement or delay in arrival date. Species that now arrive at the same or later date face higher degree-days and relatively advanced ecological processes such as insect emergence, and are thus 'thermally delayed'. Even species that have advanced their arrival may experience a thermal delay, if advancement does not fully compensate for increasing temperatures. Only a large advancement in arrival can fully compensate for climate change *(modified from Saino et al., 2010).*

## 3.2 CHANGES IN SPECIES DISTRIBUTION RANGES

There is strong observational evidence of historic species range shifts. Over the past 40 years, about 180 of 305 bird species wintering in North America expanded their range northward at an average rate of 1.4 km per year. Similarly, the breeding ranges of birds in southern North America have shifted by an average of 2.4 km per year (Federal, Provincial and Territorial Governments of Canada, 2010). Within the northeastern forests of North America, 27 of 38 species for which historical ranges are documented have expanded their ranges predominantly northward (Rodenhouse et al., 2009). Published accounts of range shifts in Canada are available for a number of species (Hitch and Leberg, 2007; Blancher et al., 2008), with detailed analyses for the Hooded Warbler (*Setophaga citrina*) (Melles et al., 2011), the Southern Flying Squirrel (*Glaucomys volans*) (Garroway et al., 2010; 2011), butterflies (Petersen et al., 2004; Kharouba et al., 2009), and a number of tree species (Gamache and Payette, 2005; Asselin and Payette, 2006; Crête and Marzell, 2006; Boisvert-Marsh, 2012).

Future range shifts are commonly projected using species distribution models or climate envelope models. These models use the statistical correlations between known occurrences of species or ecosystem types and the climate variables associated with those occurrences (e.g. Thuiller et al., 2005; Hamann and Wang, 2006) to predict distributions under projected future (or past) climate conditions (Thuiller et al., 2005; Berteaux et al., 2010, 2011; Pellatt et al., 2012). Currently, most models assume that climate is the primary determinant of habitat suitability. This assumption may be valid on broad geographic scales, but is likely less valid at smaller spatial scales (*see* section 3.5). Models project range expansion when the spatial extent of suitable climate increases, but when species have geographically limited ranges, warming may result in range contraction. Many arctic and alpine species are expected to undergo range contraction in response to warming (Alsos et al., 2012) as opportunities for range expansion up-slope or northward may not exist.

Changes in species distributions under future climate scenarios also depend on whether the capacity of the species of interest to disperse is taken into account. For example, under a scenario in which there was no limit to the ability of seeds to colonize new habitat, projections of future distributions for 130 North American tree species were for a 12% range contraction and an average 700 km northward shift of the centre of distribution by the end of the century. However, when it was assumed that trees could not migrate through seed dispersal, a 58% range contraction and a 330 km northward shift were projected (McKenney et al., 2007). The most likely outcome may lie between the two extreme dispersal scenarios, particularly in Northern Canada where the lack of fertile soil is likely to limit the northward migration of many tree species.

Major changes in forest species composition are expected under most climate projections for eastern North America, including a reduction in the area suitable for many northern hardwood species (Iverson et al., 2008). Northern hardwood species are likely to be replaced by species characteristic of an oak–hickory forest type and various pine species, but the rate of change is uncertain (Iverson et al., 2008). Local or regional soil properties are likely to slow down potential tree migration (Lafleur et al., 2010). Some research suggests that we may expect continually changing forest tree communities in the future, with tree species responding in different ways to climate variables and soil properties (Drobyshev et al., 2013).

Scenarios based on bioclimate envelope models for western Canada indicate that tree species with their northern range limit in British Columbia could expand their range at a pace of at least 100 km per decade (Hamann and Wang, 2006). While common hardwoods appear to be generally unaffected by changes in average temperature and precipitation, some economically important conifer species in British Columbia, such as Lodgepole Pine, could lose a large portion of their range (Figure 2a). It is important to note that it is unlikely that all of the properties that define a climate envelope of a species will shift together. The potential redistribution of biogeographical zones is considerable, with currently important sub-boreal and montane climate regions predicted to reduce rapidly (Figure 2b).

Animals that breed in high-elevation forests are highly vulnerable to climate change because there is little opportunity to shift to new habitat at higher locations. For example, models project that the Bicknell's Thrush will lose access to a significant area of breeding habitat with a 1°C increase in mean annual temperature (Lambert et al., 2005; Rodenhouse et al., 2008).

Range expansion and contraction can have genetic consequences for species populations. While the dispersal of individuals can increase local genetic diversity and spread beneficial genotypes (Hewitt and Nichols, 2005), genetic diversity can decrease at the outer boundaries of a species' distribution when few populations colonize new habitat. Genetic diversity also decreases when a population is extirpated at the contracting edge of the species range (Hewitt and Nichols, 2005; Hampe and Jump, 2011). Models for 27 common arctic plant species project decreases in genetic diversity in response to climate-related reductions in

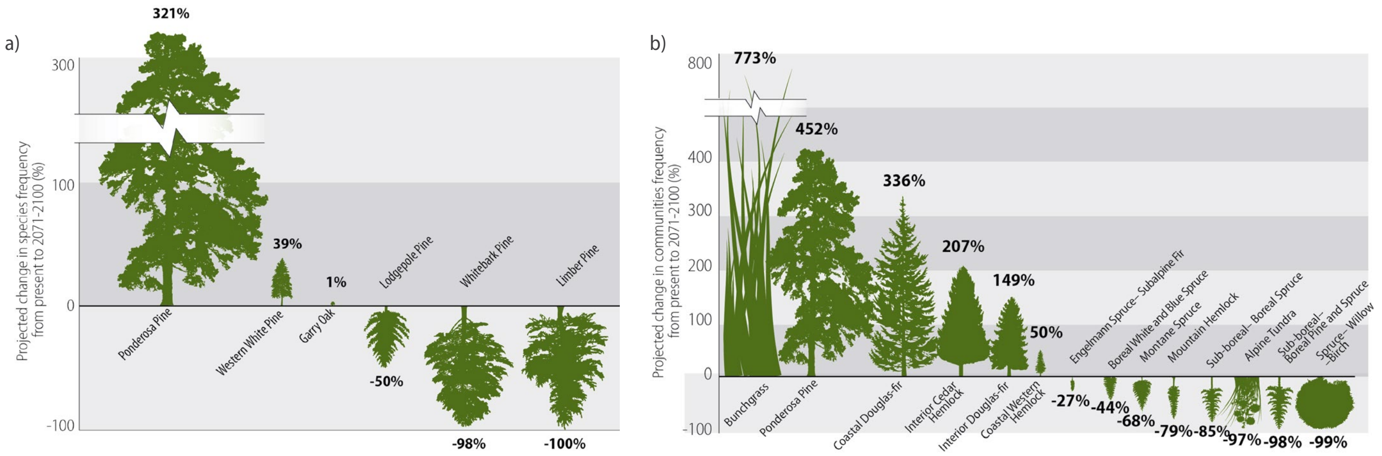


**FIGURE 2:** Projected species and community changes from present to 2071-2100 in British Columbia in response to climate change *(modified from Hamann and Wang, 2006)*. **a)** Change in the frequency of pine and oak species, with Ponderosa Pine (*Pinus ponderosa*) becoming much more common, while Whitebark Pine (*Pinus albicaulus*) and Limber Pine (*Pinus flexilis*) could disappear. **b)** Change in the distributions of biogeoclimatic ecological zones, with Bunchgrass communities and Ponderosa Pine forests becoming much more common than today, while alpine tundra, for instance, may disappear.

range size (Alsos et al., 2012). Analysis of *in situ* observations are beginning to appear in the published literature as well. For example, reductions in genetic diversity have been documented for the alpine chipmunk (*Tamia alpinus*) in response to climate-related upslope range contraction (Rubidge et al., 2012).

Climate change-related range expansion may increase the likelihood of interbreeding and hybridization when two previously distinct populations or species come into contact (Hoffmann and Sgrò, 2011). For example, the Southern Flying Squirrel (*Glaucomys volans*) expanded its northern range by approximately 200 km (Bowman et al., 2005; Garroway et al., 2010, 2011) during a series of warm winters in Ontario between 1994 and 2003. This range expansion resulted in increased co-occurrence and hybridization between the Southern and the Northern Flying Squirrel (*Glaucomys sabrinus*) (Garroway et al., 2010). Hybridization can result in: i) sterile offspring; ii) viable offspring with increased fitness; iii) viable offspring with reduced fitness, or iv) no change in fitness. In some cases, hybridization may facilitate capacity of some species to respond to change by introducing genetic variation (Hoffmann and Sgrò, 2011).

Hybridization can lead to extinction if a species is rare and hybridizes with a more abundant species. For example, the plant Lesser Pyrola (*Pyrola minor*) is locally rare at a number of locations along its southern range margin, and genetic studies of this species have revealed that hybridization with Arctic Pyrola (*Pyrola grandiflora*) is resulting in the increased presence of hybrids at the expense of *P. minor* (but not *P. grandiflora*) in Greenland and Northern Canada. This process may lead to the extinction of *P. minor* through genetic assimilation (Beatty et al., 2010). Similarly, a common North American songbird, the Black-capped Chickadee (*Poecile atricapillus*) hybridizes with the Carolina Chickadee (*Poecile carolinensis*) (Curry, 2005), with mixed parents having reduced hatching success and their offspring having reduced reproductive success (Varrin et al., 2007). A narrow area of reduced reproductive success was detected within the current hybrid zone between these species (Bronson et al., 2005). Given that the Carolina Chickadee is steadily expanding its range northward (Hitch and Leberg, 2007), the hybrid zone could expand from Ohio into Ontario within a few years. Eventually, hybrid chickadees could replace the Black-capped Chickadee in southern Ontario.

Hybridization may increase an organism's capacity to cope with climate change (Hoffmann and Sgrò, 2011). For example, Fishers (*Martes pennanti*) in Ontario demonstrate hybrid vigour between recolonizing populations (Carr et al., 2007), and the emergence dates of budworm species (*Choristoneura* spp.) are more responsive to spring temperature change when they hybridize with a closely related species of the same genus (Volney and Fleming, 2000).

Changes in the distribution of fish and other aquatic organisms are also occurring and/or projected to occur. Although the distribution of cold-water fish (e.g. Lake Trout [*Salvelinus namaycush*]) is restricted by warm summer temperatures (Rahel, 2002), physical limnology and lake geography also affect the habitability of northern waters (Minns et al., 2009). Projections of the effects of climate change on Lake Trout habitat in Ontario suggest that by 2100, Lake Trout habitat will be reduced by 30%, with declines of up to 60% in some southern watersheds. These declines would be only partly offset by habitat increases in watersheds of northwestern Ontario (Minns et al., 2009).

The northern limits of warm-water fish species is often determined by cold summer temperatures, which limit growth (Shuter and Post, 1990; Rahel, 2002). For example, waters with temperatures over 27°C and/or below 15°C do not provide adequate thermal habitat for Smallmouth Bass (*Micropterus dolomieu*), such that only lakes in more southerly locations of Canada currently provide suitable thermal habitat. However, climate projections suggest that significantly more lakes in more northerly locations will provide suitable habitat for warm-water species by the end of the century (Chu et al., 2005). Specifically, the northern range of Smallmouth Bass habitat may expand into northwestern Ontario, northeastern Manitoba, and south-central Saskatchewan, disrupting existing food webs. Jackson and Mandrak (2002) suggest that such range expansions could lead to the localized extinction of 25 000 populations of Northern Redbelly Dace (*Phoxinus eos*), Finescale Dace (*Phoxinus neogaeus*), Fathead Minnow (*Pimephales promelas*) and Pearl Dace (*Margariscus margarita*). Such extirpation would negatively affect food resources for predators such as Lake Trout (Vander Zanden et al., 1999). Barriers to migration for aquatic species, including constructed barriers and watershed divides, along with improved public understanding of risks associated with transporting species between water bodies, could impede those projected range expansions.

Marine species may respond to warmer temperatures by altering their depth and latitudinal ranges (*see* Chapter 4 – Food Production). Estimates suggest latitudinal ranges may shift northward by 30 to130 km per decade, while depth ranges may shift 3.5 m deeper per decade (Cheung et al., 2009, 2010). In Canada, species gains and losses are both predicted for marine habitats, with the greatest losses occurring at lower latitudes. However, the overall number of species in Canadian waters is likely to increase (Cheung et al., 2011). Rapid biogeographical changes are already evident, with warm-water species moving northwards more than 10 degrees of latitude over the last 30 years in the North Atlantic, along with concomitant declines in the diversity of cold-water species (Helmuth et al., 2006). A warming Arctic Ocean is expected to result in an expansion of Pacific species into the Arctic, and from there into the Atlantic Ocean (Vermeij and Roopnarine, 2008; *see also* Reid et al., 2008). Other range expansions may not be as dramatic, but could have significant impacts on coastal communities. For example, Harley (2011) documents how the Sea Star, *Pisaster ochraceus*, is favoured by warming conditions and suggests that this will reduce the areal extent of the mussel beds on which it preys, with related impacts on other species associated with mussel beds.

## 3.3 EFFECTS ON FISH AND WILDLIFE HEALTH

A number of studies document the effects of climate change on the health of fish and wildlife species in Canada. Examples of impacts on select iconic species are highlighted here.

Few species are more linked by the public to climate change than polar bears. Polar bears depend on sea ice for hunting and mating – they gain weight in April, May, and June, just prior to ice break-up when newly weaned ringed seals are abundant (Stirling et al., 1999; Derocher et al., 2004; Rosing-Asvid, 2006). Polar bears, particularly southern populations, will be affected by changes in the timing of ice break-up and freeze-up and the formation of the ice pack. As ice platforms disintegrate earlier and form later, polar bears will have less time to feed on seals, which will result in poorer condition of reproductive females and lower reproductive success (Stirling et al., 1999; Obbard et al., 2006; Peacock et al., 2011). These impacts are only part of the complex suite of ecological changes that have already been documented in the Arctic (*see* Case Study 2).

CASE STUDY 2

## CLIMATE-DRIVEN ECOLOGICAL CHANGE IN THE ARCTIC

A summary of recent research on environmental change in arctic national parks (McLennan et al., 2012) shows that these relatively pristine ecosystems are undergoing significant and accelerating change in the cryosphere (glaciers, permafrost, snow cover, lake, river and sea ice) and vegetation, while wildlife populations are just beginning to respond to the effects of warming that is more than double that of southern latitudes (*see* Chapter 2 – An Overview of Canada's Changing Climate). National parks and other protected areas can act as 'benchmarks of change' that help us understand the nature, magnitude and rate of change occurring in natural systems as a result of climate change (Lemieux et al., 2011; CPC, 2013).

Derkson et al. (2012) provide a comprehensive review of recent changes in the cryosphere of the Canadian Arctic. Glaciers in arctic national parks are receding and losing mass (Dowdeswell et al., 2007; Barrand and Sharp, 2010; Gardner et al., 2011; Sharp et al., 2011), while permafrost is warming and the depth of summer soil thaw is increasing (Burn and Kokelj, 2009; Smith et al., 2010). Increasing summer thaw depth is an important factor contributing to increased incidence of landslides (Broll et al., 2003). Permafrost degradation in ice-rich ground allows wetlands to drain and changes the water regime of tundra ecosystems (Fortier et al., 2007; Godin and Fortier, 2012).

Vegetation changes observed in arctic national parks include differential growth of individuals of species already present at a given location, as well as range expansions of Low Arctic trees and shrubs, resulting in significant changes in tundra community structure. Tundra vegetation is growing more quickly, a phenomenon correlated with sea ice reduction (Lawrence et al., 2008; Bhatt et al. 2010; Stroeve et al., 2011), and is resulting in an overall 'greening' across the north (Jia et al., 2009). In four arctic national parks, shrub coverage is expanding and herbaceous species are increasingly occupying previously bare ground (Fraser et al., 2012). In Ivvavik National Park, Yukon, seasonal peak leaf biomass more than doubled between 1985 and 2010 (Figure 3), and the growing season increased on average by over 40 days in the same period (Chen et al., 2012). Results suggest that warming is increasing plant growth in arctic national park ecosystems, but response varies among species and sites (Hill and Henry, 2011).

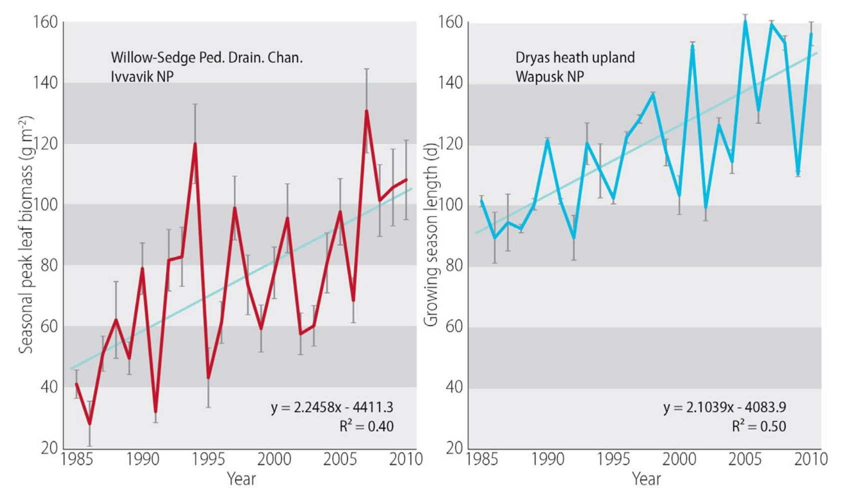


**FIGURE 3:** Seasonal peak leaf biomass (g $m^{-2}$) more than doubled between 1985 and 2010 in the Willow-sedge pediment drainage channel ecotype in Ivvavik National Park, Yukon, and growing season length almost doubled in Dryas heath upland in Wapusk National Park, Manitoba *(Chen et al., 2012)*.

Vegetation changes can have impacts ranging from local effects on habitats and soil processes (Sturm et al., 2005a; Post et al., 2009), to watershed scale effects on hydrology (McFadden et al., 2001), to global effects on climate through carbon cycle feedbacks (Sturm et al., 2005b; Ping et al., 2008; Bonfils et al., 2012).

Animal populations are also changing, with potential consequences for arctic food webs. For example, research on food webs in Sirmilik National Park, Nunavut (Figure 4) demonstrates that lemmings play a keystone role supporting arctic biodiversity because of their widespread abundance and a consequent role as prey for many arctic raptors and mammalian predators (Gauthier et al., 2004, 2011;

*Case Study 2 continued on next page*

Gauthier and Berteaux, 2011; Therrien, 2012). While there is strong evidence in northern Europe and Greenland that climate change is impacting lemming numbers and the predators that rely on them (Kausrud et al., 2008; Gilg et al., 2009), there is little evidence for this so far in Canada (Gauthier et al., 2011; Krebs et al., 2011). Difficulties inherent in projecting changes in snow depth and phenology, and the natural local-scale variability in snowfall, create a key uncertainty in predicting the future of arctic small mammals and the species they support.

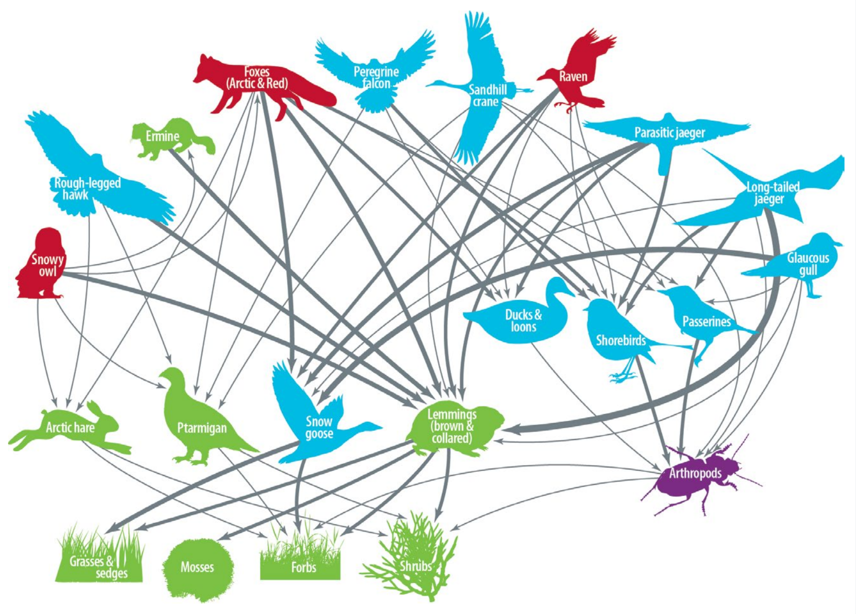


**FIGURE 4:** Bylot Island (Sirmilik National Park) food web showing four species categories: migrant (red), partial migrant (blue), resident, (green), and resident frozen (purple) in the soil during winter. Line thickness indicates the relative strength of interactions between species *(modified from Gauthier et al., 2011)*.

Arctic national parks also support key breeding ranges of several barren ground caribou herds. Caribou numbers are presently decreasing for most herds across the circumpolar arctic (CARMA, 2012). Population fluctuations in barren ground caribou are interpreted to be a natural cycle caused by the interaction of long-term climate cycling with forage quality and calf survival (Payette et al., 2004; Sharma et al., 2009). However, the ability to recover from low numbers may now be affected by climate-related stresses such as changes in vegetation phenology (White, 2008; Sharma et al., 2009), increases in icing events and insect harassment (Sharma et al., 2009, CARMA, 2012), and increases in forest fire frequency on wintering grounds (Joly et al., 2012). These climate-related factors are exacerbated by a host of increasing anthropogenic stressors (Sharma et al., 2009; CARMA, 2012, Joly et al., 2012; *see* Section 3.4). Negative factors need to be balanced against the potentially positive effects of increased biomass of caribou forage, and overall warmer temperatures (Griffith et al., 2002). The interaction of all of these factors creates uncertainty around the future of the large barren ground caribou herds that are iconic features of arctic national parks, key drivers of arctic biodiversity and ecosystem processes, and central to community culture and land-based lifestyles. Similar uncertainty exists around Peary Caribou (*Rangifer tarandus pearyi*) – a species whose populations have been negatively impacted by extreme climate events (Miller and Gunn, 2003), but which may recover if increases in forage productivity outweigh the negative effects of climate change (Tews et al., 2007).

Some southern populations of polar bears, in particular the western Hudson Bay (Wapusk National Park, Manitoba) and southern Beaufort Sea (Ivvavik National Park, Yukon) populations, have been projected to disappear over the next 30-40 years (Stirling and Derocher, 2012). It can be expected that reduced sea ice will force populations north as summer sea ice reductions continue. Although significant changes in arctic fauna are inevitable, these changes are only just beginning to occur. In the next few decades it can be expected that more mobile subarctic and boreal species of songbirds, raptors, small mammals, ungulates, and predators will move north, creating complex interactions with arctic species already present (ACIA, 2005; Berteaux et al., 2006; Gilg et al., 2012). The immigration of southern species through range shift or expansion associated with a warming climate will put pressure on obligate arctic species such as polar bears, muskox, lemmings, arctic fox and Peary caribou (Berteaux et al., 2006; Berteaux and Stenseth, 2006; Gilg et al., 2012). Areas of the Arctic with mountainous terrain, which includes several national parks, have the potential to provide climate refugia at elevation or on north-facing slopes. Understanding the potential role of refugia in harbouring species with contracting ranges, and the potential consequences for species restricted to such refugia (Barnosky, 2008; Keppel et al., 2012) will be important for predicting the fate of many obligate arctic species.

Overall, evidence from monitoring and research in national parks indicates a high level of uncertainty regarding how terrestrial ecosystems in Canada's north will respond to climate change. This uncertainty relates in part to difficulties in predicting how climates will change at spatial and temporal scales relevant to management action (ACIA, 2005; McLennan, 2011), and to the inherent complexity of natural ecosystems (Berteaux et al., 2006; Gilg et al., 2012). Managers of arctic national parks and communities who are dependent on arctic ecosystems for food supplies or livelihoods are presented with a situation where radical ecological change is inevitable.

In aquatic ecosystems, water temperature is a principal determinant of fish survival and reproduction. Mean summer water temperatures in the Fraser River of British Columbia have increased by about 1.5°C since the 1950s (Martins et al., 2011). Record high river temperatures during recent spawning migrations of Fraser River Sockeye Salmon (*Oncorhynchus nerka*) have been associated with high mortality events, raising concerns about the long-term viability of natal stocks under emerging climate regimes. Analysis of four Fraser River Sockeye Salmon stocks show varying responses, with some, but not all, affected by warm temperatures encountered in the lower river (Martins et al., 2011). A decrease of 9 to16% in survival of all of the stocks is predicted by the end of the century if the Fraser River continues to warm as projected. The study emphasized the need to integrate consideration of stock-specific responses to temperature changes into fisheries management and conservation strategies.

In marine ecosystems, changing climate is associated with a range of physiological stresses that affect species health. For example, Crawford and Irvine (2009) attribute documented hypoxia (declines in dissolved oxygen) at all depths below the mixing layer along the entire BC coast to warming waters off the coast of Asia that increase stratification and reduce ventilation (Whitney et al., 2007, *see also* Chapter 2 – An Overview of Canada's Changing Climate). Increasing greenhouse gas emissions are also increasing ocean acidification, with far-reaching implications for the long-term distribution and abundance of marine species (Feely et al., 2008, Friedlingstein et al., 2010). For example, the availability of calcium carbonate, the building block for construction of carbonate skeletal structures and hard shells by marine organisms, has declined as a result of ocean acidification. Cold northern waters absorb carbon dioxide more efficiently than southern waters, and warmer summers promote faster melting of the more acidic sea ice (Yamamoto-Kawai et al., 2009). Acidification has also been documented off the west coast of Canada (Feely et al., 2008; Cummins and Haigh, 2010) and in the Gulf of St Lawrence, where dramatic falls in pH are also linked to increased hypoxia (Dufour et al., 2010).

## 3.4 INTERACTIONS WITH DISTURBANCE REGIMES AND HUMAN-INDUCED STRESSES

Significant synergies are likely amongst the many ecological and socio-economic pathways affected by climate change. For example, Ainsworth et al. (2011) concluded that for marine environments of the northeastern Pacific Ocean, the combination of deoxygenation, acidification, primary production, zooplankton community structure and species range shifts were more severe than the sum of the individual impacts. Furthermore, climate change impacts interact with other human-induced and natural stresses, including habitat loss and fragmentation, pollution, over-harvesting, forest fire, and invasive species, such that the cumulative effects could threaten many species (Venter et al., 2006).

The cumulative effects of climate change and habitat fragmentation will likely limit adaptation success in some species (Travis, 2003; Opdam and Wascher, 2004; Inkley et al., 2004; Bowman et al., 2005; Varrin et al., 2007). Successful colonization of forest plants is higher in more connected landscapes, and plant species dispersed by animals are better able to colonize new habitats than those dispersed by other means (Honnay et al., 2002). Fragmented landscapes may also be an impediment to range expansion by birds, particularly smaller local populations at the limits of physiological tolerance (e.g. Opdam and Wascher, 2004; Melles et al., 2011). Mammals such as the Southern Flying Squirrel, which is a forest-obligate that has spread north through the contiguous forested habitats of the Precambrian Shield in eastern Ontario, but not through the fragmented forests of the southwest (Bowman et al., 2005), may also be affected. Habitat fragmentation is also a significant issue in freshwater ecosystems (Allan et al., 2005), particularly with respect to dams, diversions, revetments, lotic reaches replaced by reservoirs, channel reconfiguration, or dewatering (Stanford, 1996).

Other human-related stressors, including water pollution, wetland drainage and lowering of ground water tables have significantly degraded freshwater ecosystems in much of North America over the past 60 years (Kundzewicz and Mata, 2007) and climate change will exacerbate many of these effects. Similarly, harvesting in marine ecosystems has led to changes in the composition and abundance of fish communities in Canada's waters (*see* Chapter 4 – Food Production). These changes, along with climate-driven changes in temperature, salinity, and acidity, have led to significant changes in Canadian marine biodiversity (Benoît and Swain, 2008; Templeman, 2010).

Fire and insect outbreaks are natural drivers of ecosystem change throughout most of Canada. Climate change, however, is projected to alter the frequency and magnitude of these disturbances (*see* Chapter 3 – Natural Resources). The average area burned annually in Canada is projected to increase by 75 to 120% by 2100 (Flannigan et al., 2009; Stocks and Ward, 2011). Effects will vary regionally – for example, the average area burned per decade across Alaska and western Canada is projected to double by 2041-2050, compared to 1991-2000, and could increase up to 5.5 times by the last decade of the 21st century (Balshi et al., 2009).

Invasive species are those beyond their natural range or natural zone of potential dispersion (Mortsch et al., 2003) that can potentially cause harm by outcompeting, preying upon, or parasitizing indigenous species (Varrin et al., 2007). Many of the invasive aquatic species currently inhabiting

Canada will respond positively to warmer water temperatures, with significant implications for ecosystem health and parts of the economy. For example, many invasive species from Europe (e.g. Ponto-Caspian species) and Asia originated in warmer waters, which can give them a competitive advantage over cool- and coldwater indigenous species under climate warming (Schindler, 2001). Asian Carp species are currently thriving in the Mississippi River system and have reached waters as far north as the Chicago Sanitary and Ship Canal. Although an electric barrier currently prevents carp from entering Lake Michigan, the potential for invasion is considered significant. In addition, attempts to transport live carp into Canada have occurred in the past and will potentially occur in the future (Dove-Thompson et al., 2011). In the ocean marine environment, the European Green Crab (*Carcinus maenas*) has moved north from California into the waters of British Columbia (Klassen and Locke, 2007), and two tunicates (*Botryllus schlosseri* and *B. violaceus*) that are now found on Vancouver Island have the potential to invade most of coastal BC under warming conditions (Epelbaum et al., 2009).

While invasive plant species are commonly thought to disproportionately benefit from climate change, compared to native species, this has not been directly tested (Dukes et al., 2009). Several studies suggest that successful invasive plant species tend to have broad environmental tolerances (Goodwin et al., 1999; Qian and Ricklefs, 2006) and other characteristics that allow them to maintain or increase their fitness relative to other species in a changing climate. Such characteristics include short generation times, long and frequent periods of propagule (e.g. seed) dispersal, and traits that facilitate long-range dispersal which equip many invasive species to outcompete indigenous species that are less well-adapted to new climates (Pitelka et al., 1997; Dukes and Mooney, 1999; Malcolm et al., 2002).

Warming can also significantly affect life cycle dynamics and the distribution of indigenous eruptive insects such as the Mountain Pine Beetle (*see also* Chapter 3 – Natural Resources). Warming simulation models suggest that increases in mean temperature of 1°C to 4°C will significantly increase the risk of outbreaks, starting at higher elevations (for increases of 1°C and 2°C) and then increasing at more northern latitudes (4°C) (Sambaraju et al., 2012). In the Colorado Front Ranges, the flight season of Mountain Pine Beetle now begins more than one month earlier than reported in the past, and lasts approximately twice as long (Mitton and Ferrenberg, 2012). The life cycle in some broods has also increased from one to two generations per year. Because the Mountain Pine Beetle does not go dormant, and growth and maturation is controlled by temperature, this species is responding to climate change through faster growth (Mitton and Ferrenberg, 2012). Furthermore, the Mountain Pine Beetle has higher reproductive success in areas where its host trees have not experienced frequent beetle epidemics (Cudmore et al., 2010). This increased fecundity may be a key reason for the rapid population explosion that resulted in unprecedented host tree mortality over large areas in western Canada (*see* Chapter 3 – Natural Resources). Forest management practices, such as maintenance of a mosaic of species and age classes at the landscape level can help reduce the impacts of such outbreaks (Cudmore et al., 2010).

## 3.5 UNCERTAINTIES AND KNOWLEDGE GAPS

Although the evidence for climate-driven biodiversity change in Canada is strong, predicting and measuring such change is laden with uncertainty. The expectation that species will shift their distributions as a result of climate change generally assumes that climate is the primary influence on habitat suitability. While climatic factors drive diversity patterns at large scales and define the range of most species, many biophysical factors and interactions such as competition, predation and symbiosis also influence population distribution and abundance at local scales (McLachlan et al., 2005; Anderson and Ferree, 2010).

Overall, the extent to which species can achieve rapid large-scale migrations is still poorly understood (Pearson, 2006). The use of climate envelope models to estimate potential effects on species distribution is limited because such models are not integrated with population models that help identify extinction risks (Brook et al., 2009). For example, climate envelope models that average climate over large areas do not incorporate localized microclimates within which low-density populations can persist (e.g. *see* McLachlan et al., 2005), and may therefore be too coarse to incorporate key mechanisms by which species can persist through rapid changes in climate (Pearson, 2006). The ability of climate envelope models to predict current ranges of North American trees and birds declines with range size, and climatic parameters become less important explanatory variables for small ranges (Schwartz et al., 2006b). As a result, the extinction risk of narrowly distributed species might not be well predicted, even though sparse and endemic species are important components of predicting the overall extinction risk brought by climate change. It is also important to note that even though a species may exist within suitable climate space, factors such as competition, food availability, disease, and predation may play a more important role in whether or not they persist in an area.

Some limitations have been addressed, in part, by integrating climate with population models. Such models provide insights on how the complex interactions between life history, disturbance regime and distribution influence the increased risk of extinction for a given species under climate change (Keith et al., 2008). For instance, the levels of dispersal required to offset movement of climate envelopes were found to be beyond the biologically plausible bounds of dispersal for some plant species. Despite these advances, continued research into the effects of climate change on species "niche" patterns and response of species groups or assemblages is important to understanding the reconfiguration process of Canada's ecosystems as temperatures continue to warm.

## 3.6 SOCIAL AND ECONOMIC IMPLICATIONS OF CLIMATE-DRIVEN BIODIVERSITY CHANGE

It is well recognized that biodiversity provides ecosystem services (and goods derived from ecosystems) that ensure human well-being (Federal, Provincial and Territorial Governments of Canada, 2010). In Canada, ecosystem services contribute significantly to a range of economic sectors, including agriculture and fisheries (*see* Chapter 4 – Food Production), forestry (*see* Chapter 3 – Natural Resources) and tourism (*see* Chapter 5 – Industry). For example, biodiversity serves an important function in pollination and forest productivity (Thompson et al., 2011). Such services may be directly provided by one or more species within a community (e.g. long-term carbon sequestration by *Sphagnum* in a peat bog; *see also* McLaughlin and Webster, 2013), by the presence of rare species in a community (providing resistance to invasive species; Lyons and Schwartz, 2001) or through interactions between multiple species in an ecosystem (Cardinale et al., 2011). Species richness and abundance are key determinants of ecosystem function (Hooper et al., 2012), including the provision of ecosystem services.

Biodiversity is also linked to human health and well-being (*see* Chapter 7 – Human Health). Declines in local and regional biodiversity have been tied to increasing rates of allergies in adolescents (Hanski et al., 2012), and may also increase rates of zoonotic disease, such as the West Nile Virus and Lyme disease in humans (Ostfield, 2009). Declines in biodiversity result in declines in potential host taxa with low suitability for the pathogens. These low-suitability hosts are replaced by generalists such as the American Crow (*Corvus brachyrhynchos*) and Blue Jay (*Cyanocitta cristata*) for the West Nile virus and the White-footed Mouse (*Peromyscus leucopus*) and Eastern Chipmunk (*Tamias striatus*) for Lyme disease (Ostfield, 2009). Both diseases are expected to expand their distributions under changing climate regimes (Hongoh et al., 2011).

The economic valuation of ecosystem services is a relatively new and complex discipline. Estimates have been prepared for a number of areas in Canada where organizations are exploring ways of integrating these values into decision-making processes. The value of provisioning (market) services in Canada's boreal forest, for example, has been estimated at $37.8 billion per year, while non-market ecosystem services, including pest control and nature-related activities represent another $93.2 billion per year in services (Anielski and Wilson, 2009). The proposed Rouge National Urban Park and its surrounding watersheds are estimated to provide $115.6 million annually ($2247 per hectare per year) in non-market economic benefits for residents in the Greater Toronto Area (Wilson, 2012). The ecosystem services that contribute most to the total study area's natural capital assets are pollination services ($28.2 million per year), stored carbon ($17.8 million per year), and wetland habitat ($17.1 million per year).

The linkages between biodiversity, ecosystem services and climate change highlight the importance of ecological resilience as a foundation for societal adaptation in many areas (e.g. SCBD, 2009; Staudinger et al., 2012; Hounsell, 2012; Munang et al., 2013). Decreased quantity, quality and access to ecosystem services, which is the result of many factors and aggravated by climate change (Mooney et al., 2009; Federal, Provincial and Territorial Governments of Canada, 2010; Hounsell, 2012) increases the vulnerability of resource-dependent communities (Figure 5; Vasseur, 2010; Klein et al., 2011). In Canada, Aboriginal communities that rely on traditional (wild) food supplies are especially vulnerable to changes in species and ecological processes (*see* Chapter 4 – Food Production). This is particularly true in the North, where climate-related impacts are expected to be greatest.

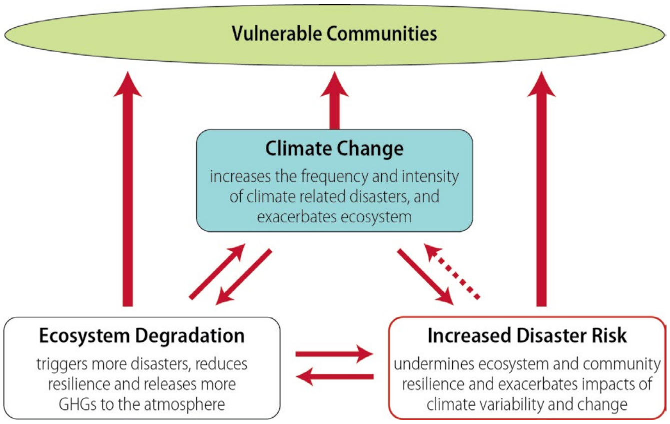


**FIGURE 5:** Illustration of the linkages between climate change impacts, ecosystem degradation, and increased risk of climate-related disasters *(modified from UNEP, 2009).*

## 3.7 SYNTHESIS

The impact of human-caused stressors, including climate change, on Canada's biodiversity is evident. Changes include the loss of old-growth forests, changes in river flows at critical times of the year, loss of wildlife habitat in agricultural landscapes, declines in some bird populations, increases in wildfire, significant shifts in marine, freshwater, and terrestrial food webs, and the increasing occurrence of some contaminants in wildlife (Federal, Provincial and Territorial Governments of Canada, 2010). Responses of species and ecosystems to climate change interact in complex ways such that an impact on one component can have cascading effects on others (Figure 6), leading in some cases to the transformation to new interspecific relationships, and to ecosystems with new characteristics (e.g. Gray, 2005). Climate change poses an additional stress on ecosystems and species that may already be reaching critical thresholds, such as fish populations recovering after the removal of fishing pressure, bird populations dropping sharply due to declines in the area and condition of grasslands, and forest-dwelling caribou at risk from fragmented forests (Federal, Provincial and Territorial Governments of Canada, 2010). The dramatic loss of sea ice in the Arctic has many current ecosystem impacts and is expected to trigger declines in ice-associated species such as polar bears (*see* Case Study 2). Important uncertainties and knowledge gaps remain, especially concerning the risks to vulnerable species and ecosystem types.

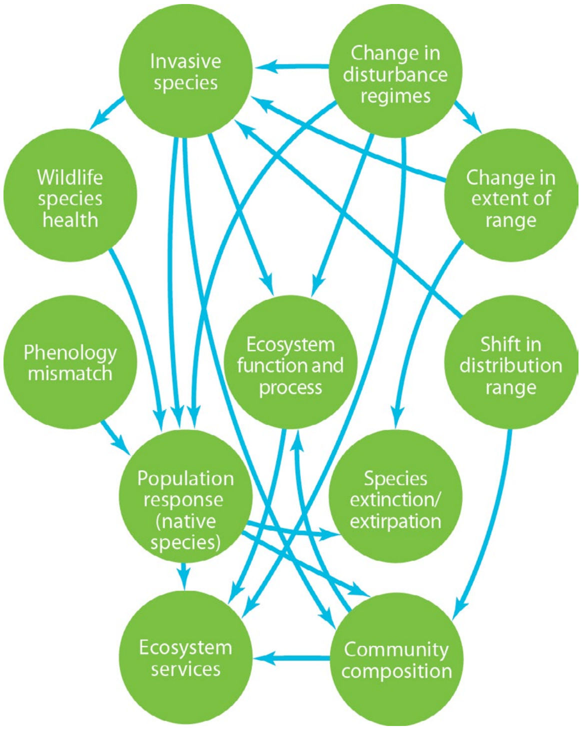


**FIGURE 6:** Illustration of the complex interactions among documented or projected responses of species and ecosystem processes to climate change. Such complexities make the outcome for any given species difficult to predict. Examples are provided throughout Section 3.

# 4. ADAPTATION AND THE ROLE OF PROTECTED AREAS

The conservation science literature contains a range of adaptation recommendations designed to reduce the effects of climate change on biodiversity (Figure 7; Heller and Zavaleta, 2009; Glick et al., 2011; Poiani et al., 2011; Oliver et al., 2012; Hounsell, 2012). These include improved institutional coordination, inclusion of spatial and temporal perspectives, and integrated coordination of climate change scenarios into planning and action related to ecosystem management. Natural responses of ecosystems to changes resulting from new environmental situations, called "autonomous adjustments" (SCBD, 2009) are generally considered insufficient to halt the loss of biodiversity and the ecosystem services it provides for people (Andrade Pérez et al., 2010). Planned adaptation aimed at maintaining or restoring biodiversity and ecosystem services, and thereby also helping people adapt to climate change, are becoming increasingly common worldwide (Andrade Pérez et al. 2010). Ecosystem-based adaptation (SCBD, 2009; Colls et al., 2009) focuses on building the resilience of local communities to climate change through ecosystem management that emphasizes the protection of biodiversity, restoration of ecosystem functions and the sustainable use of resources. Resilience refers to the capacity of an ecosystem and/or its cultural, social, and economic sub-systems to absorb or otherwise cope with change.

Conservation networks, with parks and other types of protected areas at their core, are key components of resilient socio-ecological systems because they protect ecosystem structure and function and provide connected habitats that offer the opportunity for organisms to respond to changing conditions. Protected area legislation provides the mechanisms to support "at-risk" species recovery, and protect cultural and social values (Fischer et al., 2009; Hounsell, 2012). Protected ecosystems provide important sites for research and monitoring (as relatively undisturbed benchmarks for measuring change, for example), as well as for engaging visitors and building public awareness about climate change impacts, opportunities, and solutions (NAWPA, 2012). Characteristics of successful network management programs include effective knowledge gathering and sharing, and provision for citizen engagement and participatory decision-making. Within Canada, both the Canadian Council on Ecological Areas (Lemieux et al., 2010) and the Canadian Parks Council (CPC, 2013) have examined the roles that the protection of well-functioning, well-managed ecosystems nested within sustainably managed landscapes and waterscapes play in maintaining resilience to climate change. In addition, the North American Commission for Environmental Cooperation has developed guidance for the design of resilient marine protected area networks in a changing climate (CEC, 2012). The following actions are considered core to adaption in support of ecosystem resilience (e.g. Mawdsley et al., 2009; Berteaux et al., 2010; Lemieux et al., 2010; Lindenmayer et al., 2010; CEC, 2012; Auzel et al., 2012).

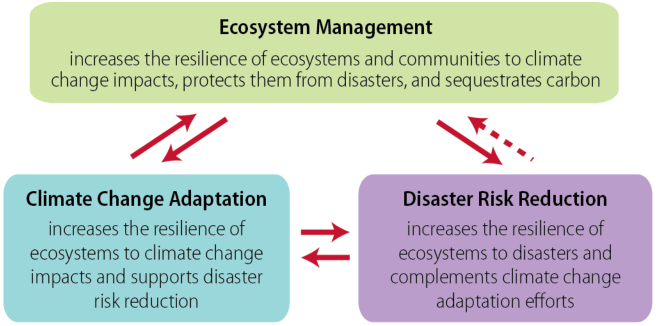


**FIGURE 7:** Illustration of the role of ecosystem management in increasing the resilience of natural systems and human societies, maximizing co-benefits of climate change mitigation, providing physical defence from climate-related disasters (e.g. coastal protection), and contributing to proactive adaptation and disaster management measures (*modified from UNEP, 2009*).

1. Protection of intact ecosystems and the diversity of species and processes that are part of them.
2. Connecting protected areas through sustainably managed landscapes and waterscapes.
3. Restoration of degraded ecosystems, and support of species recovery.
4. Maintaining or restoring natural disturbance regimes to reflect the natural range of variability characteristic for the ecosystem of interest.
5. Inclusion of conservation measures that protect and manage range limits.
6. Consideration of active management approaches, such as assisted migration, where appropriate.

This section explores these actions, provides examples of current Canadian research and initiatives, and describes their role in climate change adaptation. The effectiveness of adaptation actions requires knowledge gained through research and monitoring, along with traditional knowledge (e.g. Lalonde et al., 2012). It also requires careful planning based on shared understanding, engagement and support amongst people that enables them to assess and cope with change and take advantage of new opportunities (Chapin et al., 2009).

## 4.1 PROTECTING INTACT ECOSYSTEMS

Protected areas are critical for the conservation of biodiversity in periods of rapid environmental change. Protected areas provide habitat for native species and opportunities for autonomous adaptation, migration, and natural selection processes through maintenance of genetic diversity (Hannah et al., 2007; Hannah, 2009; Environment Canada, 2009; SCBD, 2009; Federal, Provincial and Territorial Governments of Canada, 2010). This in turn enhances species' capacity to respond to climate change impacts such as phenological mismatch and changing disturbance regimes (*see* Sections 3.1 and 3.4) with related societal benefits as a result (Dudley et al., 2010; NAWPA, 2012; CPC, 2013).

Recent protected area establishment in Canada includes a national network of connected Marine Protected Areas (MPAs) in Canada's three oceans and the Great Lakes (Government of Canada, 2011; ICES, 2011). The federal government and several provinces are beginning to incorporate climate change adaptation when planning expansions of their parks and protected areas. Examples include increasing the size of Nahanni National Park Reserve in 2009, the creation of the Nááts'ihch'oh National Park Reserve in 2012, and the establishment of the Gwaii Haanas National Marine Conservation Area Reserve and Haida Heritage Site next to the existing Gwaii Haanas National Park Reserve in 2010.

## 4.2 CONNECTING PROTECTED AREAS THROUGH SUSTAINABLY MANAGED LANDSCAPES AND WATERSCAPES

Species and ecosystems will respond to climate change through evolutionary processes, as well as through autonomous adjustments, such as migration within connected land/waterscapes to climatically and ecologically suitable areas. Conservation planning differentiates two general types of connectivity – corridors (strips of habitat connecting otherwise isolated patches) and stepping stones (series of small patches connecting otherwise isolated patches) (Baum et al., 2004). While the incorporation of information on changing climate suitability over time will be important for connectivity planning, corridors such as valleys, riparian edges and coastal areas will remain critical mechanisms for species migration into new habitats. Such corridors also allow gene flow and provide food, water and shelter during periods of natural scarcity, significant disturbances (e.g. large wild fires), or disruption by human activities (SCBD, 2009; Government of Canada, 2010; Lemieux et al., 2011).

Although few land use plans in Canada have historically addressed habitat connectivity, this is changing. For example, the province of Nova Scotia and the Town of Amherst are collaborating to protect the Chignecto Isthmus, the strip of land that connects Nova Scotia to the North American mainland, as a wilderness area while protecting Amherst's drinking water (Government of Nova Scotia, 2008, 2012). In Ontario, the Ministry of Natural Resources 50 Million Tree program has targeted areas to create corridors between core natural areas on the most densely populated, highly fragmented landscapes in Canada (G. Nielsen, Ontario Ministry of Natural Resources, personal communication).

Since many protected areas in Canada are surrounded by managed forests, forest management plans seek to protect many ecosystem goods and services including the maintenance of landscape connectivity (*see also* Chapter 3 – Natural Resources). In Ontario, 'Areas of Concern' are established within areas selected for timber harvest operations (MNR, 2004). These Areas of Concern contain one or more natural or cultural values that merit protection and are afforded special consideration in forest management and during harvest operations. These types of areas can serve as corridors and stepping stones.

Large-scale planning for connectivity is also recommended in the marine environment (CEC, 2012). Marine habitat connectivity can be particularly important for connecting critical places for different life stages (e.g. larval versus adult) as distributions of key species shift in response to climate change (CEC, 2012). The Oceans Action Plan (DFO, 2005) identifies five large-scale ocean management areas where integrated management planning is now taking place: Eastern Scotian Shelf, Gulf of St. Lawrence, Placentia Bay/Grand Banks, Beaufort Sea, and Pacific North Coast.

Both temporal and spatial connectivity need to be considered in order to maintain a suitable climate for a given species or ecosystem type over a defined period of time (Rose and Burton, 2009; Pellatt et al., 2012). When examining the results of bioclimate envelope modelling in the context of protected areas, a sense of what areas have the greatest potential to harbour species can be obtained by identifying areas that maintain a suitable climate envelope over relatively long periods of time (decades to century) (*see* Case Study 3; Hamann and Aitken, 2012; Pellatt et al., 2012).

## 4.3 RESTORING DEGRADED ECOSYSTEMS AND SUPPORTING SPECIES RECOVERY

### 4.3.1 ECOLOGICAL RESTORATION

Strategies aimed at maintaining ecological health or integrity by reducing the influence of non-climate stressors such as habitat fragmentation or pollution, or by reversing prior degradation through ecological restoration, are important for increasing resilience to climate change (Harris et al., 2006). Ecological restoration has been an important tool for decades and contributes to climate change adaptation by helping to prevent species extirpation and maintaining healthy ecosystems (e.g. Thorpe, 2012). Working landscape initiatives such as the Habitat Stewardship Program for Species at Risk (Environment Canada, 2012) include restoration strategies and techniques.

Protected-area agencies in Canada develop and apply ecological restoration techniques for individual species, biotic communities and whole ecosystems. These programs involve experimentation, modification, and adaptation, and create a culture with a capacity and willingness to adapt to change (Parks Canada, 2008). Guidelines have been developed for restoration techniques, now commonly used in many parks and other protected areas (Parks Canada Agency and the Canadian Parks Council, 2008). Examples include the restoration of grassland ecosystems in Grasslands National Park (Saskatchewan) and the restoration of riparian habitats and aquatic connectivity in La Mauricie National Park (Quebec) (Parks Canada, 2011a, b). More recent work includes explicit consideration of climate change adaptation and mitigation, relationships between the restoration of ecosystems in and around protected areas and ecological connectivity, visitor and public engagement and experience, human well-being, and the protection and provision of ecological goods and services (Keenleyside et al., 2012).

Programs to maintain or increase genetic diversity, such as seeding or sowing multiple species of native plants when converting marginal agricultural land to cover, and planting multiple tree species during forest landscape restoration, enhance the tolerance of species associations to change and can help build or maintain resilience to climate change (Thompson et al., 2009; Maestre et al., 2012) and other stressors. Efforts to restore the ecological integrity of Grasslands National Park have included the re-vegetation of previously cultivated fields with a mix of native grasses and wildflowers, and the re-introduction of disturbance regimes (e.g. the use of prescribed fire) needed for ecological integrity associated with grazing by bison (Parks Canada, 2011a).

### CASE STUDY 3

## TEMPORAL CONNECTIVITY OF GARRY OAK HABITATS IN PROTECTED AREAS OF WESTERN NORTH AMERICA

**FIGURE 8:** Garry oak on Saturna Island, Gulf Islands National Park Reserve.

Garry Oak (*Quercus garryana*) ecosystems (Figure 8), found along the southern part of Canada's west coast, are rare and contain over one hundred species-at-risk. Examining how Garry Oak (*Quercus garryana*) could respond to climate change at scales relevant to protected area management assists in the design of monitoring programs and helps guide park managers and planners in selecting sites for protecting or restoring temporally connected areas that are climatically suitable for species of interest (Pellatt et al., 2012).

Assessing climate change risks to Garry Oak (*Quercus garryana*) ecosystems involved evaluating the present level of protection of Garry Oak (*Quercus garryana*) and then forecasting how well currently protected areas in the Pacific Northwest encompass climatically suitable habitat under future climate scenarios. A down-scaled bioclimate envelope model was developed to identify areas projected to maintain climatic suitability over time. Scenarios were generated to examine temporally connected areas for Garry Oak (*Quercus garryana*) that persist throughout the 21st century, and the extent of overlap between these temporally connected regions and existing protected areas. Although climatically suitable Garry Oak (*Quercus garryana*) habitat is projected to marginally increase, mostly in the United States, this habitat will not be well represented in the World Conservation Union (IUCN) Class I-V Protected Areas. Of the protected area that currently encompasses suitable Garry Oak (*Quercus garryana*) habitat, models indicate that only 6.6 to 7.3% will be "temporally connected" between 2010 and 2099 (Figure 9; based on CGCM2-A2 model-scenario). Overlap between climatically suitable habitat for Garry Oak (*Quercus garryana*) (whether this suitable climate is currently present or not) and Class I-V protected areas in the 2010-2039 time period is approximately 40% using the same climate change scenario. Hence, Garry Oak (*Quercus garryana*) is poorly represented in temporally connected areas outside and inside protected areas, highlighting the need for public and private protected-area organizations to work cooperatively to maintain temporal connectivity in climatically suitable areas for the future of Garry Oak (*Quercus garryana*) ecosystems.

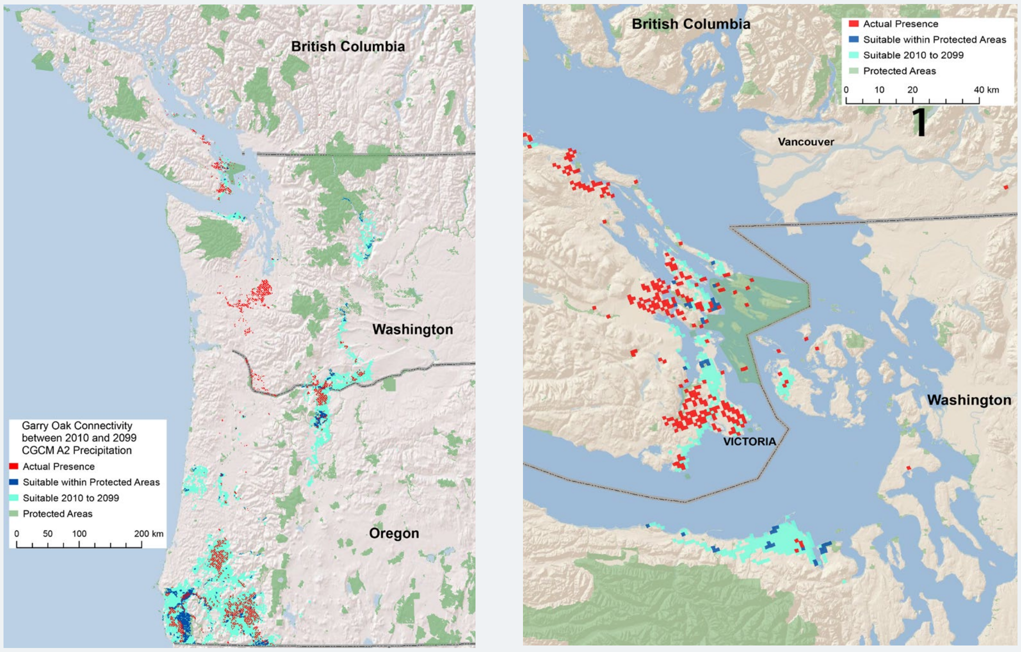


**FIGURE 9:** Climatically suitable habitat for Garry Oak *(Quercus garryana)* using scenario A2 (temporally connected) between 2010 and 2099. Green represents the location of protected areas. Light blue represents temporally connected Garry Oak habitat. Dark blue represents temporally connected Garry Oak habitat within existing protected areas. Red represents actual occurrence of Garry Oak.

Ongoing monitoring is helping to determine how the ecosystem is responding to these interventions and informing adaptive decision-making. This approach is also useful outside protected areas on the intervening land/waterscapes. For example, guidance for landowners, leaseholders and other land managers on Alberta's prairies (e.g. Saunders et al., 2006) encourages the use of native seed mixes in the restoration of rangelands to enhance the resilience of wildlife populations and the sustainability of agricultural operations.

As with other conservation measures, ecological restoration can also help to address the impacts of a changing climate on human well-being (*see* Chapter 7 – Human Health). For example, the protection and restoration of wetlands and natural drainage patterns helps to conserve water and is thus an important adaptation measure (Schindler and Bruce, 2012). The restoration of beaver populations that influence wetland hydrology and enhance water retention has led to significant increases in open water areas in Elk Island National Park (Alberta) even during exceptionally dry years (Hood and Bayley, 2008; Schindler and Bruce, 2012). Ecological restoration within and between protected areas helps to reduce landscape fragmentation and facilitates migration, gene flow, and other types of adaptation to changing conditions (*see* Case Study 4). Large-scale connectivity conservation initiatives such as the Yellowstone to Yukon Conservation Initiative (Graumlich and Francis, 2010), Algonquin to Adirondacks initiative (Algonquin to Adirondacks Collaborative, 2013), and the Wildlands Network's North American Wildways (The Wildlands Network, 2009; Dugelby, 2010) include ecological restoration as a key component of connectivity and climate change adaptation.

Climate change also creates significant challenges for ecosystem managers faced with establishing realistic targets for ecological restoration. Non-analogue, or "novel" ecosystems, may need to be accepted as management targets in some cases (Hobbs et al., 2009, 2011). Ecological restoration may thus be seen as part of a suite of interventions (i.e. "intervention ecology"; Hobbs et al., 2011) that take the form of manipulating the biotic and abiotic characteristics of the ecosystem, and can vary in intensity from deliberate non-intervention, through directed one-off interventions, to ongoing large-scale interventions. Incorporating climate change scenarios, including extreme events, into models that examine species response to climate (i.e. bioclimate envelope models, process models, observational studies, monitoring) as part of the analysis supporting ecological restoration, would permit improved assessment of whether: 1) natural recovery of a system is feasible, 2) intervention (e.g. assisted migration) would be necessary for species survival, 3) human engineering actions would be necessary (e.g. shoreline vulnerability to sea level change and coastal erosion, changes

**CASE STUDY 4**

### A LANDSCAPE APPROACH TO ECOLOGICAL RESTORATION

*(Source: Parks Canada, 2011a, b).*

Ecological restoration principles are reflected in an initiative to restore landscape connectivity within the Long Point World Biosphere Reserve, which includes the Long Point National Wildlife Area along the northern shore of Lake Erie in Ontario (Figure 10). Conservation science and state-of-the-art information management technology were used to identify Carolinian core natural areas and other significant natural areas, as well as potential habitat corridors to link the natural areas together. This interconnected system of habitat cores and corridors was designed to facilitate dispersal of plants and animals to more favourable habitats and conserve biodiversity in the face of a changing climate. Conservation partners, which include the private sector, have supported efforts to plant over 4.5 million native trees and shrubs, and use restoration techniques to mimic features of old-growth Carolinian forests. This work is helping to create corridors and enhance ecosystem resilience and adaptive capacity throughout the Biosphere Reserve.

**FIGURE 10:** A pit and mound restoration technique was used to reproduce the characteristic pattern of old-growth forests created by the decay of fallen trees. The pits have provided breeding areas for amphibians and insects, feeding and drinking holes for birds and mammals, and have contributed to ground water recharge. The mounds, with well-drained and oxygenated soils, have allowed for rapid growth of Red and White Oaks, among other tree species (*Photo courtesy of B. Craig).*

in river hydrology and surface runoff; Galatowitsch, 2012), and 4) a novel ecosystem might need to be accepted (Hobbs et al., 2011). Given the uncertainties associated with the management of complex ecological processes, an adaptive management approach that regularly re-visits objectives and decisions, and adjusts them as knowledge advances, is particularly important for ecological restoration and related interventions in the context of climate change (Keenleyside et al., 2012).

### 4.3.2 ASSISTED MIGRATION

As projected changes in climate over the next century may exceed the natural capacity of many populations to adapt through migration or other responses (Loarie et al., 2009), human-mediated transport of selected species to more favourable climatic habitat may be a management option (Eskelin et al., 2011; Pedlar et al., 2012; *see also* Chapter 3 – Natural Resources). In addition to land management initiatives that increase connected habitat for migration, three different types of assisted migration (defined as human-assisted movement of species) have been identified (Ste-Marie et al., 2011):

1. *Assisted population migration:* The human-assisted movement of populations (with different genetic makeup) of a given species within that species' current range (i.e. where it would naturally spread).
2. *Assisted range expansion:* The human-assisted movement of a given species to areas just outside its current range, assisting or mimicking how it would naturally spread.
3. *Assisted long-distance migration:* The human assisted movement of a given species to areas far outside its current range (beyond where it would naturally spread).

Assisted population migration and assisted range expansion are currently used in Canada. For example, in Quebec, climate sensitive seed transfer models are used to identify sites (within a species current range) where seedlings produced from seeds grown in seed orchards can be planted for the best chances of survival and growth to maturity (Ste. Marie et al., 2011). Assisted range expansion is employed in British Columbia, where most tree species in most regions can be planted 200 m higher in elevation, and Western Larch can be planted slightly outside its current range (O'Neill et al., 2008), and in Alberta where seed zone limits have been extended by up to 2º north latitude and by up to 200 m upward in elevation (Ste-Marie et al., 2011). Assisted long-distance migration is considered in cases where the species is threatened or geographical/physical barriers prevent natural migration. This type of assisted migration is riskier than the other two techniques because it involves the introduction of new genetic stock that may damage other species and the ecosystem into which it is introduced. No long-distance management programs are currently planned by Canadian forestry agencies (Ste-Marie et al., 2011).

There are a range of views on the practicality and appropriateness of using assisted migration as an adaption tool (Riccardi and Simerloff, 2008; St. Marie et al., 2011; Winder et al., 2011; Beardmore and Winder, 2011; Aubin et al., 2011; Pedlar et al., 2011, 2012; Larson and Palmer, 2013). A thorough understanding of the risks is essential prior to this type of work. Operationally, it requires high resolution climate projections, genecological information (the gene frequency of a species in relation to its population distribution within a particular environment), information on traits that respond to selective pressures of climate variables, and models that predict appropriate seed sources for planting (St. Clair and Howe, 2007; O'Neill et al., 2008; Rehfeldt and Jaquish, 2010; Eskelin et al., 2011).

Although assisted migration could minimize species loss under rapid climate change, it could also pose a significant risk of disrupting existing communities (McLachlan et al., 2007). While great effort has been spent studying invasive species, it is difficult to predict which species would become pests. Furthermore, the lag between introduction and population explosion in exotic invaders can be decades long, suggesting that efforts to monitor relocated species for negative ecological consequences could become impractical (McLachlan et al., 2007). While some of the risks of assisted migration can be minimized through planning, monitoring, adaptive management and regulation (Mawdsley et al., 2009), support for and uptake of assisted migration techniques will vary according to the goals and objectives in protected areas and on the intervening landscapes and waterscapes.

## 4.4 PLANNING FOR ADAPTATION

Many conservation initiatives in North America are increasingly incorporating information about climate change. In Canada, ongoing enhancements of protected area networks make a significant contribution to reducing the effects of climate change and providing opportunities for adaptation. Examples include the Natural Areas System Plan being developed by the government of Newfoundland and Labrador (Government of Newfoundland and Labrador, 2011), two new parks established in Manitoba in 2010 to protect the winter habitat of the Qamanirjuaq barren-ground caribou herd (Government of Manitoba, a, b, [n.d.]), and the 'Recommended Peel Regional Watershed Land Use Plan' in northeast Yukon. The latter is the outcome of a regional planning initiative designed to help ensure wilderness, wildlife and their habitat, cultural resources, and waters are maintained under rapid climate change (Lemieux et al., 2010). Produced as part of the implementation of Chapter 11 of the

Final Agreements for the Na-cho Nyak Dun, Tr'ondëk Hwëch'in, and Vuntut Gwitchin First Nations, the plan explicitly links climate change impacts and the need for protected areas that represent large, intact ecosystems (Peel Watershed Planning Commission, 2010).

Another strategy for conserving regional biodiversity in a dynamic climate is to ensure that conservation planning encompasses the full spectrum of physical settings; defined by elevation, geology and many other factors (Beier and Brost, 2010). As contrasting physical settings maintain distinctive ecological communities in a variety of climates (Rosenzweig, 1995), conserving representative examples of these settings should help protect biodiversity under both current and future climates (Beier and Brost, 2010). Game et al. (2011) found that protected areas identified using physical diversity captured over 90% of the diversity in vegetation communities.

## 4.5 BUILDING KNOWLEDGE TO SUPPORT PLANNING

Integrated climate change biodiversity assessments are one important means of building the necessary knowledge to identify and evaluate preparedness and intervention options, and to enhance adaptation to climate change. Pellatt et al. (2007) undertook such a study using paleoecology, dendroecology, spatial analysis, and bioclimate envelope modelling to develop a better understanding of the future of Garry Oak and Coastal Douglas-Fir ecosystems (*see* Case Study 3). This work has since been expanded to include the establishment of a long-term restoration experiment that monitors ecosystem response to environmental change, including the incorporation of prescribed fire and the exclusion of large herbivores from the ecosystem. Empirical and observational studies are required to assist the interpretation of climate suitability scenarios generated by climate models (Hamann and Wang, 2006; Hamann and Aitken, 2012).

Research is similarly informing management decisions in Kouchibouguac National Park (New Brunswick) where aerial photos, surveys and fieldwork are being used to document coastal zone change over the past few decades and to identify areas potentially requiring more protection in the future (Parks Canada, 2010). Likewise, British Columbia Parks is examining the sensitivity of the coastline to sea level rise to inform management plans for new protected areas along the north and central coast (Province of British Columbia, 2013).

Ecological monitoring is another foundation for the knowledge needed to inform climate change adaptation (Hannah et al., 2002). For example, arctic-alpine vegetation is being monitored in Quebec's parks with alpine zones (e.g. Parc national de la Gaspésie, des Hautes-Gorges-de-la-Rivière-Malbaie and des Grands-Jardins; Société des établissements de plein air du Québec, 2012) as indicators of climate-related change that will affect caribou (a species at risk) and other species that rely on habitats comprised of these plant species. Similar monitoring programs that use both land-based and remote (including space-based) technologies serve as tools to report on the state of ecological integrity in National Parks across Canada (McLennan and Zorn, 2005; Parks Canada, 2011c).

Alongside other types of scientific knowledge, Aboriginal knowledge and community experiential knowledge should contribute more broadly in informing climate change adaptation planning and conservation decision-making (CPC, 2013). This knowledge provides valuable information on historic and current ecosystem conditions and human-ecological interactions based on hundreds or even thousands of years of experience (Waithaka, 2010). For instance, Torngat Mountains National Park (Newfoundland and Labrador) is involved in research projects to study key Inuit food sources such as berries and ringed seals, and to establish baseline data to assess the effect of future climate changes on these important species (CPC, 2013).

## 4.6 ENGAGING COMMUNITIES IN ADAPTATION

Collaboration is fundamental to ensuring that adaptation actions related to other sectors (e.g. built infrastructure) do not negatively impact biodiversity or the ability of ecosystems to respond to change, and that actions aimed at helping biodiversity to respond to climate change also bring societal benefits (Andrade Pérez et al., 2010). Key players include conservation organizations, park visitors, local community groups, Aboriginal communities, and industry. Successful engagement leads to more responsible decision-making and promotes sustainable approaches to natural resource stewardship (NAWPA, 2012).

There are many examples of effective engagement and collaboration in Canada, ranging from citizen-based monitoring programs (*see* Case Study 5) to overseeing policy development at municipal, provincial/territorial and national levels. These include a climate change vulnerability assessment and adaptation options pilot study for the Clay Belt ecosystem in northeastern Ontario, where stakeholders and partners were encouraged to participate from the outset and were apprised of the results of completed work and overall study progress (Lalonde et al., 2012). An example of inter-governmental collaboration is the Manitoba-Ontario Interprovincial Wilderness Area that encompasses more than 9400 km$^2$ of boreal forest and includes core protected areas in provincial parks and conservation reserves (CPC, 2013). First Nations communities in both provinces are seeking to create a 30 000 km$^2$ network of protected areas and managed landscapes on ancestral lands.

### CASE STUDY 5

## CITIZEN-BASED MONITORING PROGRAMS

Monitoring provides critical data for adaptation planning, and can be undertaken at a range of scales involving different groups. Planners and the scientific community are increasingly drawing on information collected by community groups. Two examples described here relate to the American Pika and to marine fish and invertebrates.

Sensitive species such as American Pika (*Ochotona princeps*; Figure 11) can be used as an indicator species for detecting the impact of climate change in rocky mountainous ecosystems. In Banff and Kootenay National Parks (Alberta and British Columbia), collaboration between Parks Canada, the University of Alberta, and the Bow Valley Naturalists Society has allowed for engagement of local community members in ecological monitoring activities, while maintaining quality control. Surveyors (2 to 4 people) searched a given block of pika habitat (e.g. talus pile) for hay piles and pikas within 30 m of the talus edge. The locations of hay pile clusters that actively supported or did not support pikas were recorded with a GPS (Global Positioning System), as were actual pika observations (Timmins and Whittington, 2011). This type of monitoring will assist management in determining the impact of climate change on pika habitat and inform management decisions.

**FIGURE 11:** Pika (*Ochotona pinceps*) in a talus slope in Banff National Park.

Large-scale, long-term data on species distribution and abundance is rare for marine organisms, especially those that are not subject to monitoring for fisheries purposes. Since 1998, recreational divers in BC have been partaking in the Reef Environmental Education Foundation's (REEF) volunteer fish and invertebrate monitoring program. Participants are trained to identify target species and implement a simple roving diver survey method. More than 3700 volunteer surveys have been carried out along the British Columbia coastline through this program, representing more than 2800 hours of underwater observations at more than 300 sites, and documenting the abundance of nearly 150 fish species and 50 invertebrate species. The resulting 15-year-long time-series documents abundance trends (*see* Figure 12) for a wide range of species. Results also help to establish species range limits, as well as changes in species distribution and shifts in community assemblages over time. The program was extended to include eastern Canada in 2012.

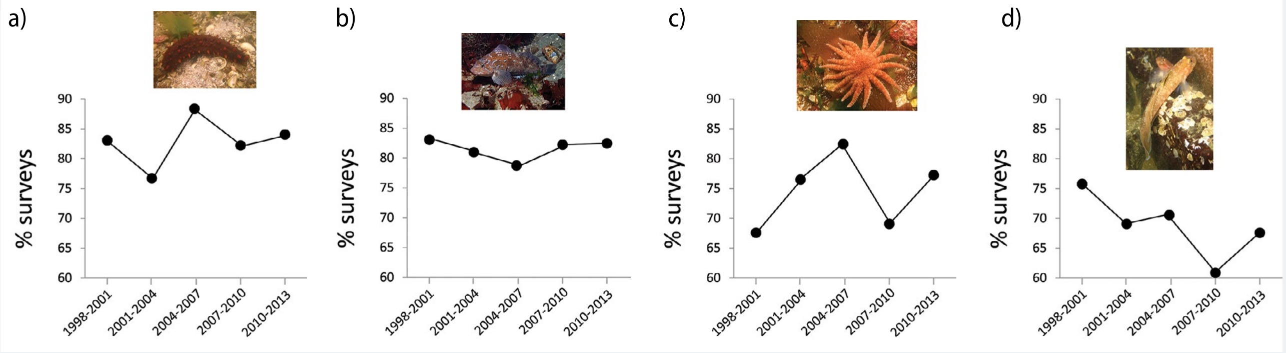


**FIGURE 12:** Abundance trends of four of the marine species most commonly encountered by recreational divers taking part in REEF surveys in British Columbia. **a)** California sea cucumber (*Parastichopus californicus*), **b)** kelp greenling (*Hexagrammos decagrammus)*, **c)** sunflower seastar (*Pycnopodia helianthoides*), and **d)** blackeye goby (*Rhinogobiops nicholsii*). Abundance is expressed as the proportion of surveys in which each species was observed. The number of surveys generating each point varied from 83 (invertebrates, 1998-2001) to 1074 (fishes, 2010-2013) *(Photos courtesy of I.M. Côté. Data derived from www.reef.org).*

# 5. CONCLUSIONS

Evidence that Canada's biodiversity is under increasing pressure from climate change continues to grow. Changes in the timing of life history events, species distribution ranges and wildlife health are already evident and are predicted to increase. Biodiversity underpins the well-being and prosperity of Canadians through the provision of ecosystem services. Strategies that help to maintain and restore biodiversity not only help ecosystems respond to climate-related changes, but also enhance ecological, social and economic resilience.

The extent and pace of climate change is creating a new ecological context in which natural resource managers are increasingly considering more interventionist approaches to biodiversity conservation (Glick et al., 2011; Poiani et al., 2011). Practices such as assisted migration are being considered alongside ecological restoration and other interventions in an effort to manage change (Glick et al., 2011).

The relationship between climate change impacts on biodiversity discussed in Section 3 of this chapter, and the adaptation strategies that are being used to help biodiversity respond to change, is illustrated in Figure 13. Actions aimed at protecting, connecting or restoring networks of well-functioning ecosystems in protected area networks, along with conservation-focused habitat stewardship on private lands and waters, and sustainable land and water use practices (e.g. sustainable forestry, agriculture, and fisheries) are enhancing the resilience of Canada's natural capital. These actions are informed by new knowledge about climate-driven changes in ecosystems, by the integration of that knowledge into conservation planning, and by the development of new partnerships and collaborative processes that include broad-based engagement of Canadians.

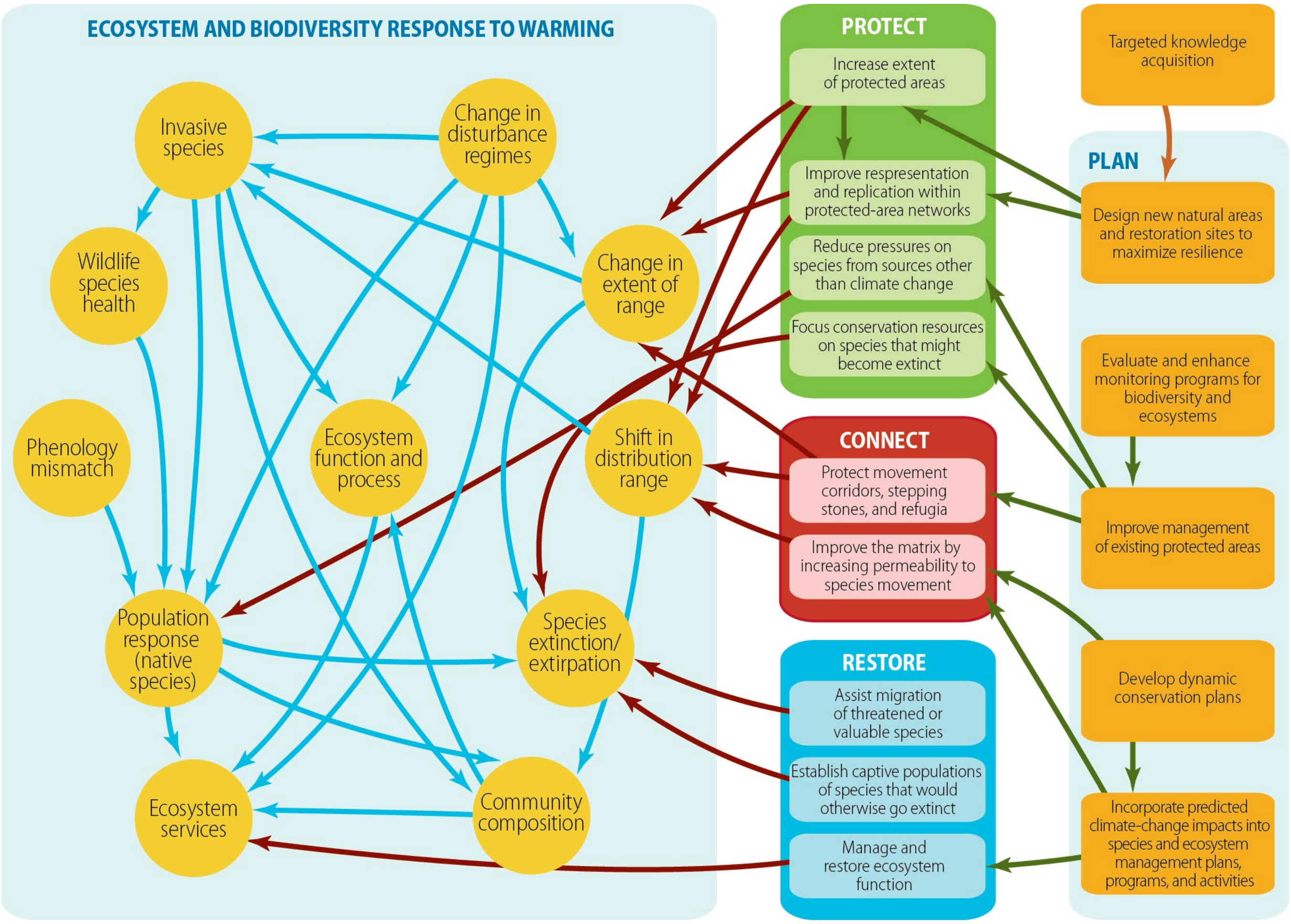


**FIGURE 13:** Linkages among elements of a conservation-based strategy for biodiversity adaptation to climate change and their potential effect on individual ecosystem response.

# REFERENCES

ACIA [Arctic Climate Impact Assessment] (2005): Impacts of a warming Arctic: Arctic climate impacts assessment; Cambridge University Press, Cambridge, 1042 p.

Ainsworth, C.H., Samhouri, J.F., Busch, D.S., Cheung, W.W., Dunne, J., and Okey, T.A (2011): Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries; ICES Journal of Marine Science: Journal du Conseil, v. 68, no. 6, p. 1217-1229.

Algonquin to Adirondacks Collaborative (2013): Algonquin to Adirondacks Collaborative; <http://www.a2alink.org>.

Allan, J.D., Palmer, M., and Poff, N.L. (2005): Climate change and freshwater ecosystems; in Climate Change and Biodiversity, (ed.) T.E. Lovejoy and L. Hannah; Yale University Press, New Haven, Connecticut, p. 274-290.

Alsos, I.G., Ehrich, D., Thuiller, W., Eidesen, P.B., Tribsch, A., Schönswetter, P., Lagaye, C., Taberlet, P., and Brochmann, C. (2012): Genetic consequences of climate change for northern plants; Proceedings of the Royal Society B: Biological Sciences, v. 279, no. 1735, p. 2042-2051.

Anderson M.G. and Ferree, C.E. (2010): Conserving the stage: climate change and the geophysical underpinnings of species diversity; PLoS ONE,v. 5, no. 7.

Andrade Pérez, A., Herrera Fernandez, B., and Cazzolla Gatti, R. (ed.) (2010): Building resilience to climate change: ecosystem-based adaptation and lessons from the field; International Union for Conservation of Nature, Gland, Switzerland, 164 p.

Anielski, M. and Wilson, S. (2009): Counting Canada's natural capital: assessing the real value of Canada's boreal ecosystems; Canadian Boreal Initiative and Pembina Institute, Ottawa, Ontario, <www.pembina.org/pub/204>.

Asselin H. and Payette, S. (2006): Origin and long-term dynamics of a subarctic tree line; Ecoscience, v. 13, p. 135-142.

Aubin, I., Garbe, C.M., Colombo, S., Drever, C.R., McKenney, D.W., Messier, C., Pedlar, J., Saner, M.A., Venier, L., Wellstead, A.M., Winder, R., Witten, E., and Ste-Marie, C. (2011): Why we disagree about assisted migration: ethical implications of a key debate regarding the future of Canada's forests; The Forestry Chronicle, v. 87, no. 6, p. 755-765.

Auzel, P., Gaonac'h, H., Poisson F., Siron, R., Calmé, S., Belanger, M., Bourassa, M., Kestrup, A., Cuerrier, A., Downing, A., Lavallée, C., Pelletier, F., Chambers, J., Gagnon, A.E., Bedard, M.C., Gendreau, Y., Gonzalez, A., Mitchell, M., Whiteley, J., and Larocque, A. (2012): Impacts of climate change on the biodiversity of Quebec: literature review summary; Le Centre de la Science de la Biodiversité du Québec, Ministère du Développement durable, de l'Environnement et des Parcs, Ouranos, 29 p.

Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E.G., Harrington, R., Hartley, S., Jones, T.H., Lindroth, R.L., Press, M.C., Symrnioudis, I., Watt, A.D., and Whittaker, J.B. (2002): Herbivory in global climate change research: direct effects of rising temperature on insect herbivores; Global Change Biology, v. 8, no. 1, p. 1-16.

Balshi, M.S., Mcguire, A.D., Duffy, P., Flannigan, M., Walsh, J., and Melillo, J. (2009): Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach; Global Change Biology, v. 15, p. 578-600.

Barnosky, A. (2008): Climate change, refugia, and biodiversity: where do we go from here? An editorial comment; Climatic Change, v. 86, p. 29-32.

Barrand, N.E. and Sharp, M.J. (2010): Sustained rapid shrinkage of Yukon glaciers since the 1957-1958 international geophysical year; Geophysical Research Letters, v. 37, L07501.

Baum, A.K., Haynes, K.J., Dillemuth, F.P., and Cronin, J.T. (2004): The matrix enhances the effectiveness of corridors and stepping stones; Ecology, v. 85, no. 10, p. 2671-2676.

Beardmore, T. and Winder, R. (2011): Review of science-based species vulnerability assessments: contributions to assisted migration decision making; The Forestry Chronicle, v. 87, p. 745-754.

Beatty, G. E., Philipp, M., and Provan, J. (2010): Unidirectional hybridization at a species' range boundary: implications for habitat tracking; Diversity and Distributions, v. 16, no. 1, p. 1-9.

Beaubien, E.G. and Freeland, H.J. (2000): Spring phenology trends in Alberta, Canada: links to ocean temperature; International Journal of Biometereology, v. 44, no. 2, p. 53-59.

Beier, P. and Brost, B. (2010): Use of land facets to plan for climate change: conserving the arenas, not the actors; Conservation Biology, v. 24, p. 701-710.

Benoît, H.P. and Swain, D.P. (2008): Impacts of environmental change and direct and indirect harvesting effects on the dynamics of a marine fish community; Canadian Journal of Fisheries and Aquatic Sciences, v. 65, no. 10, p. 2088-2104.

Berteaux, D. and Stenseth, N.C., (2006): Measuring, understanding and projecting the effects of large-scale climatic variability on mammals; Climate Research, v. 32, no. 2, p. 95-97.

Berteaux, D., Humphries, M.M., Krebs, C.J., Lima, M., McAdam, A.G., Pettorelli, N., Réale, D., Saitoh, T., Tkadlec, E., Weladji, R.B., and Stenseth, N.C. (2006): Constraints to projecting the effects of climate change on mammals; Climate Research, v. 32, p. 151-158.

Berteaux, D., DeBlois, S., Angers, J., Bonin, J., Casajus, N., Darveau, M., Fournier, F., Humphries, M.M., McGill, B., Larivée, J., Logan, T., Nantel, P., Périé, C., Poisson, F., Rodrigue, D., Rouleau, S., Siron, R., Thuiller, W., and Vescovi, L. (2010): The CC-Bio Project: studying the effects of climate change on Quebec biodiversity; Diversity, v. 2, p. 1181-1204.

Berteaux, D., Casajus, N., and Gendreau, Y. (2011): Impacts des changements climatiques sur la biodiversité du Québec; Unpublished report to Canadian Wildlife Service (March 2011), 25 p.

Bertram, D.F., Harfenist, A., and Hedd, A. (2009): Seabird nestling diets reflect latitudinal temperature-dependent variation in availability of key zooplankton prey populations; Marine Ecology Progress Series, v. 393, p. 199-210.

Bhatt, U.S., Walker, D.A., Raynolds, M.K., Cosimo, J.C., Epstein, H.E., Jia, G., Gens, R., Pinzon, J.E., Tucker, C.J., Tweedie, C.E., and Webber, P.J. (2010): Circumpolar arctic tundra vegetation change is linked to sea ice decline; Earth Interaction, v. 14, no. 8, p. 1.

Blancher, P., Cadman, M.D., Pond, B.A., Couturier, A.R., Dunn, E.H., Francis, C.M., and Rempel, R.S. (2008): Changes in bird distributions between atlases; in Atlas of the Breeding Birds of Ontario, 2001-2005, (ed.) M.D. Cadman, D.A. Sutherland, G.G. Beck, D. Lepage and A.R. Couturier; Bird Studies Canada, Environment Canada, Ontario Field Ornithologists, Ontario Ministry of Natural Resources, and Ontario Nature, Toronto, Ontario, p. 32-48.

Boisvert-Marsh, L. (2012): Spatiotemporal changes at the northern limit of tree distribution in Quebec since 1970; Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science. Department of Plant Sciences, Macdonald Campus, McGill University, Sainte-Anne-de-Bellevue, Quebec, Canada.

Bonfils C.J.W, Phillips, T.J., Lawrence, D.M., Cameron-Smith, P., Riley, W.J., and Subin, Z.M. (2012): On the influence of shrub height and expansion on northern high latitude climate; Environmental Research Letters, 7 015503.

Both, C., van Asch, M., Bijlsma, R.G., van den Burg, A.B., and Visser, M.E. (2009): Climate change and unequal phenological changes across four trophic levels: constraints or adaptations; Journal of Animal Ecology, v. 78, p. 73-83.

Bourque, A. and Simonet, G. (2008): Quebec; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush (2008), Government of Canada, Ottawa, p. 171-226.

Bowman, J., Holloway, G.L., Malcolm, J.R., Middel, K.R., and Wilson, P.J. (2005): Northern range boundary dynamics of southern flying squirrels: evidence of an energetic bottleneck; Canadian Journal of Zoology, v. 83, p. 1486-1494.

Broll, G., Tarnocai, C., and Gould, J. (2003): Long-term High Arctic ecosystem monitoring in Quttinirpaaq National Park, Ellesmere Island, Canada; in Permafrost, (ed.) M, Philips, S. Springman and L.U. Arenson, v. 2; A.A. Balkema Publishers, Swets & Zeitlinger, Lisse, The Netherlands, ISBN 90 5809 582 7, v. 1, p. 89-94.

Brook, B., Akçakaya, H.R., Keith, D.A., Mace, G.M., Pearson, R.G., and Araujo. M.B. (2009): Integrating bioclimate with population models to improve forecasts of species extinctions under climate change; Biology Letters, published online 22 July 2009.

Bronson, C.L., Grubb, T.C., Sattler, G.D., and Braun, M.J. (2005): Reproductive success across the Black-capped chickadee (Poecile atricapillus) and Corolina chickadee (P. Carolinensis) hybrid zone in Ohio; The Auk, v. 122, p. 759-772.

Burn, C.R. and Kokelj, S.V. (2009): The environment and permafrost of the Mackenzie Delta area; Permafrost and Periglacial Processes, v. 20, no. 2, p. 83-105.

Cardinale, B.J., Matulich, K.L., Hooper, D.U., Byrnes, J.E., Duffy, E.. Gamfeldt, L., Balvanera, P., O'Connor, M.I., and Gonzalez, A. (2011): The functional role of producer diversity in ecosystems; American Journal of Botany, v. 98, p. 572-592.

CARMA [CircumArctic Rangifer monitoring and assessment] (2012): Circumpolar rangifer monitoring and assessment network, <www.carmanetwork.com/display/public/home>.

Carr, D., Bowman, J., and Wilson, P.J. (2007): Density-dependent dispersal suggests a genetic measure of habitat suitability; Oikos, v. 116, p. 629-635.

CEC [Commission for Environmental Cooperation] (2012): Guide for planners and managers to design resilient marine protected areas networks in a changing climate; Commission for Environmental Cooperation, Montreal, Canada, 42 p.

CESC [Canadian Endangered Species Conservation Council] (2011): Wild species 2010: the general status of species in Canada; National General Status Working Group, 302 p.

Chambers, D., Périé, C., Casajus, N., and de Blois, S. (2013): Challenges in modeling the abundance of 105 tree species in eastern North America using climate, edaphic, and topographic variables; Forest Ecology and Management, v. 291, p. 20-29.

Chapin III, F.S., Carpenter, S.R., Kofinas, G.P., Folke, C., Abel, N., Clark, W.C., Olsson, P., Stafford Smith, D.M., Walker, B., Young, O.R., Berkes, F., Biggs, R., Grove, J.M., Naylor, R.L., Pinkerton, E., Steffen, W., and Swanson, F.J., (2009): Ecosystem stewardship: sustainability strategies for a rapidly changing planet; Trends in Ecology and Evolution, v. 25, no. 4, p. 241-249.

Chen, W., Zorn, P., Foy, N., Olthof, I., Zhang, Y., Li, J., Fraser, R., Chen, Z., McLennan, D.S., Poitevin, J., Quirouette, J. and. . . Stewart, H.M. (2012): Final report on plant growth and seasonality changes in Canada's four northern national parks during 1985-2010, monitored using satellite remote sensing; Final IPY report to Parks Canada, Hull, QC, Canada.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., and Pauly, D. (2009): Projecting global marine biodiversity impacts under climate change scenarios; Fish and Fisheries, v. 10, p. 235–251.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., and D. Pauly (2010): Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change; Global Change Biology, v. 16, p. 24-35.

Cheung, W.W.L., Zeller, D., and Pauly, D. (2011): Projected species shifts due to climate change in the Canadian marine ecoregions; A report prepared for Environment Canada, <www.seaaroundus.org/researcher/dpauly/PDF/2011/Books_Reports_OrChaptersTherein/ProjectedSpeciesShiftduetoClimateChange.pdf>.

Chiotti, Q. and Lavender, B. (2008): Ontario; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush, 2008, Government of Canada, Ottawa, p. 227-274.

Chu, C., Mandrak, N.E., and Minns, C.K. (2005): Potential impacts of climate change on the distributions of several common and rare freshwater fishes in Canada; Diversity and Distributions, v. 11, p. 299-310.

Clarke, A. and Fraser, K.P.P. (2004): Why does metabolism scale with temperature?; Functional Ecology, v. 18, p. 243-251.

Colls, A., Ash, N., and Ikkala, N. (2009): Ecosystem-based adaptation: a natural response to climate change; The International Union for Conservation of Nature, Gland, Switzerland, 16 p., <cmsdata.iucn.org/downloads/iucn_eba_brochure.pdf>.

COSEWIC [Committee on the Status of Endangered Wildlife in Canadal (2007a): COSEWIC assessment and status report on the Common Nighthawk, Chordeiles minor, in Canada; Committee on the Status of Endangered Wildlife in Canada, Ottawa, v. i, 25 p., <www.registrelep-sararegistry.gc.ca/sar/assessment/status_e.cfm>.

COSEWIC [Committee on the Status of Endangered Wildlife in Canada] (2007b): COSEWIC assessment and status report on the Chimney Swift, Chaetura pelagic, in Canada; Committee on the Status of Endangered Wildlife in Canada, Ottawa, v. ii, 49 p. <www.registrelep-sararegistry.gc.ca/sar/assessment/status_e.cfm>.

COSEWIC [Committee on the Status of Endangered Wildlife in Canada] (2008): COSEWIC assessment and status report on the Canada Warbler, Wilsonia Canadensis, in Canada; Committee on the Status of Endangered Wildlife in Canada, Ottawa, v. i, 35 p., <www.registrelep-sararegistry.gc.ca/sar/assessment/status_e.cfm>.

COSEWIC [Committee on the Status of Endangered Wildlife in Canada] (2011): COSEWIC assessment and status report on the Eastern Meadowlark, Sturnella magna, in Canada; Committee on the Status of Endangered Wildlife in Canada, Ottawa, v. x, 40 p.

Coristine, L.E. and Kerr, J.T. (2011): Habitat loss, climate change, and emerging conservation challenges in Canada; Canadian Journal of Zoology, v. 89, p. 435-451.

CPC [Canadian Parks Council] (2013): Canadian parks and protected areas: helping Canada weather climate change; Report of the Canadian Parks Council Climate Change Working Group, 52 p.

Crawford, W.R. and Irvine, J.R. (2009): State of physical, biological and selected fishery resources of Pacific Canadian marine ecosystems; Canadian Science Advisory Secretariat Research Document 2009/022, Fisheries and Oceans Canada, Ottawa.

Crête, M. and Marzell, L. (2006): Evolution of the Quebec forests in view of wildlife habitats: analysis of the big trends over three decades; Forestry Chronicle, v. 82, p. 368-382.

Crozier, L.G., Zabel, R.W., and Hamlet, A.F. (2008): Predicting differential effects of climate change at the population level with life-cycle models of spring Chinook salmon; Global Change Biology, v. 14, p. 236-249.

Cudmore, T.J., Bjorklund, N., Carroll, A.L., and Staffan Lindgren, B. (2010): Climate change and range expansion of an aggressive bark beetle: evidence of higher beetle reproduction in naive host tree populations; Journal of Applied Ecology, v. 47, no. 5, p. 1036-1043.

Cummins, P. and Haigh, R. (2010): Ecosystem status and trends report for north coast and Hecate Strait ecozone; Canadian Science Advisory Secretariat Research Document 2010/045, Department of Fisheries and Oceans, Ottawa.

Curry, R.L. (2005): Hybridization in chickadees: much to learn from familiar birds; The Auk, v. 122, p. 747-758.

Derocher, A.E., Lunn, N.J., and Stirling, I. (2004): Polar bears in a warming climate; Integrative and Comparative Biology, v. 44, p. 163-176.

Desgranges, J.L. and Morneau, F. (2010): Potential sensitivity of Quebec's breeding birds to climate change; Avian Conservation and Ecology, v. 5, no. 2.

Derksen, C., Smith, S. L., Sharp, M., Brown, L., Howell, S., Copland, L., D. R. Mueller, Y. Gauthier, C. Fletcher, A. Tivy, M. Bernier, J. Bourgeois, R. Brown, C. R. Burn, C. Duguay, P. Kushner, A. Langlois, A. G. Lewkowicz, A. Royer, and Walker, A. (2012): Variability and change in the Canadian cryosphere; Climatic Change, v. 115, p. 59-88.

DFO [Department of Fisheries and Oceans] (2005): Canada's oceans action plan: for present and future generations; Department of Fisheries and Oceans, Ottawa, 20 p., <www.dfo-mpo.gc.ca/oceans/publications/oap-pao/pdf/oap-eng.pdf>.

DFO [Department of Fisheries and Oceans] (2010): Canadian marine ecosystem and trends report; Fisheries and Oceans, Canadian Science Advisory Secretariat Science Advisory Report 2010/030, Ottawa.

Dove-Thompson, D., Lewis, C., Gray, P.A., Chu, C., and Dunlop, W.I. (2011): A summary of the effects of climate change on Ontario's ecosystems; Climate Change Research Report CCRR-11, Applied Research and Development Branch, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario, 37 p.

Dowdeswell, E. K., Dowdeswell, J.A., and Cawkwell, F. (2007): On the glaciers of Bylot Island, Nunavut, Arctic Canada; Arctic, Antarctic and Alpine Research, v. 39, p. 402-411.

Drobyshev, I., Gewehr, S., Berninger, F., and Bergeron, Y. (2013): Species specific growth responses of black spruce and trembling aspen may enhance resilience of boreal forest the climate change; Journal of Ecology, v. 101, p. 231-242.

Dudley, N., Stolton, S., Belokurov, A., Krueger, L., Lopoukhine, N., MacKinnon, K., Sandwith, T., and Sekhran, S. (ed.) (2010): Natural solutions: protected areas helping people cope with climate change; IUCN-WCPA, TNC, UNDP, WCS, The World Bank and WWF, Gland, Switzerland, Washington DC and New York.

Dufour, R., Benoît, H., Castonguay, M. Chassé, J., Devine, L., Galbraith, P., Harvey, M., Larouche, P., Lessard, S., Petrie, B., Savard, L., Savenkoff, C., St-Armand, L., and Starr, M. (2010): Ecosystem status and trends report: estuary and gulf of St. Lawrence ecozone; Department of Fisheries and Oceans, Canadian Scientific Advisory Research Document 2010/030, 187 p.

Dugelby, B.L (2010): Climate change and connectivity: toward a strategy for nature protection; Prepared for the Wildlands Network, <www.twp.org/sites/default/files/Climate%20Paper_Full_FINAL-1.pdf>.

Dukes, J.S. and Mooney, H.A. (1999): Does global change increase the success of biological invaders?; Trends in Ecology and Evolution, v. 14, no. 4, p. 135-139.

Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N., Cooke, B., Theoharides, K.A., Stange, E.E., Harrington, R., Ehrenfeld, J., Gurevitch, J., Lerdau, M., Stinson, K., Wick, R., and Ayres,M.(2009): Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can we predict?; Canadian Journal of Forest Research, v. 39, no. 2, p. 231-248.

Dunn, P.O., Winkler, D.W., Whittingham, L.A., Hannon, S.J., and Robertson, R.J. (2011): A test of the mismatch hypothesis: how is timing of reproduction related to food abundance in an aerial insectivore?; Ecology, v. 92, no. 2, p. 450-461.

Environment Canada (2009): Canada's 4th National Report to the United Nations Convention on Biological Diversity; Ottawa, 192 p.

Environment Canada (2012): Ecosystem Initiatives, <www.ec.gc.ca/nature/default.asp?lang=En&n=2C63408C-1>.

Epelbaum, A., Herborg, L.M., Therriault, T.W., and Pearce, C.M. (2009): Temperature and salinity effects on growth, survival, reproduction and potential distribution of two non-indigenous botryoid ascidians in British Columbia; Journal of Experimental Marine Biology and Ecology, v. 360, p. 43-52.

Eskelin, N., Parker, W.C., Colombo, S.J., and Lu, P. (2011): Assessing assisted migration as a climate change adaptation strategy for Ontario's forests: project overview and bibliography; Climate Change Research Report CCRR-19, Applied Research and Development Branch, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario, 44 p.

Federal, Provincial and Territorial Governments of Canada (2010): Canadian biodiversity: ecosystem status and trends 2010; Canadian Councils of Resource Ministers, Ottawa, Ontario, v. i, 142 p.

Feely, R.A., Sabine, C.L, Hernandez-Ayon, J.M., Ianson, D., and Hales, B. (2008): Evidence for upwelling of corrosive "acidified" water onto the continental shelf; Science, v. 320, p. 1490-1492.

Fischer, J., Peterson, G.D., Gardner, T.A., Gordon, L.J., Fazey, I., Elmqvist, T., Felton, A., Folke, C., and Dovers, S. (2009): Integrating resilience thinking and optimisation for conservation; Trends in Ecology and Evolution, v. 24, p. 549-554.

Flannigan, M., Stocks, B., Turetsky, M., and Wotton, M. (2009): Impacts of climate change on fire activity and fire management in the circumboreal forest; Global Change Biology, v. 15, p. 549-560.

Fortier, D., Allard, M., and Shur, Y. (2007): Observation of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago; Permafrost and Periglacial Processes, v. 18, p. 229-243.

Fraser, R.H., Olthof, I., Carrière, M., Deschamps, A., and Pouliot, D. (2012): A method for trend-based change analysis in Arctic tundra using the 25-year Landsat archive; Polar Record, v. 48, p. 83-93.

Friedland, K.D., Reddin, D.G., McMenemy, J.R., and Drinkwater, K.F. (2003): Multidecadal trends in North American Atlantic salmon (Salmo salar) stocks and climate trends relevant to juvenile survival; Canadian Journal of Fisheries and Aquatic Sciences, v. 60, p. 563-583.

Friedlingstein, P., Houghton, R.A., Marland, G., Hackler, J., Boden, T.A., Conway, T.J., Canadell, J.G., Raupach, M.R., Ciais, P., and Le Quere, C. (2010): Update on CO2 emissions; Nature Geoscience, v. 3, p. 811-812.

Friends of Algonquin Park (2012): Algonquin Park birding report, <www.algonquinpark.on.ca/news/algonquin_park_birding_report.php>.

Furgal, C. and Prowse, T.D. (2008): Northern Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen,F.J. Warren, J. Lacroix and E. Bush, 2008, Government of Canada, Ottawa, p. 57-118.

Galatowitsch, S.M. (2012): Ecological Restoration; Sinauer Association, SunderLand, Massachusetts, ch. 6, Landforms and Hydrology, p. 169-229, 630 p.

Gamache, I. and Payette, S. (2005): Latitudinal response of subarctic tree lines to recent climate change in eastern Canada; Journal of Biogeography, v. 32, p. 849-862.

Game, E.T., Lipsett-Moore, G., Saxon, E., Peterson., N., and Sheppard, S. (2011): Incorporating climate change adaptation into national conservation assessments; Global Change Biology, v. 17, p. 3150-3160.

Gardner, A.S., Moholdt, G., Wouters, B., Wolken, G.J., Burgess, D.O., Sharp, M.J., Cogley, J.G., Braun, C., and Labine, C. (2011): Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago; Nature Letters, 10089.

Garroway, C. J., Bowman, J., Cascaden, T.J., Holloway, G.L., Mahan, C.G., Malcolm, J.R., Steele, M.A., Turner, G., and Wilson, P.J. (2010): Climate change induced hybridization in flying squirrels; Global Change Biology, v. 16, no. 1, p. 113-121.

Garroway, C. J., Bowman, J., Holloway G.L., Malcolm, J.R., and Wilson, P.J. (2011): The genetic signature of rapid range expansion by flying squirrels in response to contemporary climate warming; Global Change Biology, v. 17, no. 5, p. 1760-1769.

Gaston, A.J., Bertram, D.F., Boyne, A., Chardine, J., Davoren, G., Diamond, A.W., Hedd, A., Montevecchi, W.A., Hipfner, J.M., Lemon, M.J.F., Mallory, M.L., Rail, J.F., and Robertson, G.J. (2009): Changes in Canadian seabird populations and ecology since 1970 in relation to changesin oceanography and food webs; Environmental Reviews, v. 17,p. 267-286.

Gauthier, G. and Berteaux, D. (ed.) (2011): ArcticWOLVES: Arctic wildlife observatories linking vulnerable ecoSystems, final synthesis report; Centre d'études nordiques, Université Laval, Quebec City, Quebec, Canada, 133 p.

Gauthier, G., Bêty, J., Giroux, J.F., and Rochefort, L. (2004): Trophic interactions in a high Arctic snow goose colony; Integrative and Comparative Biology, v. 44, no. 2, p. 119-129.

Gauthier, G., Berteaux, D., Bêty, J., Tarroux, A., Therrien, J.F., McKinnon, L., Legagneux, P., and Cadieux, M.C. (2011): The tundra food web of Bylot Island in a changing climate and the role of exchanges between ecosystems; Ecoscience, v. 18, p. 223-235.

Gilg, O., Sittler, B., and Hanski, I. (2009): Climate change and cyclic predator-prey population dynamics in the high Arctic; Global Change Biology, v. 15, p. 2634-2652.

Gilg, O., Kovacs, K.M., Aars, J., Fort, J., Gauthier, G., Gremillet, D., Ims, R.A., Meltofte, H., Moreau, J., Post, E., Schmidt, N.M., Yannic, G., and Bollache, L. (2012): Climate change and the ecology and evolution of Arctic vertebrates; Annals of the New York Academy of Sciences, v. 1249, p. 166-190.

Gillooly, J.F., Brown, J.H., West, G.B., Savage, V.M., and Charnov, E.L. (2001): Effects of size and temperature on metabolic rate; Science, v. 293, p. 2248-2251.

Glick, P., Stein, B.A., and Edelson, N.A. (ed.) (2011): Scanning the conservation horizon: a guide to climate change vulnerability assessment; National Wildlife Federation, Washington, D.C., 168 p.

Godin, E. and Fortier, D. (2012): Geomorphology of a thermo-erosion gully, Bylot Island, Nunavut, Canada; Canadian Journal of Earth Science, v. 49, no. 8, p. 979-986.

Goodwin, B.J., McAllister, A.J., and Fahrig, L. (1999): Predicting invasiveness of plant species based on biological information; Conservation Biology, v. 13, p. 422-426.

Government of Canada (2010): Fifth national communication on climate change; Submitted to the UNFCCC Secretariat on February 12th 2010, Government of Canada, Ottawa.

Government of Canada (2011): National framework for Canada's network of marine protected areas; Fisheries and Oceans Canada, Ottawa, 31 p., <www.dfo-mpo.gc.ca/oceans/publications/dmpaf-eczpm/framework-cadre2011-eng.asp>.

Government of Manitoba (n.d.[a]): Nuelton Lake Provincial Park; Manitoba's Protected Areas Initiative, <www.gov.mb.ca/conservation/pai/pdf/nueltin_lake_provincial_park.pdf>.

Government of Manitoba (n.d.[b]): Colvin Lake Provincial Park Proposal; Manitoba's Protected Areas Initiative, <www.gov.mb.ca/conservation/parks/pdf/planning/colvin_lake_proposal.pdf>.

Government of Newfoundland and Labrador (2011): Charting our course: climate change action plan 2011, 83 p., <www.exec.gov.nl.ca/exec/cceeet/2011_climate_change_action_plan.html>.

Government of Nova Scotia (2008): Wilderness area protects Amherst's water (news release), <www.gov.ns.ca/news/details.asp?id=20081211001>.

Government of Nova Scotia (2012): Chignecto Isthmus wilderness area – Amherst Town Lands, <www.gov.ns.ca/nse/protectedareas/wa_ChignectoIsthmus.asp>.

Graumlich, L. and W.L. Francis (ed.) (2010): Moving toward climate change adaptation: the promise of the Yellowstone to Yukon Conservation Initiative for addressing the region's vulnerabilities; Yellowstone to Yukon Conservation Initiative, Canmore, AB.

Gray, P.A. (2005): The Impacts of Climate Change on Diversity in Forested Ecosystems: Some Examples. The Forestry Chronicle, 81: 655-661.

Griffith, B., Douglas, D., Walsh, N., Young, D.T.M., Russell, D.E., White, R.G., Cameron, R., and Whitten, K. (2002): The porcupine caribou herd; in Arctic Refuge Coastal Plain Terrestrial Wildlife Research Summaries.

Hamann, A. and Wang, T. (2006): Potential effects of climate change on ecosystem and tree species distribution in British Columbia; Ecology, v. 87, no. 11, p. 2773-2786.

Hamann, A. and Aitken. S.N. (2012): Conservation planning under climate change: accounting for adaptive potential and migration capacity in species distribution models; Diversity and Distributions, v.19, no. 3, p. 268-280.

Hampe, A. and Jump, A.S. (2011): Climate relicts: past, present, future; Annual Review of Ecology, Evolution, and Systematics, v. 42, p. 313-333.

Hampe, A. and Petit, R.J. (2005): Conserving biodiversity under climate change: the rear edge matters; Ecology Letters, v. 8, p. 461-467.

Hannah, L. (2009): A global conservation system for climate-change adaptation; Conservation Biology, v. 24, p. 70-77.

Hannah, L., Midgley, G.F., Lovejoy, T., Bond, W.J., Bush, M., Lovett, J.C., Scott, D., and Woodward, F.I. (2002): Conservation of biodiversity in a changing climate; Conservation Biology, v. 16, p. 264-268.

Hannah, L., Midgley, G., Andelmon, S., Araujo, M., Hughes, G., Martinez-Meyer, E., Pearson, R., and Williams, P. (2007): Protected area needs in a changing climate; Frontiers in Ecology and the Environment, v. 5, p. 131-138.

Hanski, I., von Hertzen, L., Fyhrquist, N., Koskinen, K., Torppa, K., Laatikainen, T., Karisola, P., Auvinen, P., Paulin, L., Mäkelä, M.J., Vartiainen, E., Kosunen, T.U., Alenius, H., and Haahtela, T. (2012): Environmental biodiversity, human microbiota, and allergy are interrelated; Proceedings of the National Academy of Sciences, 109:8334-8339, <www.pnas.org/content/early/2012/05/01/1205624109.full.pdf>.

Harley, C.D.G. (2011): Climate change, keystone predation, and biodiversity loss; Science, v. 334, p. 1124-1127.

Harris, J.A., Hobbs, R.J., Higgs, E., and Aronson, J. (2006): Ecological restoration and global climate change; Restoration Ecology, v. 14, no. 2, p. 170-176.

Harrington, R., Fleming, R., and Woiwod, P. (2001): Climate change impacts on insect management and conservation in temperate regions: can they be predicted?; Agricultural and Forest Entomology, v. 3, p. 233-240.

Heller, N.E. and Zavaleta, E.S. (2009): Biodiversity management in the face of climate change: a review of 22 years of recommendations; Biological Conservation, v. 142, p. 14-32.

Helmuth, B., Mieszkowska, N., Moore, P., and Hawkins, S.J. (2006): Living on the edge of two changing worlds: forecasting the responses of rocky intertidal ecosystems to climate change; Annual Review of Ecology, Evolution and Systematics, v. 37, p. 373-404.

Hewitt, G.M. and Nichols, R.A. (2005): Genetic and evolutionary impacts of climate change; in Climate Change and Biodiversity, (ed.) R.L. Peters and T.E. Lovejoy; Yale University Press, New Haven, Connecticut, p. 176-192.

Hill, G.B. and Henry, G.H.R. (2011): Responses of high Arctic wet sedge tundra to climate warming since 1980; Global Change Biology, v. 17, p. 276-287.

Hitch, A.T. and Leberg, P.L. (2007): Breeding distributions of North American bird species moving north as a result of climate change; Conservation Biology, v. 21, p. 534-539.

Hobbs, R.J., Higgs, E., and Harris, J.A. (2009): Novel ecosystems: implications for conservation and restoration; Trends in Ecology and Evolution, v. 24, p. 599-605.

Hobbs , R.J., Hallett, L.M., Ehrlich, P.R., and Mooney, H.A. (2011): Intervention ecology: applying ecological science in the twenty-first century; BioScience, v. 61, no. 6, pg. 442-450.

Hoffmann, A.A. and Sgrò, C.M. (2011): Climate change and evolutionary adaptation; Nature, v. 470, no. 7335, p. 479-485.

Hongoh, V., Berrang-Ford, L., Scott, M.E., and Lindsay, L.R. (2011): Expanding geographical distribution of the mosquito, Culex pipiens, in Canada under climate change; Applied Geography, v. 33, p. 53-62.

Honnay, O., Verheyen, K., Butaye, J., Jacquemyn, H., Bossuyt, B., and Hermy, M. (2002): Possible effects of habitat fragmentation and climate change on the range of forest plant species; Ecology Letters, v. 5, p. 525-530.

Hood, G.A. and Bayley, S.E. (2008): Beaver (Castor canadensis) mitigate the effects of climate on the area of open water in boreal wetlands in western Canada; Biological Conservation, v. 141, p. 556-567.

Hooper, D.U., Adair, E.C., Cardinale, B.J., Byrnes, J.E.K., Hungate, B.A., Matulich, K.L., Gonzalez, A., Duffy, J.E., Gamfeldt, L., and O'Connor, M.I. (2012): A global synthesis reveals biodiversity loss as a major driver of ecosystem change; Nature, v. 486, p. 105-108.

Hounsell, S. (2012): Biodiversity; in Climate Change Adaptation: A Priorities Plan for Canada. Report of the Climate Change Adaptation Project (Canada). Intact Foundation and University of Waterloo, (ed.) B. Feltmate and J. Thistlethwaite, p. 37-48, 122 p.

Hurlbert, A.H. and Liang Z. (2012): Spatiotemporal variation in avian migration phenology: citizen science reveals effects of climate change; PLoS ONE, v. 7, no. 2, e31662.

ICES [International Council for the Exploration of the Sea (2011): Report of the study group on designing marine protected area networks in a changing climate; SGMPAN, v. 15-19, November 2010, Woods Hole, Massachusetts, USA, ICES CM 2011/SSGSUE:01, 155 p.

Inkley, D.B., Anderson, M.G., Blaustein, A.R., Burkett, V.R., Felzer, B., Griffith, B., Price, J., and Root, T.L. (2004): Global climate change and wildlife in North America; Technology Review, The Wildlife Society, Bethesda, MD, v. 4, no. 2.

Iverson, L.R., Prasad, A.M., and Matthews, S. (2008): Potential changes in suitable habitat for 134 tree species in the northeastern USA; Mitigation and Adaptation Strategies, v. 13, p. 541-560.

Jackson, D.A. and Mandrak, N.E. (2002): Changing fish biodiversity: Predicting the loss of cyprinid biodiversity due to global climate change; American Fisheries Society Symposium, v. 32 89-98.

Jaramillo-Correa J.P., Jean Beaulieu, J., Damase, P., Khasa, D.P., and Jean Bousquet, J. (2009): Inferring the past from the present phylogeographic structure of North American forest trees: seeing the forest for the genes; Canadian Journal of Forest Research, v. 39, no. 2, p. 286-307.

Jia, G.J., Epstein, H.E., and Walker, D.A. (2009): Vegetation greening in the Canadian Arctic related to decadal warming; Journal of Environmental Monitoring, v. 11, p. 2231-2238.

Joly, K., Duffy, P.A., and Rupp, T.S. (2012): Simulating the effects of climate change on fire regimes in Arctic biomes: implications for caribou and moose habitat; Ecosphere, v. 3, no. 5:36.

Jones, T. and Cresswell, W. (2010): The phenology mismatch hypothesis: are declines of migrant birds linked to uneven global climate change?; Journal of Animal Ecology, v. 79, p. 98-108.

Kausrud K.L., Mysterud, A., Steen, H., Vik, J.O., Ostbye, E., Cazelles, B., Framstad, E., Eikeset, A.M., Mysterud, I., Solhøy, T., and Stenseth, N.C. (2008): Linking climate change to lemming cycles; Nature, v. 456, p. 93-97.

Keenleyside, K.A., Dudley, N., Cairns, S., Hall, C.M., and Stolton, S. (2012): Ecological restoration for protected areas: principles, guidelines and best practices; The International Union for Conservation of Nature, Gland, Switzerland, v. x, 122 p.

Keith, D.A., Akçakaya, H.R., Thuiller, W., Midgley, G.F., Pearson, R.G., Phillips, S.J., Regan, H.M., Araujo, M.B., and Rebelo, T.G. (2008): Predicting extinction risks under climate change: coupling stochastic population models with dynamic bioclimatic habitat models; Biology Letters, v. 4, p. 560-563.

Keppel, G.K.P., Van Niel, G.W., Wardell-Johnson, C.J., Yates, M., Byrne, L., Mucina, A., Schut, G.T., Hopper, S.D., and Franklin, S.E. (2012): Refugia: identifying and understanding safe havens for biodiversity under climate change; Global Ecology and Biogeography, v. 21, p. 393-404.

Kharouba, H.M., Algar, A.C., and Kerr, J.T. (2009): Historically calibrated predictions of butterfly species' range shift using global change as a pseudo-experiment; Ecology, v. 90, no. 8, p. 2213-2222.

Klassen, G. and Locke, A. (2007): A biological synopsis of the European green crab, Carcinus maenas; Canadian Manuscript Report of Fisheries and Aquatic Sciences, no. 2818, Fisheries and Oceans Canada.

Klein, J.A., Yeh, E., Bump, J., Nyima, Y., and Hopping, K. (2011): Coordinating environmental protection and climate change adaptation policy in resource-dependent communities: a case study from the Tibetan Plateau; in Climate Change Adaptation in Developed Nations: From Theory to Practice, Advances in Global Change Research 42. Springer, (ed.) J.D. Ford and L. Berrang-Ford, ch. 31, p. 423-438.

Knudsen, E., Lindéen, A., Both, C., Jonz´en, N., Pulido, F., Saino, N., Sutherland, W.J., Bach, L.A., Coppack, T., Ergon, T., Gienapp, P., Gill, J.A., Gordo, O., Hedenström, A., Lehikoinen, E., Marra, P.P., Møller, A.P., Nilsson, A.L.K., Péron, G., Ranta, E., Rubolini, D., Sparks, T.H., Spina, F., Studds, C.E., Sæther, S.A., Tryjanowski, P., and Stenseth, N.C. (2011): Challenging claims in the study of migratory birds and climate change; Biology Letters, 2011, v. 86, no. 4, p. 928-946.

Koeller. P., Fuentes-Yaco, C., Platt, T., Sathyendranath, S., Richards, A., Ouellet, P., Orr, D., Skuladottir, U., Wieland, K., Savard, L., and Aschran, M. (2009): Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean; Science, v. 324, p. 791-793.

Krebs, C.J., Reid, D., Kenney, A.J., and Gilbert, S. (2011): Fluctuations in lemming populations in north Yukon, Canada, 2007–2010; Canadian Journal of Zoology, v. 89, p. 297-306.

Kundzewicz, Z.W. and Mata, L.J. (2007): Freshwater resources and their management; in Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziana, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Cambridge University Press, Cambridge, United Kingdom, p. 173-210, 976 p.

Lafleur, B., Paré, D., Munson, A.D., and Bergeron, Y. (2010): Response of Northeastern North American forests to climate change: will soil conditions constrain tree species migration?; Environmental Reviews, v. 18, p. 279-289.

Lalonde, R., Gleeson, J., Gray, P.A., Douglas, A., Blakemore, C., and Ferguson, L. (2012): Climate change vulnerability assessment and adaptation options for Ontario's clay belt - a case study; Applied Research and Development Branch, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario. Climate Change Research Report CCRR-24, 51 p.

Lambert, J.D., McFarland, K.P., Rimmer, C.C., Faccio, S.D., and Atwood, J.L. (2005): A practical model of Bicknell's thrush distribution in the northeastern United States; Wilson Bulletin, v. 117, p. 1-11.

Larson, B.M.H. and Palmer, C. (2013): Assisted colonization is no panacea, but let's not discount it either; Ethics, Policy and Environment, v. 16, no. 1, p. 16-18.

Lawrence, D.M., Slater, A.G., Tomas, R.A., Holland, M.M., and Deser, C. (2008): Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss; Geophysical Research Letters, v. 35, L11506.

Lemieux, C.J., Beechey, T.J., Scott, D.J., and Gray, P.A. (2010): Protected areas and climate change in Canada: challenges and opportunities for adaptation; Canadian Council on Ecological Areas (CCEA), Occasional Paper No. 19. CCEA Secretariat, Ottawa.

Lemieux, C.J., Beechey, T.J., and Gray, P.A. (2011): Prospects for Canada's protected areas in an era of climate change; Land Use Policy, v. 28, no. 4, p. 928-941.

Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E. (ed.) (2008): From impacts to adaptation: Canada in a changing climate 2007; Government of Canada, Ottawa, 448 p.

Lindenmayer, D.B., Steffen, W., Burbidge, A.A., Hughes, L., Kitching, R.L., Musgrave, W., Smith, M.S., and Werner, P.A. (2010): Conservation strategies in response to rapid climate change: Australia as a case study; Biological Conservation, v. 143, p. 1587-1593.

Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., and Ackerly, D.D. (2009): The velocity of climate change; Nature, v. 462, p. 1053-1057.

Logan, J.A., Regnière, J., and Powell, J.A. (2003): Assessing the impacts of global warming on forest pest dynamics; Frontiers in Ecology and the Environment, v. 1, no. 3, 130-137.

Lyons, K.G. and Schwartz, M.W. (2001): Rare species loss alters ecosystem function - invasion resistance; Ecology Letters, v. 4, p. 358-365.

Maestre, F.T., Quero, J.L., Gotelli, N.J.,A. Escudero, V. Ochoa, M. Delgado-Baquerizo, M. Garcia-Gomez, M.A. Bowker, S. Soliveres, C. Escolar, P. Garcia-Palacios, M. Berdugo, E. Valencia, B. Gozalo, A. Gallardo, L. Aguilera, T. Arredondo, J. Blones, B. Boeken, D. Bran, A.A. Conceicao, O. Cabrera, M. Chaieb, M. Derak, D.J. Eldridge, C.I. Espinosa, A. Florentino, J. Gaitan, M.G. Gatica, W. Ghiloufi, S. Gomez-Gonzalez, J.R. Gutierrez, R.M. Hernandez, X.W. Huang, E. Huber-Sannwald, M. Jankju, M. Miriti, J. Monerris, R.L. Mau, E. Morici, K. Naseri, A. Ospina, V. Polo, A. Prina, E. Pucheta, D.A. Ramirez-Collantes, R. Romao, M. Tighe, C. Torres-Diaz, J. Val, J.P. Veiga, D.L. Wang, and E. Zaady. (2012): Plant species richness and ecosystem multifunctionality in global drylands; Science, v. 335, no. 6065, p. 214-218.

Malcolm, J.R., Markham, A., Neilson, R.P., and Oaraci, M. (2002): Estimated migration rates under scenarios of global climate change; Journal of Biogeography, v. 29, p. 835-849.

Martins, E.G., Hinch, S.G., Patterson, D.A., Hague, M.J., Cooke, S.J., Miller, K.M., Lapointe, M.F., English, K.K., and Farrell, A.P. (2011): Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (Oncorhynchus nerka); Global Change Biology, v. 17, no. 1, p. 99-114.

Mawdsley, J.R., O'Malley, R., and Ojima, D.S. (2009): A review of climate-change adaptation strategies for wildlife management and biodiversity conservation; Conservation Biology, v. 23, p. 1080-1089.

McFadden, J.P., Liston, G.E. Sturm, M., Pilke, R. Sr., and Chapin, F.S. (2001): Interactions of shrubs and snow in arctic tundra: measurements and models; Symposium held during the Sixth IAHS Scientific Assembly at Maastricht, The Netherlands, July 2001, IAHS Publ. no. 270.

McKenney, D.W., Pedlar, J.H., Lawrence, K.M. Campbell, K.L., and Hutchinson, M.F. (2007): Potential impacts of climate change on the distribution of North American trees; BioScience, v. 57, no. 11, p. 939-948.

McLachlan, J.S., Clark, J.S., and Manos, P.S. (2005): Molecular indicators of tree migration capacity under rapid climate change; Ecology, v. 86, no. 8, p. 2088-2098.

McLachlan, J.S., Hellmann, J.J., and Schwartz, M.W. (2007): A framework for debate of assisted migration in an era of climate change; Conservation Biology, v. 21, no. 2, p. 297-302.

McLaughlin, J. and Webster, K. (2013): Effects of a changing climate on peatlands in permafrost zones: a literature review and application to Ontario's far North; Climate Research Report CCRR-34, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario, 157 p.

McLennan, D.S. (2011): Dealing with uncertainty: managing and monitoring Canada's northern national parks in a rapidly changing world; in Ecological Consequences of Climate Change: Mechanisms, Conservations and Management, (ed.) J.A. Bellant and E.A. Beever; CRS Press, Taylor and Francis Group, Boca Raton, FL.

McLennan, D.S., Bell, T., Berteaux, D., Chen, W., Copland, L., Fraser, R., Gallant, D., Gauthier, G., Hik, D., Krebs, C.J., Myers-Smith, I., Olthof, I., Reid, D., Sladen, W., Tarnocai, C., Vincent, W., and Zhang, Y. (2012): Recent climate-related terrestrial biodiversity research in Canada's Arctic national parks: review, summary and management implications; Biodiversity, v. 13, no. 3-4, p. 35-39.

McLennan, D.S. and Zorn, P. (2005): Monitoring for ecological integrity and state of the parks reporting; Parks Research Forum of Ontario (PRFO) State-of-the-Art Workshop. <http://casiopa.mediamouse.ca/wp-content/uploads/2010/06/PRFO-2005-MonitoringProceedings-p35-39-McLennan-and-Zorn.pdf>.

Melles, S.J., Fortin, M.J., Lindsay, K.L., and Badzinski, D. (2011): Expanding northward: influence of climate change, forest connectivity, and population processes on a threatened species' range shift; Global Change Biology, v. 17, no. 1, p. 17-31.

Miller, F.L. and Gunn, A. (2003): Catastrophic die-off of Peary caribou on the western Queen Elizabeth Islands, Canadian High Arctic; Arctic, v. 56, p. 381-390.

Miller-Rushing, A.J., Høye, T.T., Inouye, D.W., and Post, E. (2012): The effects of phenological mismatches on demography; Philosophical Transactions of the Royal Society B: Biological Sciences, v. 365, no. 1555, p. 3177-3186.

Minns, C.K., Shuter, B.J., and McDermid. J.L. (2009): Regional projections of climate change effects on Ontario lake trout (Salvelinus namaycush) populations; Ontario Ministry of Natural Resources, Applied Research and Development Branch, Sault Ste. Marie, ON., Climate Change Research Report CCRR-14, 10 p.

Mitton, J.B. and Ferrenberg, S.M. (2012): Mountain pine beetle develops an unprecedented summer generation in response to climate warming; American Naturalist, v. 179, no. 5, E163-E171.

MNR [Ministry of Natural Resources] (2004): Forest management planning manual for Ontario's crown forests; Ministry of Natural Resources, Toronto, Ontario.

Møller, A.P., Rubolini, D., and Lehikoinen, E. (2008): Populations of migratory bird species that did not show a phenological response to climate change are declining; Proceedings of the National Academy of Sciences, USA, v. 105, p. 16195-16200.

Mooney, H., Larigauderie, A. Cesario, M., Elmquist, T., Hoegh-Gulberg, O., Lavorel, S., Mace, G.M., Palmer, M., Scholes, R., and Yahara, T. (2009): Biodiversity, climate change, and ecosystem services; Current Opinion in Environmental Sustainability, v. 1, p. 46-54.

Mortsch, L., Alden, M., and Scheraga, J.D. (2003): Climate change and water quality in the Great Lakes region: risks, opportunities and responses; A Report Prepared for the Great Lakes Water Quality Board of the International Joint Commission, 135 p.

Munang, R., Thiaw, I., Alverson, K., Liu, J., and Han, Z. (2013): The role of ecosystem services in climate change adaptation and disaster risk reduction; Current opinion in Environmental Sustainability, v. 5, p. 1-6.

NAWPA [North American Intergovernmental Committee on Cooperation for Wilderness and Protected Areas Areas Conservation Network] (2012): North American protected areas as natural solutions for climate change, <nawpacommittee.org/wp-content/uploads/2012/08/NAWPA-CCWG-Brochure.pdf>.

Nebel, S., Mills, A., McCracken, J.D., and Taylor, P.D. (2010): Declines of aerial insectivores in North America follow a geographic gradient; Avian Conservation and Ecology - Écologie et conservation des oiseaux, v. 5, no. 2, <www.ace-eco.org/vol5/iss2/art1/>.

North American Bird Conservation Initiative Canada (2012): The state of Canada's birds, 2012; Environment Canada, Ottawa, Canada, 36 p.

Obbard, M.E., Cattet, M.R.L., Moody, T., Walton, L.R., Potter, D., Inglis, J., and Chenier, C. (2006): Temporal trends in the body condition of Southern Hudson Bay polar bears; Applied Research and Development Branch, Ontario Ministry of Natural Resources, Sault Ste. Marie, ON.

Oliver, T.H., Smithers, R.J., Bailey, S., Walmsley, C.A., and Watts, K. (2012): A decision framework for considering climate change adaptation in biodiversity conservation planning; Journal of Applied Ecology, v. 49, p. 1247-1255.

O'Neill, G.A., Carlson, M.R., Berger, V., and Ukrainetz, N.K. (2008a): Assisted migration adaptation trial: workplan; B.C. Ministry of Forests and Range - Research Branch, <www.for.gov.bc.ca/HRE/forgen/interior/AMAT_workplan_22.pdf> 140 kb.

Opdam, P. and Wascher, D. (2004): Climate change meets habitat fragmentation: linking landscape and biogeographical scale levels in research and conservation; Biological Conservation, v. 117, p. 285-297.

Ostfield, R.S. (2009): Biodiversity loss and the rise of zoonotic pathogens; Clinical Microbiology and Infection, v. 15, p. 40-43.

Parks Canada (2008): Action on the ground II: working with Canadians to improve ecological integrity in Canada's national parks, <http://www.pc.gc.ca/eng/docs/v-g/ie-ei/at-ag/agir2-action2.aspx >.

Parks Canada (2010): Kouchibouguac National Park of Canada: management plan; Ottawa, Canada, 91 p.

Parks Canada (2011a): Restoration case studies: grasslands ecosystem restoration (Grasslands National Park), <www.pc.gc.ca/eng/progs/np-pn/re-er/ec-cs/ec-cs01.aspx>.

Parks Canada (2011b): Restoration case studies: aquatic ecosystem restoration (La Mauricie National Park), <www.pc.gc.ca/eng/progs/np-pn/re-er/ec-cs/ec-cs02.aspx>.

Parks Canada (2011c): Consolidated guidelines for ecological integrity monitoring in Canada's National Parks; Protected Areas Establishment and Conservation Branch, Parks Canada.

Parks Canada Agency and Canadian Parks Council (2008): Principles and guidelines for ecological restoration in Canada's protected natural areas; Parks Canada Agency and Canadian Parks Council, <www.pc.gc.ca/docs/pc/guide/resteco/index_e.asp>.

Payette, S., Boudreau, S., Morneau, C., and Pitre, N. (2004): Long term interactions between migratory caribou, wildfires and Nunavik hunters inferred from tree rings; Ambio, v. 33, no. 8, p. 482-486.

Peacock, E., Derocher, A.E., Thiemann, G.W., and Stirling, I. (2011): Conservation and management of Canada's polar bears (Ursus maritimus) in a changing Arctic; Canadian Journal of Zoology, v. 89, no. 5, p. 371-385.

Pearce-Higgins, J.W., Yalden, D.W., and Whittingham, M.J. (2005): Warmer springs advance the breeding phenology of golden plovers Pluvialis apricaria and their prey (Tipulidae); Oecologia 143, p. 470-476.

Pearson, R.G. (2006): Climate change and the migration capacity of species; TRENDS in Ecology and Evolution, v. 21, no. 3, p. 111-113.

Pedlar, J.H., McKenney, D.W., Beaulieu, J., Colombo, S.J., McLachlan, J.S., and O'Neill, G.A. (2011): The implementation of assisted migration in Canadian forests; The Forestry Chronicle, v. 87, no. 6, p. 766-777.

Pedlar, J.H., McKenney, D.W., Aubin, I, Beardmore, T., Beaulieu, J., Iverson, L., O'Neill, G.A., Winder, R.S., and Ste-Marie, C. (2012): Placing forestry in the assisted migration debate; BioScience, v. 62, no. 9, p. 835-842.

Peel Watershed Planning Commission (2010): Recommended Peel watershed regional land use plan; Peel watershed Planning Commission, Whitehorse, Yukon Territory, Canada.

Pellatt, M.G., Gedalof, Z., McCoy, M., Bodtker, K., Cannon, A., Smith, S., Beckwith, B., Mathewes, R., and Smith, D. (2007): Fire history and ecology of Garry oak and associate ecosystems in British Columbia; Parks Canada Agency, Western and Northern Service Centre Publication, Vancouver, Canada.

Pellatt, M.G., Goring, S.J., Bodtker, K.M., and Cannon, A.J. (2012): Using a down-scaled bioclimate envelope model to determine long-term temporal connectivity of Garry oak (Quercus garryana) habitat in western North America: implications for protected area planning; Environmental Management, v. 49, p. 802-815.

Petersen, A.T., Martinez-Meyer, E., Gonzalez-Salazar, C., and Hall, P.W. (2004): Modeled climate change effects on distributions of Canadian butterfly species. Canadian Journal of Zoology, v. 82, p. 851-858.

Ping, C.L., Michaelson, G.J., Jorgenson, M.T., Kimble, J.M., Epstein, H., Romanovsky, V.E., and Walker, D.A. (2008): High stocks of soil organic carbon in North American Arctic region; Nature Geoscience, v. 1, p. 615-619.

Pitelka, L.F., Gardner, R.H., Ash, J., Berry, S., Gitay, H., Noble, I.R., Saunders, A., Bradshaw, R.H.W., Brubaker, L., Clark, J.S., Davis, M.B., Sugita, S., Dyer, J.M., Hengeveld, R., Hope, G., Huntley, B., King, G.A., Lavorel, S., Mack, R.N., Malanson, G.P., Mcglone, M., Prentice, I.C., and Rejmanek, M. (1997): Plant migration and climate change. American Scientist, v. 85, no. 5, p. 464-473.

Poiani, K.A., Goldman, R.L. Hobson, J., Hoekstra, J.M., and Nelson, K.S. (2011): Redesigning biodiversity conservation projects for climate change: examples from the field; Biodiversity Conservation, v. 20, p. 185-201.

Post, E., Forchhammer, M.C., Bret-Harte, M.S., Callaghan, T.V., Christensen, T.R., Elberling, B., Fox, A.D., Gilg, O., Hik, D.S., Hoye, T.T., Ims, R.A., Jeppesen, E., Klein, D.R., Madsen, J., McGuire, A.D., Rysgaard, S., Schindler, D.E., Stirling, I., Tamstorf, M.P., Tyler, N.J.C., van der Wal, R., Welker, J., Wookey, P.A., Schmidt, N.M., and Aastrup, P. (2009): Ecological dynamics across the Arctic associated with recent climate change; Science, v. 325, p. 1355-1358.

Province of British Columbia (2013): Recent Climate Change Projects, <www.env.gov.bc.ca/bcparks/conserve/climate_change/CCProjects.html>.

Qian, H. and Ricklefs, R.E. (2006): The role of exotic species in homogenizing the North American flora; Ecology Letters, v. 9, p. 1293-1298.

Rahel, F.J. (2002): Using current biogeographic limits to predict fish distributions following climate change. American Fisheries Society, v. 32, p. 99-110.

Rehfeldt, G.E. and Jaquish, B.C. (2010): Ecological impacts and management strategies for western larch in the face of climate change; Mitigation and Adaptation Strategies for Global Change, v. 15, p. 283-306.

Reid, P.C., Edwards, M., and Johns, D.G. (2008): Trans-Arctic invasion in modern times; Science, v. 24, 528 p.

Riccardi, A. and Simberloff, D. (2008): Assisted colonization is not a viable conservation strategy; Trends in Ecology and Evolution, v. 24, no. 5, p. 248-253.

Rodenhouse, N.L., Matthews, S.N., McFarland, K.P., Lambert, J.D., Iverson, L.R., Prasad, A., Sillett, T.S., and Holmes, R.T. (2008): Potential effects of climate change on birds of the Northeast; Mitigation and Adaptation Strategies to Global Change, v. 13, p. 517-540.

Rodenhouse, N.L., Christenson, L.M., Parry, D., and Green, L.E. (2009): Climate change effects on native fauna of Northeastern forests; Canadian Journal of Forest Research, v. 39, p. 249-263.

Rose, N.A. and Burton, P.J. (2009): Using bioclimatic envelopes to identify temporal corridors in support of conservation planning in a changing climate; Forest Ecology and Management, v. 258, p. S64-S74.

Rosenzweig, M.L. (1995): The four questions: what does the introduction of exotic species do to diversity?; Evolutionary Ecology Research, v. 3, p. 361-367.

Rosing-Asvid, A. (2006): The influence of climate variability on polar bear (Ursus maritimus) and ringed seal (Pusa hispida) population dynamics. Canadian Journal of Zoology, v. 84, p. 357-364.

Rubidge, E.M., Patton, J.L., Lim, M., Burton, A.C., Brashares, J.S., and Moritz, C. (2012): Climate-induced range contraction drives genetic erosion in an alpine mammal; Nature Climate Change, v. 2, no. 4, p. 285-288.

Saino, N., Ambrosini, R., Rubolini, D., von Hardenberg, J., Provenzale, A., Hüppop, K., Hüppop, O., Lehikoinen, A., Lehikoinen, E., Rainio, K., Romano, M., and Sokolov, L. (2010): Climate warming, ecological mismatch at arrival and population decline in migratory birds; Proceedings of the Royal Society of London, Series B: Biological Sciences, v. 278, no. 1707, p. 835-842.

Sambaraju, K.R., Carroll, A.L., Zhu, J., Stahl, K., Moore, R.D., and Aukema, B.H. (2012): Climate change could alter the distribution of mountain pine beetle outbreaks in western Canada; Ecography, v. 35, no. 3, p. 211-223.

Sauchyn, D. and Kulshreshtha, S. (2008): Prairies; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, p. 275-328.

Sauer, J.R., Hines, J.E., Fallon, J.E., Pardieck, K.L., Ziolkowski, D.J. Jr., and Link, W.A. (2011): The North American breeding bird survey, results and analysis 1966 - 2010; Version 12.07.2011 USGS Patuxent Wildlife Research Center, Laurel, MD.

Saunders, E., Quinlan, R. Jones, P., Adams, B., and Pearson, K. (2006): At home on the range: living with Alberta's prairie species at risk; Alberta Conservation Association and Alberta Sustainable Resource Development, Lethbridge, Alberta.

SCBD [Secretariat of the Convention on Biological Diversity] (2009): Connecting biodiversity and climate change mitigation and adaptation: report of the second ad hoc technical expert group on biodiversity and climate change; CBD Technical Services No. 41, 126 p.

Schindler, D.W. (2001): The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Canadian Journal of Fisheries and Aquatic Sciences, v. 58, p. 18-29.

Schindler, D.W. and Bruce, J. (2012): Freshwater resources; in Climate Change Adaptation: A Priorities Plan for Canada; Report of the Climate Change Adaptation Project (Canada), (ed.) B. Feltmate and J. Thistlethwaite; Intact Foundation and University of Waterloo. p. 51-64.

Schwartz, M.D., Ahas, R., and Aasa, A. (2006a): Onset of spring starting earlier across the Northern Hemisphere; Global Change Biology, v. 12, p. 343-351.

Schwartz, M.W., Iverson, L.R., Prasad, A.M., Matthews, S.N., and O'Connor, R.J. (2006b): Predicting extinctions as a result of climate change; Ecology, v. 87, no. 7, p. 1611-1615.

Sharma, S., Couturier, S., and Côté, S.D. (2009): Impacts of climate change on the seasonal distribution of migratory caribou; Global Change Biology, v. 15, no. 10, p. 2549-2562.

Sharp, M., Burgess, D.O., Gogley, J.G., Ecclestone, M., Labine, C., and Wolken, G.J. (2011): Extreme melt on Canada's arctic ice caps in the 21st century; Geophysical Research Letters, v. 38, L11501.

Shuter, B.J. and Post, J.R. (1990): Climate, population viability, and the zoogeography of temperate fishes; Transactions of the American Fisheries Society, v. 119, p. 314-336.

Smith, S.L., Romanovsky, V.E., Lewkowicz , A.G., Burn, C.R., Allard, M., Clow, G.D., Yoshikawa, K., and Throop, J. (2010): Thermal state of permafrost in North America: contribution to the International Polar Year; Permafrost and Periglacial Processes, v. 21, p. 117-135, < http://onlinelibrary.wiley.com/doi/10.1002/ppp.690/abstract >.

Société des établissements de plein air du Québec (2012): Ecological integrity monitoring program; Parcs Québec Network, Quebec City, Quebec, 111 p., <www.parcsquebec.com/ecologicalintegrity>.

St. Clair, J.B. and Howe, G.T. (2007): Genetic maladaptation of coastal Douglas-fir seedlings to future climates; Global Change Biology, v. 13, p. 1441-1454.

Stanford, J.A. (1996): Landscapes and catchment basins; in Methods in Stream Ecology, (ed.) F.R. Hauer and G.A. Lambert; Academic Press Inc., New York, NY, 674 p.

Staudinger, M.D., Grimm, N.B., Staudt, A., Carter, S.L., Chapin III, F.S., Kareiva, P., Ruckelshaus, M., and Stein, B.A. (2012): Impacts of climate change on biodiversity; Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment, Cooperative Report to the 2013 National Climate Assessment, 296 p.

Ste-Marie, C., Nelson, E.A., Dabros, A., and Bonneau, E.A. (2011): Assisted migration: introduction to a multifaceted concept; The Forestry Chronicle, v. 87, no. 6, p. 724-730.

Stirling, I., Lunn, N.J., and Iacozza, J. (1999): Long-term trends in the population ecology of polar bears in Western Hudson Bay in relation to climatic change; Arctic, v. 52, p. 59-67.

Stirling, I. and Derocher, A.E. (2012): Effects of climate warming on polar bears: a review of the evidence; Global Change Biology, v. 18, no. 9, p. 2694-3706.

Stocks, B.J. and Ward, P.C. (2011): Climate change, carbon sequestration, and forest fire protection in the Canadian boreal zone; Climate Change Research Report CCRR-20, Applied Research and Development Branch, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario, 26 p.

Stroeve, J., Serreze, M., Holland, M., Kay, J., Maslanik, J., and Barrett, A. (2011): The Arctic's rapidly shrinking sea ice cover: a research synthesis; Climatic Change, v. 100, no. 3-4, p. 1005-1027.

Stuchbury, B. (2007): Silence of the songbirds; HarperCollins, Toronto, Canada, 256 p.

Sturm, M., Schimel, J. Michaelson, G., and Welker, J.M. (2005a): Winter biological processes could help convert Arctic tundra to shrubland; BioScience, v. 55, p. 17-26.

Sturm, M., Douglas, T., Racine, C., and Liston, G. (2005b): Changing snow and shrub conditions affect albedo with global implications; Journal of Geophysical Research, Biogeosciences, v.110, no. G1.

Templeman, N.D. (2010): Ecosystem and trends report for the Newfoundland and Labrador Shelf; Canadian Science Advisory Secretariat Research Document 2010/026, Fisheries and Oceans Canada. Ottawa.

Tews, J., Ferguson, M.A.D., and Fahrig, L. (2007): Potential net effects of climate change on high Arctic Peary caribou: lessons from a spatially explicit simulation model; Ecological Modelling, v. 207, p. 85-98.

The Wildlands Network (2009): <www.twp.org/wildways>.

Therrien, J.F. (2012): Réponses des prédateurs aviaires aux fluctuations d'abondance de proies dans la toundra; PhD thesis, dépt. biologie, Université Laval, Québec.

Thompson, I., Mackey, B., McNulty, S., and Mosseler, A. (2009): Forest resilience, biodiversity, and climate change, a synthesis of the biodiversity/resilience/stability relationship in forest ecosystems; Secretariat of the Convention on Biological Diversity, Montreal, Technical Series no. 43, 67 p., <www.cbd.int/doc/publications/cbd-ts-43-en.pdf>.

Thompson, I.D., Okabe, K., Tylianakis, J.M., Kumar, P., Brockerhoff, E.G., Schellhorn, N.A., Parrotta, J.A., and Nasi, R. (2011): Forest biodiversity and the delivery of ecosystem goods and services: translating science into policy; BioScience, v. 61, p. 972-981.

Thorpe, J. (2012): Limited report: adaptation to climate change in management of prairie grasslands; Prepared for Prairies Regional Adaptation Collaborative (PRAC), Saskatchewan Research Council (SRC) Publication No. 12855-1E12, <www.parc.ca/rac/fileManagement/upload/12855-1E12%20Adaptation%20to%20ClimateChange%20in%20Grassland%20Management.pdf>.

Thuiller, W., Lavorel, S., and Araújo, M.B. (2005): Niche properties and geographical extent as predictors of species sensitivity to climate change; Global Ecology and Biogeography, v. 14, p. 347-358.

Timmins, J. and Whittington, J. (2011): Pika monitoring in Banff National Park: 2011 pilot study; Banff National Park of Canada, Parks Canada Agency, Banff, Alberta.

Travis, J.M.J. (2003): Climate change and habitat destruction: a deadly anthropogenic cocktail. Proceedings of the Royal Society B: Biological Sciences, v. 270, no. 467-473.

UNEP [United Nations Environment Programme] (2009): The role of ecosystem management in climate change adaptation and disaster risk reduction; Copenhagen discussion series, (ed.) R. Munang, J. Liu, and I. Thiaw, no. 2, 8 p., <http://www.unep.org/climatechange/Portals/5/documents/UNEP-DiscussionSeries_2.pdf>.

Vander Zanden, M.J., Casselman, J.M., and Rasmussen, J.B. (1999): Stable isotope evidence for the food web consequences of species invasions in lakes; Nature, v. 401, p. 464-467.

Varrin, R., Bowman, J., and Gray, P.A. (2007): The known and potential impacts of climate change on biodiversity in Ontario's terrestrial ecosystems: case studies and recommendations for adaptation; Climate Change Research Report CCRR-09, Applied Research and Development Branch, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario, 48 p., <www.mnr.gov.on.ca/stdprodconsume/groups/lr/@mnr/@climatechange/documents/document/196749.pdf>.

Vasseur, L. (2010): Championing climate change adaptation at the community level by using an ecosystem approach; in Building Resilience to Climate Change: Ecosystem-based adaptation and lessons from the field, (ed.) A. Andrade Pérez, B. Herrera Fernandez and R. Cazzolla Gatti; Gland, Switzerland: IUCN, 164 p.

Vasseur, L. and Catto, N. (2008): Atlantic Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D.S Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, p. 119-170.

Venter, O., Brodeur, N.N., Nemiroff, L., Belland, B., Dolinsek, I.J., and Grant, J.W.A. (2006): Threats to endangered species in Canada; Bioscience, v. 56, p. 903-910.

Vermeij, G. and Roopnarine, P.D. (2008): The coming Arctic invasion; Science, v. 321, p. 780-781.

Volney, W.J. and Fleming, R.A. (2000): Climate change and impacts of boreal forest insects; Agriculture, Ecosystems & Environment, v. 82, p. 283-294.

Waite, T.A. and Strickland, D. (2006): Climate change and the demographic demise of a hoarding bird living on the edge; Proceedings of the Royal Society B: Biological Sciences, v. 273, p. 2809-2813.

Waithaka, J. (2010): Parks Canada science: providing knowledge for better service to Canadians; The George Wright Forum, v. 27, no. 2, p. 213-221.

Walker, I. and Sydneysmith, R. (2008): British Columbia; in Impacts to Adaptation: Canada in a Change Climate 2007, (ed.) D.L. Lemmen, F.J. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, Ontario, p. 329-386.

Walpole, A.A. and Bowman, J. (2011): Wildlife vulnerability to climate change: an assessment for the Lake Simcoe watershed; Climate Change Research Report CCRR-22, Applied Research and Development Branch, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario, 15 p.

Walpole, A.A., Bowman, J., Tozer, D.C., and Badzinski, D.S. (2012): Community level response to climate change: shifts in Anuran calling phenology; Herpetological Conservation and Biology, v. 7, no. 2, p. 249-257.

Walther, G.R. (2010): Community and ecosystem response to recent climate change; Philosophical Transactions of the Royal Society B: Biological Sciences, v. 365, p. 2019-2024.

White, T.C.R. (2008): The role of food, weather and climate in limiting the abundance of animals; Biological reviews of the Cambridge Philosophical Society, v. 83, no. 3, p. 227-248.

Whitney, F., Freeland, H., and Robert, M. (2007): Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific; Progress in Oceanography, v. 75, p. 179-199.

Wilson, S. (2012): Canada's wealth of natural capital: Rouge National Park; Report for the David Suzuki Foundation, 60 p., <www.davidsuzuki.org/publications/downloads/2012/report_Rouge_Natural_Capital_web.pdf>.

Winder, R., Nelson, E.A., and Beardmore, T. (2011): Ecological implications for assisted migration in Canadian forests; The Forestry Chronicle, v. 87, p. 731-744.

Yamamoto-Kawai, M., McLaughlin, F.A., Carmack, E.C., Nishino, S., and Shimada, K. (2009): Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice melt; Science, v. 326, p. 1098-1100.

# CHAPTER 7:
# HUMAN HEALTH

Lead Authors:

**Peter Berry** and **Kaila-Lea Clarke** *(Health Canada)*,
**Manon D. Fleury** and **Stephen Parker** *(Public Health Agency of Canada)*

Contributing Authors:

**Marie-Claire Brisbois** *(Environmental Consultant)*, **Megan Duncan**, **Nigel Edmonds** and **Barry Jessiman** *(Health Canada)*, **Robbin Lindsay** *(Public Health Agency of Canada)*, **Paul Makar** *(Environment Canada)*, **Toni Morris-Oswald** *(Manitoba Health)*, **Nicholas Ogden** *(Public Health Agency of Canada)*, **Jaclyn Paterson** *(Health Canada)*, **David Plummer** *(Environment Canada)*, **Anastasia Rogaeva** *(Public Health Agency of Canada)*, **Craig Stephen** *(Centre for Coastal Health)*

Recommended Citation:

Berry, P., Clarke, K., Fleury, M.D. and Parker, S. (2014): Human Health; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 191-232.

# TABLE OF CONTENTS

# KEY FINDINGS

- Stronger evidence has emerged since 2008 that a wide range of health risks to Canadians are increasing as the climate continues to change. For example, climate-sensitive diseases (e.g. Lyme disease) and vectors are moving northward into Canada and will likely continue to expand their range. In addition, new research suggests climate change will exacerbate air pollution issues in some parts of Canada, although further reductions of air contaminant emissions could offset climate change impacts on levels of ground-level ozone and particulate matter.
- A range of climate-related natural hazards continue to impact communities and will pose increasing risks to health in the future. For example, recent flood and wildfire events have severely impacted communities through destruction of infrastructure and displacement of populations.
- Many adaptation activities are being taken from local to national levels to help Canadians prepare for the health impacts of climate change. Adaptation planning should consider the important differences in factors responsible for health vulnerability among urban, rural, coastal and northern communities.
- Provincial, territorial, and local health authorities are gaining an increasing knowledge of climate change and health vulnerabilities through assessments and targeted research, and some jurisdictions have begun mainstreaming climate change considerations into existing health policies and programs. Greater efforts are also being made to increase public awareness about how to reduce climate-related health risks.
- Addressing key knowledge gaps and strengthening adaptation efforts would reduce the growing risks from climate change, which leave some individuals and communities highly vulnerable to associated impacts. Adaptation tools and measures, such as heat alert and response systems, projections of vector-borne disease expansion and greening urban environments can help protect Canadians from the effects of climate change being felt now and from future impacts.

# 1. INTRODUCTION

Climate change poses significant risks to human health and well-being, with impacts from extreme weather events and natural hazards, air quality, stratospheric ozone depletion and water-, food-, vector- and rodent-borne diseases (Seguin, 2008; Costello et al., 2009; WHO, 2012b) (*see* Table 1). Vulnerability is a function of the exposure to hazards associated with changing weather and climate patterns, the sensitivity of specific populations, and the ability of individuals and communities to take protective measures (Seguin, 2008; WHO, 2012b). For example, some populations or regions, such as Canadians living in the North, face particular health challenges related to high exposure to climate hazards (Seguin and Berry, 2008). The extreme heat events in Europe in 2003 and more recently in Russia in 2010, which together caused an estimated 125 000 deaths (Robine et al., 2008; Barriopedro et al., 2011) show that countries not well prepared for climate-related events can be severely impacted. The economic costs of climate change on communities is expected to increase (Stern, 2006; NRTEE, 2011) and the costs of weather-related disasters in Canada have been rising rapidly for decades (*see* Figure 2, Chapter 5). Previous Canadian assessments indicate that Canada is vulnerable to the health impacts of climate change as a result of changing health, social, demographic and climate conditions (Lemmen et al., 2008; Seguin and Berry, 2008; Commissioner of the Environment and Sustainable Development, 2010).

In recent years, greater efforts have been taken by public health and emergency management officials and non-governmental organizations to better prepare Canadians for climate change impacts on health (Berry, 2008; Paterson et al., 2012; Poutiainen et al., 2013). Health adaptation is defined in this chapter as actions taken by health sector officials, in collaboration with those in related sectors, to understand, assess, prepare for and help prevent the health impacts of climate change, particularly on the most vulnerable in society. Adaptation is a planned and comprehensive approach to address climate change risks that supports broader goals of sustainability and resiliency, while coping is concerned primarily with minimizing immediate damages associated with a climate-related impact. Adaptation actions include raising awareness of health risks and the need for adaptive actions, as well as the provision of information and tools to help address current and projected future vulnerabilities (Pajot and Aubin, 2012; Paterson et al., 2012; Poutiainen et al., 2013; OCFP, 2011).

This chapter reports on the findings of recent research (post-2006), focusing on health outcomes from current climate-related impacts, how risks to health could increase as the climate continues to change, and what adaptation options and tools are available to public health and emergency management officials. Regional vulnerabilities are highlighted where data permits and case studies of impacts and adaptation initiatives are included. New research findings regarding characteristics and circumstances that increase the vulnerability of some individuals or certain groups are highlighted to help address barriers to action. Analysis in this chapter draws from information in Chapter 2 – An Overview of Canada's Changing Climate, and also builds upon findings from previous Government of Canada assessments (Lemmen et al., 2008; Seguin, 2008) that reported on health vulnerabilities (*see* Table 2).

| Health Impact Categories | Potential Changes | Projected/Possible Health Effects |
|---|---|---|
| Temperature extremes | • More frequent, severe and longer heat waves<br>• Overall warmer weather, with possible colder conditions in some locations | • Heat-related illnesses and deaths<br>• Respiratory and cardiovascular disorders<br>• Possible changed patterns of illness and death due to cold |
| Extreme weather events and natural hazards | • More frequent and violent thunderstorms, more severe hurricanes and other types of severe weather<br>• Heavy rains causing mudslides and floods<br>• Rising sea levels and coastal instability<br>• Increased drought in some areas, affecting water supplies and agricultural production, and contributing to wildfires<br>• Social and economic changes | • Death, injury and illness from violent storms, floods, etc.<br>• Psychological health effects, including mental health and stress-related illnesses<br>• Health impacts due to food or water shortages<br>• Illnesses related to drinking water contamination<br>• Effects of the displacement of populations and crowding in emergency shelters<br>• Indirect health impacts from ecological changes, infrastructure damages and interruptions in health services |
| Air quality | • Increased air pollution: higher levels of ground-level ozone and airborne particulate matter, including smoke and particulates from wildfires<br>• Increased production of pollens and spores by plants | • Eye, nose and throat irritation, and shortness of breath<br>• Exacerbation of respiratory conditions<br>• Chronic obstructive pulmonary disease and asthma<br>• Exacerbation of allergies<br>• Increased risk of cardiovascular diseases (e.g. heart attacks and ischemic heart disease)<br>• Premature death |
| Contamination of food and water | • Increased contamination of drinking and recreational water by run-off from heavy rainfall<br>• Changes in marine environments that result in algal blooms and higher levels of toxins in fish and shellfish<br>• Behavioural changes due to warmer temperatures resulting in an increased risk of food- and water-borne infections (e.g. through longer BBQ and swimming seasons)<br>• Increased economic pressures on low income and subsistence food users | • Sporadic cases and outbreaks of disease from strains of water-borne pathogenic micro-organisms<br>• Food-borne illnesses<br>• Other diarrheal and intestinal diseases<br>• Impacts on nutrition due to availability of local and traditional foods |
| Infectious diseases transmitted by insects, ticks and rodents | • Changes in the biology and ecology of various disease-carrying insects, ticks and rodents (including geographical distribution)<br>• Faster maturation for pathogens within insect and tick vectors<br>• Longer disease transmission season | • Increased incidence of vector-borne infectious diseases native to Canada (e.g. eastern & western equine encephalitis, Rocky Mountain spotted fever)<br>• Introduction of infectious diseases new to Canada<br>• Possible emergence of new diseases, and re-emergence of those previously eradicated in Canada |
| Stratospheric ozone depletion | • Depletion of stratospheric ozone by some of the same gases responsible for climate change (e.g. chloro- and fluorocarbons)<br>• Temperature-related changes to stratospheric ozone chemistry, delaying recovery of the ozone hole<br>• Increased human exposure to UV radiation owing to behavioural changes resulting from a warmer climate | • More cases of sunburns, skin cancers, cataracts and eye damage<br>• Various immune disorders |

**TABLE 1:** Key health concerns from climate change in Canada *(Source: Adapted from Seguin, 2008)*.

|  | Key Findings |
|---|---|
| Risks to Health | • Climate change will bring increased risks to health from extreme weather and other climate-related events such as floods, drought, forest fires and heat waves<br>• Air quality is already a serious public health issue in a number of Canadian communities and is likely to be impacted by increased smog formation, wildfires, pollen production and greater emissions of air contaminants due to changed personal behaviours<br>• Climate change is likely to increase risks associated with some infectious diseases across the country, and may result in the emergence of diseases that are currently thought to be rare in or exotic to Canada<br>• With climate change, it is expected that the number of high to extreme ultraviolet radiation (UV) readings could increase, even in the far North |
| Regional Vulnerabilities | • Climate change will impact regions across Canada differently. For example, cities tend to experience higher temperatures and tend to have higher levels of air pollution than do rural areas<br>• Northern communities are already reporting environmental changes and corresponding risks to health and well-being (e.g. food spoilage, sunburns, dangerous travel) associated with a changing climate, and are taking many actions to adapt<br>• Coastal regions may be impacted by sea level rise due to climate change which can increase the risk of storm-surge flooding in these regions |
| Adaptive Capacity | • The combined effects of projected health, demographic and climate trends in Canada, as well as changes related to social conditions and infrastructure, could increase the vulnerability of Canadians to future climate-related health risks in the absence of effective adaptation strategies<br>• Concerns exist about the effectiveness of current adaptations to mitigate health risks from climate variability. Existing gaps in public health and emergency management activities that are not addressed will reduce our ability to plan and respond to climate change in Canada<br>• Actions are being taken to adapt to the health impacts of climate change but barriers to adaptation exist. These include an incomplete knowledge of health risks, uneven access to protective measures, limited awareness of best adaptation practices to protect health, and challenges in undertaking new adaptive actions |
| Future Needs | • Further adaptation to reduce health risks is needed. Measures should be tailored to meet the needs of the most vulnerable Canadians – seniors, children and infants, the socially disadvantaged, and the chronically ill<br>• The health sector needs to maintain current efforts to protect health from climate-related risks, incorporate climate change information and engage other sectors in their plans for future programs<br>• Regional and community-level assessments of health vulnerabilities are needed to support adaptation through preventative risk reduction<br>• Multi-disciplinary research and collaborations across all levels of government can build the knowledge base on vulnerabilities to climate change to address existing adaptation gaps |

**TABLE 2:** Summary of health risks and vulnerabilities facing Canadians from climate change *(Sources: Lemmen et al., 2008; Seguin and Berry, 2008)*.

# 2. OVERVIEW OF KEY HEALTH RISKS FROM CLIMATE CHANGE

Since the release of previous Government of Canada assessments (Lemmen et al., 2008; Seguin, 2008), stronger evidence has emerged that a wide range of climate-related impacts are of public health concern in Canada. The following sections draw from recent research findings from peer-reviewed publications and technical and government reports.

## 2.1 AIR QUALITY

The direct and indirect influence of climate on air quality in Canada is substantial and well established (McMichael et al., 2006; Lamy and Bouchet, 2008; IOM, 2011; Union of Concerned Scientists, 2011). Recent studies increase confidence that climate change will exacerbate existing health risks associated with poor air quality through heat and other meteorologically-related increases in ambient air pollutants (e.g. $O_3$ and PM) (Frumkin et al., 2008; Bambrick et al., 2011), aeroallergens, and biological contaminants and pathogens (Greer and Fisman, 2008; Schenck et al., 2010). Climate change may also impact ambient air quality by increasing wildfires (*see* Section 2.4.3), while indoor air quality can be affected by climate extremes and efforts to reduce the carbon footprint of buildings.

### 2.1.1 AIR POLLUTANT TRENDS IN CANADA

Air pollution poses significant risks to the health of Canadians (*see* Box 1). While Canadians have experienced better air quality since monitoring began in the 1970s (Environment Canada, 2013b), some air pollutants that pose risks to human health are increasing and are spatially variable. Average levels of ground-level ozone ($O_3$) increased by 10% between 1990 and 2010 (Environment Canada, 2012a), although peak $O_3$ levels are declining (Health Canada, 2012e). Climate is an important factor in the formation of some air pollutants (e.g. ozone) that cause harm to health (IPCC, 2007), but the degree to which air pollutant levels in Canada are attributed to climate change is unclear. Ambient concentrations of fine particulate matter ($PM_{2.5}$) showed no significant national trend in Canada between 2000 and 2010. Some urban locations experience high ambient levels of $PM_{2.5}$ due to their proximity to large point sources of emissions (Environment Canada, 2012b). Furthermore, residential wood burning may contribute to local $PM_{2.5}$ pollution in Canada (Larson et al., 2007; Smargiassi et al., 2012).

**BOX 1**

### HEALTH IMPACTS OF GROUND-LEVEL OZONE ($O_3$) AND PARTICULATE MATTER (PM)

The Canadian Medical Association (CMA) estimated that air pollution was responsible for the death of 21 000 Canadians in 2008 (CMA, 2008). Exposure to $O_3$ is associated with premature mortality (especially acute exposure-related) and a variety of morbidity effects. Evidence is especially persuasive in terms of the effects of $O_3$ on lung function, respiratory symptoms, inflammation, and immunological defenses (Government of Canada, 2012). Significant associations exist between short-term exposure to ozone and respiratory emergency room and hospital visits (especially asthma-related), and premature mortality (Government of Canada, 2012). Recent evidence increasingly links ozone to some cardiac effects, adverse long-term respiratory impacts and chronic-exposure mortality (Gauderman et al., 2004; Islam et al., 2009; Jerrett et al., 2009; Salam et al., 2009; Zanobetti and Schwartz, 2011).

Particulate matter also poses significant health risks to Canadians. PM is usually categorized as coarse ($PM_{10-2.5}$), fine ($PM_{2.5}$) and ultrafine ($PM_{0.1}$). Fine particulate matter can form as a result of reactions involving other air pollutants and can be emitted directly from vehicles, industrial sources, forest fires, and wood and waste burning (Environment Canada, 2012b). Recent epidemiologic evidence confirms earlier observations of significant harm from PM, especially, but not confined to, the fine fraction. This includes confirmation of mortality from long-term exposure to PM, and the linkage to adverse cardiac outcomes, both from acute and chronic exposures. Additionally, there is a robust relationship between fine PM and lung cancer mortality (Krewski et al., 2005). Research suggests that PM is linked to morbidity through a range of adverse effects including restricted activity days, respiratory symptoms, bronchitis (both acute and chronic), asthma exacerbation, as well as respiratory and cardiac impacts, which result in increased emergency room visits, hospital admission, and premature mortality (Government of Canada, 2012).

Certain population groups are particularly susceptible to adverse effects following exposure to PM and $O_3$ including healthy and asthmatic children, the elderly (especially those with a pre-existing respiratory or cardiac condition), individuals who hyper-respond to respiratory irritants, and those who are more active outdoors. It is possible that thresholds for population-level health effects do not exist or exist at very low levels (Government of Canada, 2012).

### 2.1.2 AIR POLLUTION PROJECTIONS

While uncertainty still exists regarding the potential impacts of climate change on air quality in Canada, regional-scale modeling of climate change and air quality has evolved considerably since the first studies appeared approximately ten years ago. Simulations now better account for inter-annual variability in meteorology and include both ozone and particulate matter (e.g. Tagaris et al., 2007). Simulations of ten summer seasons of current (circa 2000) and future (ca. 2045) air quality in North America by Kelly et al. (2012) suggest that $O_3$ concentrations are expected to increase by up to 9 to 10 parts per billion by volume (ppbv) with climate change, when anthropogenic air pollutant emissions are kept constant (*see* Figure 1a, b). Changes across Canada are generally smaller than those found in the U.S., with local increases of 4 to 5 ppbv in parts of southern Ontario and 1 to 2 ppbv in various regions across the rest of the country. In contrast, if anthropogenic air pollutant emissions are reduced, decreases of 5 to 15 ppbv in $O_3$ concentrations could occur for much of Canada and the U.S. even with the effects of climate change (*see* Figure 1c).

The same simulations forecast lower magnitude increases of $PM_{2.5}$ (< 0.2 µg $m^{-3}$) over much of North America (*see* Figure 2a and b). Large increases (> 1.0 µg $m^{-3}$) over Hudson's Bay will be driven by increases in natural sea-salt aerosol emissions as a result of decreased sea ice cover combined with increased regional winds. Overall, in most cities, $PM_{2.5}$ is seen to increase with climate change, but decrease when the effects of climate change are offset by possible future reductions in anthropogenic emissions (*see* Figure 2c) (Kelly et al., 2012).

These results suggest that while climate change negatively affects air quality, the impact can be modulated through reductions in air pollutant emissions. Reducing air pollution would contribute to reductions in acute air-quality episodes, acidifying deposition and ozone deposition, and their associated impacts (e.g. increased mortality, damage to buildings and crops, etc.) (Kelly et al., 2012). Where greenhouse gas (GHG) mitigation actions have associated 'co-benefits' in the form of air pollutant emission reductions, some of the costs associated with reducing GHGs would be offset (Kelly et al., 2012).

Changes at the global scale, including inter-continental transport of pollutants and changes in wildfires, can be expected to impact air quality over Canada and were not addressed in the study by Kelly et al. (2012). A regional study projected future air pollution and extreme heat events under different climate change scenarios in four Canadian cities: Toronto, Calgary, Montreal, and Vancouver. Results indicated increased $O_3$ concentrations due to warming, suggesting climate change would bring increased risks to health in these cities (NRTEE, 2011). The increased use of bio-fuels may also have implications for health (e.g. respiratory disease, cardiovascular disease, cancer), although recent analysis suggested that use of E10 (a mixture of gasoline with 10% ethanol), and of low level bio-diesel blends would be associated with minimal incremental health impacts in Canada (Health Canada, 2013a; 2013b).

Black carbon, a component of fine particulate matter formed from the incomplete combustion of fossil fuels, biofuels, and biomass, has been linked to premature mortality and morbidity. Diesel exhaust, which contains black carbon, is now recognized as a human carcinogen (WHO, 2012a). Black carbon is a short-lived climate forcer with roughly one million times the heat trapping power of carbon dioxide (Schmidt, 2011). The pollutant is able to travel long distances on air currents, and in northern regions accelerates the melting of ice and snow once it is deposited (Schmidt, 2011), with potential health and safety concerns for First Nations and Inuit communities. Recent studies suggest potentially large GHG mitigation benefits and significant health co-benefits from efforts aimed at reducing black carbon emissions (Anenberg et al., 2012; US EPA, 2012; Shindell et al., 2013).

### 2.1.3 AEROALLERGENS AND HUMAN PATHOGENS

Aeroallergens such as pollens from trees, grasses or weeds, molds (indoor and outdoor), and dust mites are air-borne substances that once inhaled trigger allergic responses in sensitized individuals. Increased aeroallergen formation has been associated with exacerbation of respiratory diseases (Frumkin et al., 2008), such as asthma and chronic obstructive pulmonary disease (COPD) leading to increased hospital admissions (Hess et al., 2009).

Climate change is expected to impact aeroallergens by leading to an earlier onset of the pollen season in temperate zones, increasing the amount of pollen produced and the allergenicity or severity of allergic reaction (US EPA, 2008 *as cited in* Ziska et al., 2009; Rosenzweig et al., 2011; Ziska et al., 2011). In North America, the ragweed season is becoming longer, a pattern most prevalent in northern latitudes. Ragweed is pervasive in highly populated areas of Canada and the leading cause of seasonal allergic rhinitis in north-eastern North America, responsible for approximately 75% of seasonal allergy symptoms (Ziska et al., 2011). Between 1995 and 2009, the length of the ragweed season increased by 27 days in Saskatoon and increased by 25 days in Winnipeg (Ziska et al., 2011).

$O_3$

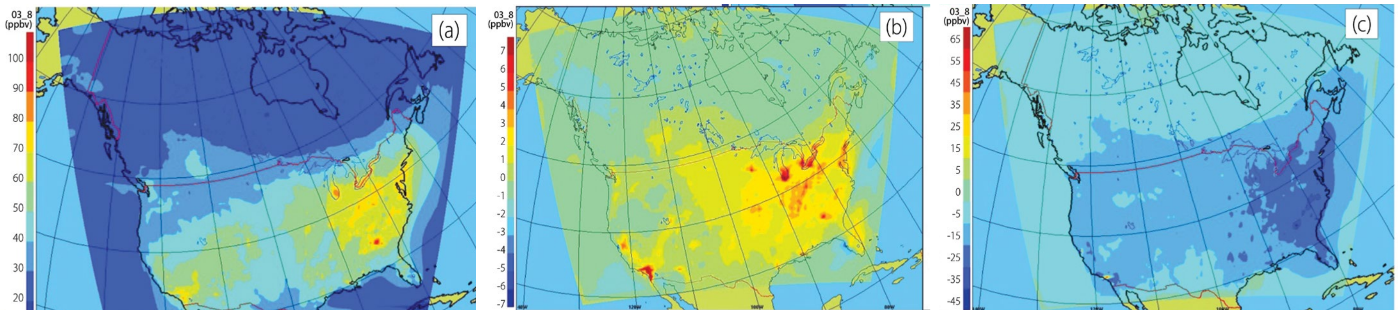


**FIGURE 1:** **a)** The ten year average "current" mean summer (June-July-August) daily maximum 8-hour average $O_3$ concentration; **b)** projected changes in the summer average daily maximum 8-hour $O_3$ between the "current" case and the "future" case with climate change using constant air pollutant emissions; and the **c)** "current" case and "future" case with possible reductions in future air pollutant emissions *(Source: Kelly et al., 2012)*. Note the different contour intervals used in each panel.

$PM_{2.5}$

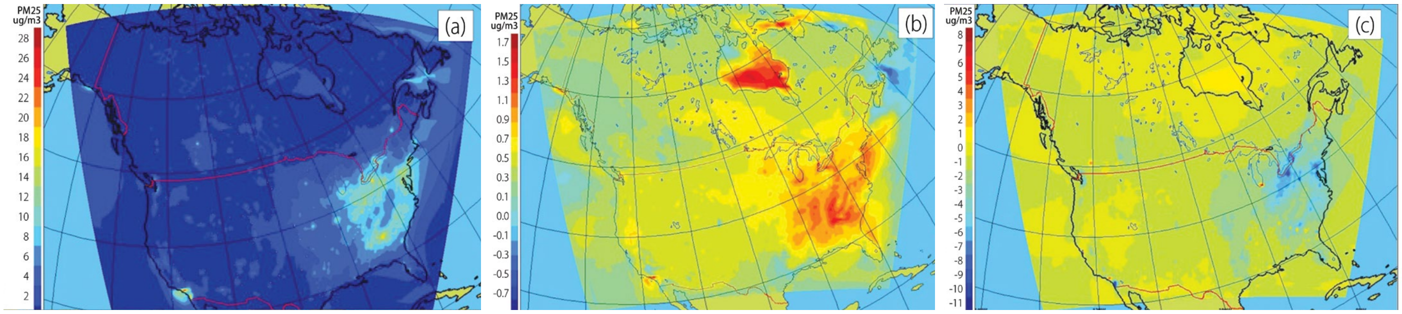


**FIGURE 2:** **a)** The ten year average "current" mean summer (June-July-August) 24-hour average $PM_{2.5}$ concentration; **b)** projected changes in the summer 24-hour average $PM_{2.5}$ concentration due to climate change with constant air pollutant emissions; and **c)** projected changes to $PM_{2.5}$ for the future with the combined effects of climate change and possible future decreases in air pollutant emissions *(Source: Kelly et al., 2012)*. Note the different contour intervals used in each panel.

In Canada, higher temperatures and drier conditions due to climate change could facilitate the establishment of fungal pathogens in new locations (Greer et al., 2008). For example, *Cryptococcus gattii*, a fungal pathogen typically found in tropical and sub-tropical regions, was identified on Vancouver Island in 1999 and has since spread to the British Columbia mainland. Its prevalence may be linked to warmer and drier summers in western Canada (Kidd et al., 2007; BC CDC, 2012). Sensitive populations who are exposed to this fungus may become sick with cryptococcal disease (cryptococcosis) which can be serious and result in pneumonia or meningitis (BC CDC, 2012).

### 2.1.4 INDOOR AIR QUALITY

Efforts to reduce the greenhouse gas footprint of buildings or adapt to climate change impacts may have unanticipated effects on health. Changes in the design of buildings (residential or commercial) and their building methods and materials in order to improve energy efficiency may affect health through reductions in indoor air quality (IOM, 2011). For example, some actions to weatherize buildings can reduce airflow, lower ventilation and trap pollutants that enter from outdoors (e.g. particulate matter, and volatile organic compounds or VOCs) or that are emitted indoors (e.g. tobacco smoke, radon, or various chemicals from building materials) (Potera, 2011).

An increase in the frequency of intense precipitation events (*see* Chapter 2) could also create indoor health risks to Canadians. Moisture in buildings from infiltration of rain or flooding, poorly designed ventilation and air-conditioning systems, and poor building maintenance can lead to growth of biological contaminants, such as fungi and infectious bacteria, which may impact health (e.g. respiratory disease) (Değer et al., 2010; Schenck et al., 2010; Potera, 2011). Dampness in buildings may increase emissions of VOCs and semi-volatile organic compounds (SVOCs) from building materials or products that may increase risks of asthma and allergies (Tuomainen et al., 2004; Jaakola and Knight, 2008). Inadequate or inappropriate remediation measures after a disaster may also contribute to poor indoor air quality (Chew et al., 2006).

In addition, power outages associated with extreme weather events (e.g. ice storms) lead to the indoor use of portable gas-powered or electric generators (which emit carbon monoxide), oil and gas furnaces, fireplaces, or candles. When used improperly, these devices are a fire hazard and can lead to high levels of indoor air pollutants, toxicity, hospitalization or even death. For example, the ice storm in Eastern Canada in 1998 resulted in 28 deaths, mostly due to carbon monoxide poisoning (Berry et al., 2008b).

## 2.2 FOOD AND WATER QUALITY

### 2.2.1 FOOD-BORNE ILLNESSES AND FOOD SECURITY

While surveillance systems are in place to identify food-borne illnesses and reduce the burden of these diseases within communities, there are still a large number of unreported cases. It has been estimated that approximately 4 million episodes of food-borne illness occur in Canada annually (Thomas et al., 2013). Every summer, reports of food-borne bacterial illness peak in Canada (Isaacs et al., 1998) and this peak is due in part to increased replication rates and persistence of pathogens with increased temperature, as well as to seasonal changes in eating behaviour, with barbeques and picnics providing greater opportunities for bacteria to survive cooking or to produce harmful toxins.

In Canada, human cases of salmonellosis have been associated with higher temperatures, and occurrences of acute gastrointestinal illness (AGI) have been shown to increase with both high and very low precipitation levels, especially during the summer and fall (Febriani et al., 2010; Ravel et al., 2010). A study evaluating the impact of temperature on food-borne illness in the United Kingdom from 1981 to 2006 (Lake et al., 2009) found that food-borne infections continue to be associated with temperature, but that there was a significant reduction in the association between temperature and food-borne illness over time that could be a result of improved food safety and increased food safety measures. Warmer temperatures due to climate change may also impact other pathogens and result in increased outbreaks of food-borne diseases such as botulism in Arctic communities (Parkinson and Evengard, 2009).

There are only a limited number of studies on the impacts of climate change on food security and subsequent impacts on human health in Canada, with most of the studies focused on the Canadian Arctic (Lemmen et al., 2008; Seguin, 2008). Climate change and weather variability (e.g. flooding, drought, temperature) can impact agriculture and fisheries in Canada (*see* Chapter 4 – Food Production). In addition, almost all Canadians depend on imported food to supplement their diet. Climate change could affect the availability of some foods, potentially increasing food costs and reducing accessibility for people with low incomes or living in isolated communities (Meakin and Kurvits, 2009).

### 2.2.2 WATER-BORNE DISEASES AND WATER SECURITY

Water-borne illnesses result from exposure to chemicals or microbes in contaminated drinking water supplies, recreational water and/or food. In Canada, there are guidelines in place to protect water quality and drinking water, although water can still become contaminated and result in people becoming ill (Health Canada, 2012b). Small drinking water systems can be more vulnerable than larger systems to climate change due to infrastructure and financial, technological and training constraints (Moffatt and Struck, 2011; Brettle et al., 2013). A recent study among Canadian water utility officials found that over half of those surveyed do not envisage drinking water challenges from climate change and have no plans to address future climate change impacts (CWWA, 2012).

In Canada, water-borne disease outbreaks have been linked to weather events, particularly heavy rains and drought, and to increasing temperatures (Thomas et al., 2006; Seguin, 2008; Moffatt and Struck, 2011). Heavy rainfall two to four weeks prior to illness was found to increase the number of gastrointestinal illness-related clinic visits in two Inuit communities in Nunatsiavut, Canada (Harper et al., 2011). While most research focuses on the impacts of climate on microbiological contamination, climate change could also affect the pathways by which chemical contamination occurs. Flooding, storms and precipitation can all transport chemical contaminants such as pesticides, nutrients, heavy metals and persistent organic pollutants into water bodies (Hilscherova et al., 2007; Harmon and Wyatt, 2008; Noyes et al., 2009). Pesticide concentrations in water supplies have been found to increase with the effects of greater storm intensity, such as water runoff and flooding (Chiovarou and Siewicki, 2007). Therefore, more frequent and intense storms, increased precipitation, and increased flooding associated with climate change may increase chemical contamination of water bodies and watersheds.

Climate change could increase the proliferation of cyanobacteria, also known as blue-green algae, in Canada (Barbeau et al., 2009; DesJarlais and Blondlot, 2010). Cyanobacteria can result in unacceptable taste and odours and some also produce various toxins (cyanotoxins) that taint drinking and recreational water and that contaminate fish and shellfish. Some cyanotoxins can impact the health of people and animals if contaminated water is ingested or becomes airborne and is inhaled. In other cases, skin contact with the algal cells may result in an allergic-type reaction (Health Canada, 2000). Blue-green algae blooms have been reported in every province of Canada and in the Yukon (Orihel et al., 2012). Blooms of cyanobacteria and filamentous green algae have increased in Ontario in the last 15 years (Winter et al., 2011). Globally, increases in algal blooms are attributed to nutrient enrichment and warming weather (Heisler et al., 2008; Paerl and Huisman, 2008). Water management strategies to reduce harmful cyanobacterial blooms include decreasing nutrient input in water sources (Paerl and Huisman, 2009) and utilizing processes such as adsorption with powdered activated carbon or oxidization treatments which are effective for treating drinking water (Barbeau et al., 2009).

## 2.3 ZOONOSES AND VECTOR-BORNE DISEASES (VBDS)

Climate change may affect health risks from both zoonoses (diseases transmitted from animals to humans) and vector-borne diseases (VBD – diseases transmitted either human-to-human or animal-to-human by arthropod vectors). Four main outcomes that may occur in isolation or in concert may increase health risks including: i) changes to the geographic footprint of the occurrence of transmission cycles; ii) changes in the abundance of pathogens and vectors where zoonosis/VBD transmission cycles already occur; iii) changes in evolutionary pressures on pathogens with potential consequences for their transmissibility to humans and capacity to cause disease; and iv) changes to human activities that alter the frequency with which humans are exposed to zoonoses/VBDs (Ogden et al., 2010).

There are few quantitative assessments of the current and future risks of zoonoses and VBDs in Canada. In 2007, Lyme disease (*see* Box 2) was considered to be, for the most part, a risk that may emerge in the future. However, maps developed by Ogden et al. (2008a) (*see* Figure 3) highlighting current and projected future risk of Lyme disease based on the geographic distribution of the tick vector *Ixodes scapularis* (the blacklegged tick) have now been validated in the field. These validation studies (Ogden et al., 2010; Bouchard et al., 2011; Koffi et al., 2012; Public Health Agency of Canada, 2014) reveal that the emergence of Lyme risk in the Canadian environment is underway, with the annual incidence of Lyme disease having increased from approximately 30 cases a year to 315 in 2012.

Surveillance data indicates that Lyme vectors (as a proxy for Lyme disease risk) are spreading into Canada at a rate of 35-55 km per year and are following climate-determined geographic trajectories (Leighton et al., 2012), further supporting the validity of the risk maps (*see* Figure 4).

**BOX 2**

### THE SYMPTOMS OF LYME DISEASE

*(Source: Public Health Agency of Canada, 2013a)*

Lyme disease is a serious illness that usually begins with a characteristic rash at the site of the tick bite. The disease can be treated with antibiotics. If untreated in the early stages it may progress to 'disseminated Lyme disease' with symptoms of weakness, multiple skin rashes, painful, swollen or stiff joints, abnormal heartbeat, central and peripheral nervous system disorders including paralysis, and extreme fatigue.

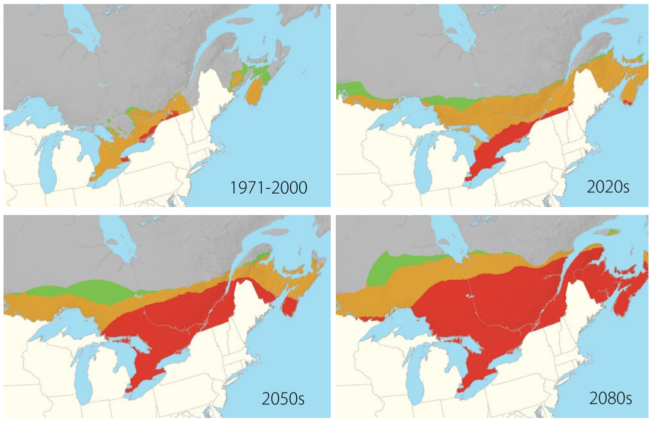


**FIGURE 3:** Risk maps for establishment and spread of the Lyme disease vector Ixodes scapularis under (1971-2000) and projected future climate (2020s to 2080s) after Ogden et al., 2008a. The green zone indicates the main extent of locations where *I. scapularis* may become established. The orange and red zones indicate areas with increasingly high risk for *I. scapularis* population emergence. The grey zone indicates areas where the risk of *I. scapularis* population emergence is very low *(Source: Ogden et al., 2008a)*.

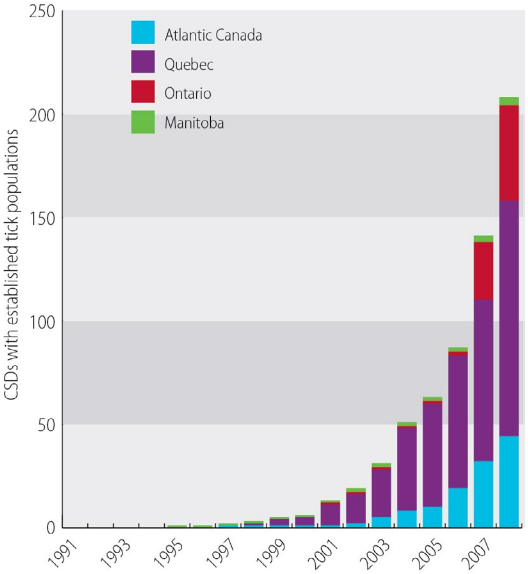


**FIGURE 4:** Expansion of *I. scapularis* populations in Canada, 1991-2007 *(Source: reproduced from Leighton et al., 2012)*. CSD = Census Sub-Division.

Similar studies have assessed the range expansion of West Nile Virus (WNV) risk with climate change within Canada (Hongoh et al., 2012), Lyme disease risk in British Columbia (Mak et al., 2010) and expansion of Tularaemia and plague risk in Canada, and spread from the U.S. (Nakazawa et al., 2007). More qualitative approaches have been taken to assess changing risk from zoonotic VBDs caused by viruses (arboviruses) due to climate and other environmental changes. For example, Hongoh et al. (2009) predicted a northward expansion of zoonotic VBD risks into Canada from their current range in the U.S., and a northwards spread within Canada for those arboviruses already endemic here as the climate continues to change. The recent spread of Eastern Equine Encephalitis virus (EEEV) into Canada may be evidence of this expansion (unpublished data by L.R. Lindsay). Like WNV, this mosquito-transmitted arbovirus uses wild birds as its reservoir hosts, and has spread from the U.S. to locations in Nova Scotia, Quebec and Ontario in recent years. It has caused a number of fatal cases in horses and emus; although, no human cases have occurred to date.

Risks of other diseases transmitted by blacklegged ticks (Human anaplasmosis caused by *Anaplasma phagocytophilum*, Human babesiosis caused by *Babesia microti*) are also beginning to emerge in Canada (Cockwill et al., 2009; unpublished data by L.R. Lindsay). It is not clear as to whether the increasing environmental risk is resulting in an increased number of cases in humans because these diseases are not under national surveillance.

### 2.3.1 WILDLIFE-BORNE ZOONOSES

Only a limited number of recent studies on the occurrence of climate-sensitive wildlife-borne zoonoses in southern Canada are available (e.g. Wobeser et al., 2009; Jardine et al., 2011). Studies targeted to specific aspects of zoonosis ecology, such as Lyme dispersion (Ogden et al., 2008b; 2011), Hantavirus risk (Safronetz et al., 2008) and toxoplasma risk (Simon et al., 2011) have provided data that have been, or will be, useful for assessing the effects of climate change on zoonosis risk. More effort has been expended on understanding the risk from zoonoses in northern Canada via studies of wildlife (Simon et al., 2011), domesticated animals (Salb et al., 2008; Himsworth et al., 2010a, b) and humans (Messier et al., 2009; Gilbert et al., 2010; Campagna et al., 2011; Sampasa-Kanyinga et al., 2012). These studies highlight zoonoses as a public health issue in the North and provide qualitative assessments of how the risk from these diseases may be affected by climate change. However, our knowledge of the ecology of these diseases remains too limited to confidently predict the extent to which climate change will impact risks to people in northern communities (Jenkins et al., 2011). Recent studies have also identified that known endemic wildlife diseases in Canada, particularly arboviruses such as the Snowshoe Hare virus, can be pathogenic in humans and are likely to be sensitive to climate change. As a result, they could emerge as significant, public health risks in the future in terms of number of cases and case severity (Meier-Stephenson et al., 2007).

### 2.3.2 EXOTIC ZOONOSES/VBDS

A number of studies have begun to assess Canada's vulnerability to 'exotic' zoonoses/VBDs such as malaria, chikungunya, dengue, Japanese encephalitis, and Rift Valley Fever imported from countries further afield than the United States. These studies suggest that as temperature increases, southern Canada will become increasingly suitable for malaria transmission, where competent vectors already exist (Berrang-Ford et al., 2009) (*see* Figure 5).

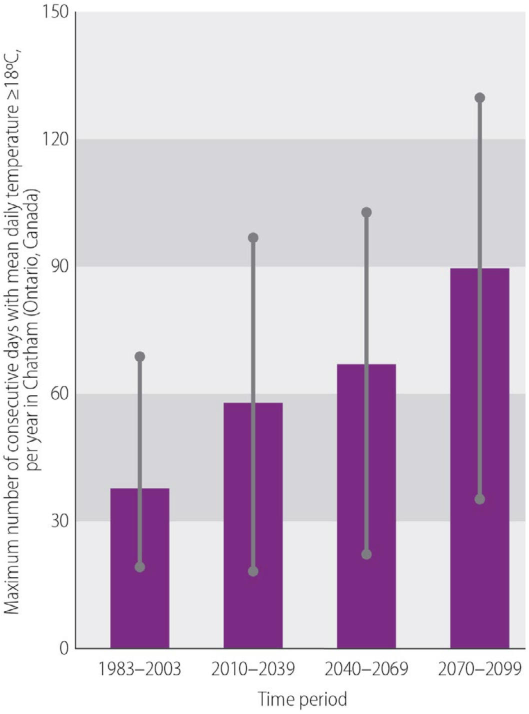


**FIGURE 5:** Recent and projected (for 2010-2099) annual number of consecutive days ≥18˚C for Chatham, Ontario. 18˚C is the threshold temperature condition for transmission of the malaria parasite *Plasmodium vivax*. At 18˚C development in the vector takes 30 days, a duration which is the limit for survival of the mosquito *(Source: Berrang-Ford et al., 2009)*.

As would be expected, current risk of malaria transmission in southern Canadian communities is highest in those communities with high proportions of immigrants from malaria-endemic parts of the world (Eckhardt et al., 2012). Studies have also identified the ability of mosquito species present in Canada to acquire and transmit Rift Valley Fever virus (Iranpour et al., 2011). Models that use multi-criteria decision analysis (MCDA) identify the potential for emergence of exotic vector-borne diseases in Canada due to both climate warming and import by infected migrants (Jackson et al., 2010; Cox et al., 2012). Recent epidemics of imported chikungunya in Italy (Angelini et al., 2008) and dengue in Florida (Bouri et al., 2012) have raised awareness of the threat of imported/invasive VBDs. Increasing climatic suitability in Canada is expected to increase the likelihood of these events (Berrang-Ford et al., 2009). Infected mosquitoes can be readily imported via global trade and travel (Medlock et al., 2012). Exotic VBD incidence is likely to increase with climate change, especially in developing countries (Ermert et al., 2012), and economic/disaster-driven migration of infected people from developing countries is anticipated to increase with climate change (McMichael et al., 2012). Thielman and Hunter (2006) have identified the establishment of exotic mosquitoes and mosquito vectors in Canada.

Tools to allow risk-based decision-making for the management (i.e. surveillance, prevention and control) of emerging/re-emerging zoonoses/VBDs include MCDA (*see* Case Study 1). Research continues to develop improved methods of surveillance for zoonoses/VBDs (e.g. Pabbaraju et al., 2009; Vrbova et al., 2010), as not all potential methods end up being useful in the field (Millins et al., 2011).

Diagnostic delays, due to a lack of expertise and diagnostic capacity within the medical profession for unexpected and emerging exotic zoonoses/VBDs, mean that disease severity can be very high (Berrang-Ford et al., 2009). Efforts to address VBDs are also faced with a lack of trained personnel, as well as uneven public health and clinical measures in place (Public Health Agency of Canada, 2013b).

## 2.4 NATURAL HAZARDS

Climate change is affecting extreme weather and climate events around the world (WMO, 2013) and is expected to make weather more variable, affecting the frequency, intensity, spatial extent, duration, and timing of these events (IPCC, 2012). The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012) notes that these changes can result in "unprecedented" extreme events that can have severe impacts on individuals and communities in both developed and developing countries. Projections suggest that Canada can expect an increase in the intensity of heavy rain events and storms, and in the occurrence of wildfires and droughts. Climate change is also expected to increase the frequency of extreme heat events in many Canadian communities (Lemmen et al., 2008; Seguin, 2008; Health Canada, 2011a) (*see* Chapter 2).

**CASE STUDY 1**

### DESCRIPTION OF USES OF MULTI-CRITERIA DECISION ANALYSIS (MCDA)

*(Source: Cox et al., 2012)*

Multi-criteria decision analysis is a powerful tool that allows integration of multiple considerations in risk-based decision making. In the context of the selection of surveillance and control methods for emerging infectious diseases, these considerations can include health and environmental impacts, performance, acceptability and cost-benefit. MCDA allows weighting of the importance of a given consideration to align with the needs and priorities of different jurisdictions and end users. It supports consensus-building among multiple jurisdictions and integrates public perception of risk with expert-driven analyses. MCDA also ensures that decisions are made in an open and transparent fashion, with due diligence applied to documented consultations with experts, stakeholders and end users. Officials with the Québec Public Health Program have tested this approach in the decision-making process for methods of surveillance for Lyme disease.

The Canadian Disaster Database (CDD) provides information on the frequency of disasters, including hydrometeorological disasters in Canada.[1] However, published literature documenting trends in the frequency of extreme weather events and the resulting impacts is scarce. There is limited surveillance of direct and indirect health impacts from extreme weather-related events in Canada, and data at the national level are often sparse and not systematically collected. The following sections discuss recent evidence related to the health impacts of extreme weather events which are projected to increase from climate change in Canada.

### 2.4.1 STORMS AND FLOODING

Canadians across the country can be vulnerable to the health impacts of thunderstorms and lightning, snow storms, freezing rain, tornadoes, hurricanes, and hailstorms – particularly when widespread power outages occur (Environment Canada, 2007) and where health, social, and emergency services are insufficiently robust to handle large or concurrent events (Berry, 2008). Recent evidence from the U.S. indicates that storms that produce wind damage

---

[1] Disasters are events that result in broad environmental, health or economic impacts that disrupt the everyday functioning of a community which may require the help of other partners for recovery (IPCC, 2012).

and flooding, such as hurricanes, are often associated with physical injuries sometimes causing death (Cretikos et al., 2007; Brunkard et al., 2008; Frumkin et al., 2008; English et al., 2009; Hess et al., 2009), drowning (the most common cause of death during Hurricane Katrina; Brunkard et al., 2008; Frumkin et al., 2008), the aggravation of chronic diseases (e.g. through lack of food and potable water; English et al., 2009; Hess et al., 2009; Bethel et al., 2011), hypothermia (Cretikos et al., 2007) and mental illness such as post-traumatic stress disorder (PTSD) (*see* Section 2.4.5). Storm events have also been associated with an exacerbation of heart conditions (English et al., 2009) and gastrointestinal illness resulting from the failure of refrigerators and freezers and the inability to prepare hot food (Cretikos et al., 2007). Rainstorms have been observed to worsen asthma symptoms (Hess et al., 2009).

Storms can also affect health through the disruption of medical care (Cretikos et al., 2007; Brunkard et al., 2008; Frumkin et al., 2008) and other social services due to building, infrastructure and medical vehicle damage, and effects on staff resulting from physical impacts (e.g. blocked roadways) or event-related stress (Cretikos et al., 2007). Hospitals, for example, may be affected directly (Cretikos et al., 2007; Brunkard et al., 2008; Clarke, 2009) and ongoing medical care such as routine laboratory testing, newborn screening, dialysis, provision of oxygen, and home intravenous therapy can be disrupted, putting patients at increased health risk (Cretikos et al., 2007; Frumkin et al., 2008). Many hospitals in Canada have limited capacity to deal with the surge in patients due to public health emergencies (Gomez et al., 2011).

An increase in freezing rain events has been observed and is expected to continue into the future (Ebi and Paulson, 2010; Cheng at al., 2011). Evidence from the U.S. suggests that the health effects of freezing rain can include slips and falls (Frumkin et al., 2008; Du et al., 2010), injury or illness resulting from critical infrastructure and building failure (Du et al., 2010; Auger et al., 2011), challenges regarding access to health care services (Auger et al., 2011), and an increase in motor vehicle accidents due to poor road conditions (Frumkin et al., 2008).

Cheng et al. (2011) project that days with freezing rain between December and February will increase from averaged historic conditions for Ontario communities by 35% to 100% for the period 2046-2065, and by 35% to155% for the period 2081-2100. The more northern the community, the greater the projected increase. For example, by 2046-2065, days with freezing rain are projected to increase by 35% to 55% for Toronto and Windsor, by 50% to 70% for Montreal and Ottawa, and by 70% to 100% for Kenora, Thunder Bay, and Timmins.

Cunderlik and Ouarda (2009) found evidence of increasing intensity of rainfall events between 1974-2003 in Canada as well as weak evidence that floods are occurring earlier in the year, particularly in southern Canada. The number of flood disasters has increased in Canada throughout the 20th century with about 70% occurring after 1959 (Laforce et al., 2011). Floods remain one of the costliest and most frequent types of natural disaster in Canada (Public Safety Canada, 2013a). Population growth, a continued trend of people settling on flood plains, and urbanization, which generally reduces the capacity of watersheds to absorb storm water run-off, are expected to exacerbate risks of floods. Studies of recent flood events have increased knowledge of primary and secondary (including mid-to-long term) impacts on health (*see* Table 3).

There are a number of ways in which climate change is expected to increase flooding, including earlier spring runoff (Bedsworth and Hanak, 2010), increasing storm surges (Bedsworth and Hanak, 2010) and increases in heavy precipitation (Cunderlik and Ouarda, 2009; DesJarlais and Blondlot, 2010; Ostry et al., 2010). Projections of future flood events in specific regions of Canada are limited. The City of Toronto recently completed a Climate Drivers Study that predicts significant increases in heavy rainstorms in the summer by 2040-2049 (City of Toronto, 2012). Flooding due to heavy rainfall in Southern Ontario (Grand, Humber, Rideau and Upper Thames River Basins) from April to November is expected to increase 10 to 35% by 2046-2065, and 35 to 50% by 2081-2100 (Cheng et al., 2011). Future flooding from climate change has also been identified as a key risk in British Columbia (Ostry et al., 2010) and in Quebec (DesJarlais and Blondlot, 2010).

| Primary Health Impacts from Floods | |
|---|---|
| Impact | Cause |
| Mortality | Drowning or acute trauma (e.g. debris or building collapse) (Acharya et al., 2007; Fundter et al., 2008; Jonkman et al., 2009), usually attributable to motor vehicle accidents or inappropriate behavior in flooded areas (e.g. swimming, surfing) (Haines et al., 2006; English et al., 2009; Du et al., 2010; Fitzgerald et al., 2010) |
| Shock, hypothermia | Exposure to floodwater which is often below human core body temperature (Acharya et al., 2007; Carroll et al., 2010; Du et al., 2010) |
| High blood pressure, heart attacks and strokes | Exertion and stress related to the event (Acharya et al., 2007; Jonkman et al., 2009; Carroll et al., 2010; Du et al., 2010) |
| Physical injuries such as lacerations, skin irritations, bruises, wound infections | Direct contact with flood water (Acharya et al., 2007; Fundter et al., 2008; Carroll et al., 2010; Du et al., 2010) |
| Infection, pulmonary swelling, lung irritation, fungal infection | Aspiration of water into lungs (Robinson et al., 2011) |
| Sprains, strains and orthopedic injuries | Contact with water-borne debris, attempts to escape from collapsed structures, falls from ladders, attempts to rescue people or possessions, etc. (Acharya et al., 2007; Fundter et al., 2008; Carroll et al., 2010; Du et al., 2010) |
| Electrical injuries | Contact with downed power cables/lines, circuits and electrical equipment in contact with standing water (Du et al., 2010) |
| Burns (fire-related or chemical) and explosion-related injuries | Disturbed propane and natural gas lines, tanks, power lines and chemical storage tanks; toxic gas emissions; rescue boats coming in to contact with power lines (Du et al., 2010) |

| Secondary Health Impacts from Floods | |
|---|---|
| Impact | Cause |
| Exacerbation of existing illnesses, including chronic diseases | Disruption/decreased availability of emergency and ongoing health services, especially if health infrastructure is affected, including: decreased ability to provide/access care; displacement of patients and staff; impaired surveillance of illness, injury, toxic exposure; loss of medical records; loss/impairment of medication and medical devices (Haines et al., 2006; Du et al., 2010; Ebi and Paulson, 2010) |
| Carbon monoxide poisoning | Inappropriate use of unventilated cooking tanks (e.g. barbeques), pressure washers and gas powered generators (Du et al., 2010) |
| Burns/smoke inhalation | House fires started by candles (Du et al., 2010) |
| Dehydration, heat stroke, heart attack, stroke | Exposure of vulnerable populations to environmental stresses in days following event (Jonkman et al., 2009) |
| Water- and food-borne diseases – upset stomach/gastrointestinal problems, infectious diseases with longer incubation periods including *Legionella pneumophila* (Marcheggiani et al., 2010) *Norovirus, Rotavirus, Hepatitis A* and *C* | Water and food contamination (e.g. from sewage overflows, flooding of agricultural areas and transport of sediment, fertilizers, pesticides, etc., leakage from tanks holding petroleum products, landfill materials)(Haines et al., 2006; Acharya et al., 2007; Du et al., 2010; Ebi and Paulson 2010; Ostry et al., 2010; ten Veldhuis et al., 2010), chemical contamination of water (e.g. from flooding of industrial sites) (Du et al., 2010) |
| Respiratory problems/symptoms | Respiratory contaminants from mold[2], bacteria[3], fungal growth on damp structures (Carroll et al., 2010; Du et al., 2010; Robinson et al., 2011; Taylor et al., 2011). Also, due to *Legionaella, Chlamydia, pneumonia, Burkholderia cepacia*, and *Mycobacterium avium* (Taylor et al., 2011) |

**TABLE 3:** Primary, secondary and mid- to long-term health impacts of floods.

---

[2] *Cladosporium, Aspergillus, Penicillium, Alternaria* and *Stachybotrys* have been observed in damp and flooded buildings (Taylor et al., 2011).

[3] *Streptomycetes, Caulobacter* and *Agrobacterium* have been observed (Taylor et al., 2011).

## 2.4.2 EXTREME HEAT

Internationally, recent events have demonstrated the catastrophic impacts that extreme heat can have on communities in developed countries (Robine et al., 2008; Barriopedro et al., 2011). Extreme heat events pose serious health risks to Canadians; for example, they are associated with sudden, short-term increases in mortality, especially among older adults, people who are chronically ill, people on certain medications and the socially disadvantaged (Kovats and Hajat, 2008; Hajat and Kosatsky, 2010; Kenny et al., 2010; CIHI, 2011; Health Canada, 2011a). A 2009 extreme heat event in British Columbia contributed to 156 excess deaths in the province's lower mainland area (Kosatsky, 2010) and in 2010 an extreme heat event in Quebec resulted in an excess of 280 deaths (Bustinza et al., 2013). The National Drowning Report (Drowning Prevention Research Centre Canada, 2011) suggests that increases in drowning deaths in 2005 (492 deaths), 2006 (508 deaths), and 2007 (480 deaths) are a departure from the long-term trend toward fewer fatalities from drowning and are partly due to the warmer and drier conditions in those years resulting in more people participating in aquatic activities.

Studies of the association between daily maximum temperatures and excess mortality in select Canadian cities (*see* Figure 6) indicate that high temperatures are a health risk. Latitude, elevation, proximity to bodies of water, urban heat islands, access to air conditioning, population demographics and local acclimatization, among other factors, influence how each city experiences a heat event and the severity of the health impacts (Martel at al., 2010). Some cities, including Toronto, ON, Windsor, ON and Winnipeg, MB have undertaken heat-health vulnerability assessments to inform the development or revision of heat alert and response systems (HARS) (Berry et al., 2011a; City of Toronto, 2011).

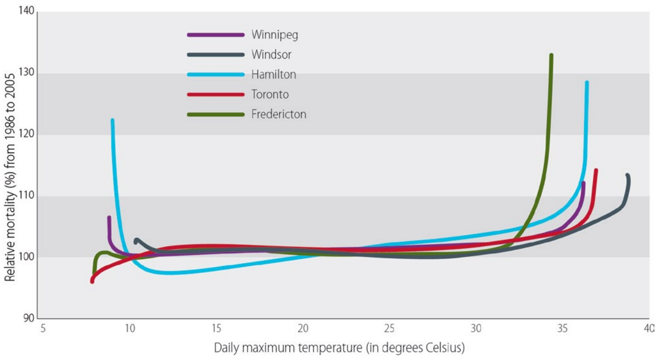


**FIGURE 6:** Relationship between daily maximum temperatures in June, July and August and all non-traumatic deaths for selected Canadian cities, 1986-2005 *(Source: Casati et al., in press)*.

Extreme heat can cause skin rashes, cramps, dehydration, syncope (fainting), exhaustion, and heat stroke. It can also exacerbate many pre-existing conditions such as cardiovascular, cerebrovascular and respiratory diseases, and neurological disorders (Kenny et al., 2010; Health Canada, 2011b; Lowe et al., 2011). These conditions are not normally coded as heat-related in the International Classification of Diseases (ICD); therefore, measures of the impact of extreme heat events on health are often underestimated (Kravchenko et al., 2013). Extreme heat events are associated with greater utilization of health care services (Vida et al., 2012; Anderson et al., 2013). In Toronto, a significant positive correlation was found between heat and utilization of emergency medical services for various groups of heat-related adverse health outcomes during the summer of 2009-2011 (Bassil, 2012). The 2010 extreme heat event in Quebec resulted in an extra 3400 emergency department admissions with significant variation among regions (Bustinza et al., 2013).

Canada can expect an increase in the length, frequency, and/or intensity of warm spells or heat waves; a 1-in-20 year hottest day is likely to become a 1-in-2 year event by the end of the 21st century (IPCC, 2012)[4]. Temperature projections indicate that the number of days with temperatures above 30°C in cities such as Toronto, ON, Winnipeg, MB and Windsor, ON (*see* Figure 7) are expected to double between 2011-2040 and 2071-2100. In many communities, the projected increase in warm nights will limit nighttime relief from the heat (Health Canada, 2012c). Ebi and Mills (2013) suggest that heat-related mortality associated with warmer temperatures from climate change is likely to be higher than reductions in cold-related mortality.

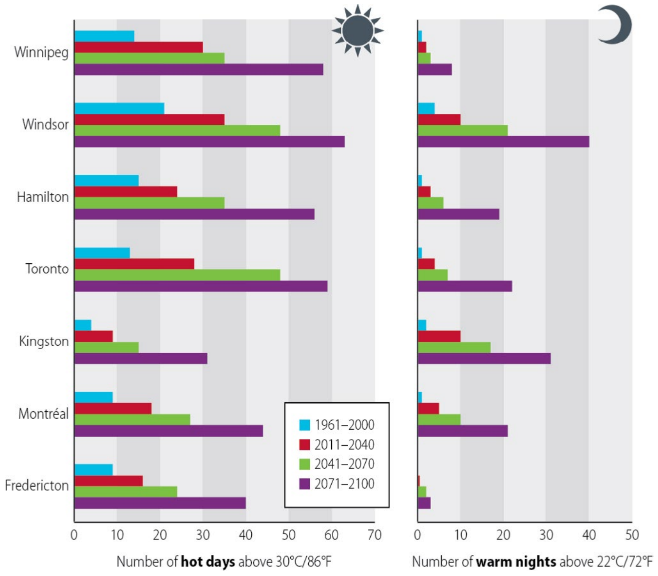


**FIGURE 7:** Historical and projected number of hot days and warm nights for selected cities in Canada *(Source: Casati and Yagouti, 2010)*.

---

[4] Based on the A1B and A2 emissions scenarios (IPCC, 2012)

## 2.4.3 WILDFIRES

Wildfires or forest fires are a common occurrence across Canada (*see* Chapter 3 – Natural Resources) and present risks to thousands of private homes and businesses (Seguin, 2008). On average, 5500 people are evacuated from 10 communities, and twenty communities with a total of 70 000 people are threatened by large fires in Canada each year (Flannigan and Wotton, 2010) (*see* Case Study 2).

Immediate health consequences of wildfires include increased respiratory complaints (Künzli et al., 2006; Moore et al., 2006; Bambrick et al., 2011) such as smoke inhalation, respiratory tract burns and injury, and impaired oxygenation (Hess et al., 2009; Robinson et al., 2011; Johnston et al., 2012). Other health impacts such as radiant heat injury, dehydration and heat exhaustion (Johnston, 2009) have been reported with overall increases in mortality (Künzli et al., 2006; Johnston, 2009). Wildfires are also often associated with increased physician and emergency room visits (Henderson et al., 2011), reduced access to health and community services, and health concerns associated with emergency/temporary shelters (Johnston, 2009). Mid- to long-term health impacts of wildfires may include mental exhaustion, anxiety, depression and post-traumatic stress disorder (PTSD) related to loss of friends, relatives, homes and livelihoods (Johnston, 2009; Ostry et al., 2010). Significant challenges may arise for health and emergency services when whole communities are affected by wildfires and need to be evacuated.

Wildfires can significantly impact air quality in nearby communities and also contribute to the long-range transport of pollutants in North America (Committee on the Significance of International Transport of Air Pollutants, 2009). This may exacerbate chronic diseases such as asthma (especially in children), COPD, ischaemic heart disease, and other chronic lung diseases leading to increased hospital admission rates (Künzli et al., 2006; Johnston, 2009; Robinson et al., 2011). Increased rates of infant mortality have also been associated with wildfires due to an increased risk of cardiovascular and respiratory mortality (Robinson et al., 2011). Wildfires in Canada have affected air quality in the past; average levels of $PM_{2.5}$ in 2010 in Canada exceeded those of 2009 by 24% due to wildfires in British Columbia, Saskatchewan and Quebec (Environment Canada, 2012b). There is an expected increase in wildfires in much of Canada's forest cover due to projected increases in temperature and seasonal reductions in precipitation (Flannigan et al., 2009; Bambrick et al., 2011; *see also* Chapter 3 – Natural Resources).

**CASE STUDY 2**

### HEALTH IMPACTS OF FOREST FIRES IN NORTHERN ONTARIO, JULY 2011

On July 6, 2011, a lightning storm sparked a series of forest fires that rapidly spread across northwestern Ontario, lasting from July 6 to 23 (120 fires were reported on July 20). Many First Nations communities were directly threatened by the fires and those at increased risk of suffering from smoke inhalation were ordered to evacuate, as were communities suffering from power outages, food shortages, and a lack of food storage capacity (Public Safety Canada, 2013a). In total, 3292 people were evacuated from 8 First Nations communities (Public Safety Canada, 2013a), in addition to the entire communities of Keewaywin and Koocheching First Nations. Residents were relocated to 14 communities as far away as Southern Ontario and Manitoba.

## 2.4.4 DROUGHT

Droughts can have significant impacts on human health (Wheaton et al., 2008) by lowering groundwater levels and streamflows, increasing wind erosion of soils, and causing cracking of cisterns and septic tanks, creating the potential for increased sediment levels in water. They can also result in an increase in water-borne pathogens and water contamination (English et al., 2009; Ostry et al., 2010; Wittrock et al., 2011) leading to gastroenteritis (US CDC et al., 2010). Certain vector-borne diseases may spread more easily during periods of drought (Frumkin et al., 2008) and health can be impacted through wind erosion and dust storms (Wheaton et al., 2008). Droughts can decrease agricultural and crop production (Wheaton et al., 2008; *see* Chapter 4 – Food Production) leading to suboptimal nutrition due to food shortages, lack of food availability, and high costs (Horton et al., 2010), particularly for low income people and those relying on fishing or agriculture for their livelihoods (US CDC et al., 2010). Increased stress and mental health issues, particularly among farmers, have been linked to drought conditions (US CDC et al., 2010; Polain et al., 2011; Wittrock et al., 2011). Summer continental interior drying, drought risk and areas impacted by drought are all projected to increase in Canada (Wheaton et al., 2008; Wittrock et al., 2011, *see also* Chapter 4 – Food Production).

### 2.4.5 PSYCHOSOCIAL AND MENTAL HEALTH IMPACTS

An increase in the frequency, severity, and duration of extreme weather may adversely affect mental health, creating psychosocial impacts (Fritze et al., 2008; Berry et al., 2009; Kjellstrom and Weaver, 2009; Vida et al., 2012). The term "psychosocial" relates to the psychological, social and livelihood aspects of an individual's life, and acknowledges the interplay and co-dependencies that exist between individual and community well-being. Natural hazards can affect psychosocial and mental health by exposing people to distressing conditions and events that influence their physical health (e.g. asthmatic attacks triggered by forest fire smoke; injury from flying debris; disruption of medical care) (Brunkard et al., 2008; Auger et al., 2011). They may also negatively affect mental health and stress levels through, for example, the disruption of daily life and livelihoods as a result of evacuations and limited access to medical services (Bethel et al., 2011). Similarly, such impacts may result from alterations in the natural and social environment (e.g. loss of sense of place and belonging through extensive damage to community spaces and altered patterns of social interaction) (Higginbotham et al., 2007). The causal pathways by which climate change affects mental health are depicted in Figure 8.

Symptoms of psychosocial impacts from an extreme weather event or disaster may take various forms such as alterations in mood, thoughts, behaviour, an increased level of distress, and a reduction of one's ability to function in everyday life (Berry et al., 2008a). Disaster-induced cognitive and emotional issues may manifest in the form of concentration and memory loss, learning disorders, anxiety, acute stress disorders, PTSD, depression, sleep difficulties, aggression, substance abuse, and high risk behaviour in adolescents (Somasundaram and Van De Put, 2006; Boon et al., 2011).

Numerous studies have examined the relationship between specific natural hazards and negative mental health outcomes (Salcioglu et al., 2007), including drought (US CDC et al., 2010; Polain et al., 2011; Wittrock et al., 2011), heat waves (Nitschke et al., 2007; Hanson et al., 2008; Bambrick et al., 2011), wild fires (Johnston, 2009; Ostry et al., 2010), storms and hurricanes (Cretikos et al., 2007; Bethel et al., 2011; Boon et al., 2011), and ice and snow (Auger et al., 2011). Floods, for example, have been associated with a range of mental health problems, including PTSD (Adhern et al., 2005; Acharya et al., 2007; Carroll et al., 2009; Ebi and Paulson, 2010; Carnie et al., 2011), increased social disruption, violent behaviour (e.g. assaults) and substance abuse (Ebi and Paulson, 2010), and increased suicide risk (Du et al., 2010).

Knowledge of effective measures to reduce psychosocial impacts from extreme weather events and disasters has increased (Berry et al., 2009; Clarke, 2009). For example, a number of lessons were gained as a result of responding to and recovering from the unprecedented flood that impacted the province of Manitoba in 2011 (*see* Case Study 3).

## 2.5 ULTRAVIOLET RADIATION

Ambient ultraviolet radiation (UVR) levels vary with geographic location, season, time of day, altitude, cloud cover, and atmospheric pollution (Thomas et al., 2012). A range of short-term health effects (e.g. DNA damage, immune suppression) (Norval and Halliday, 2011; Thomas et al., 2012) and long-term health effects (e.g. skin cancer, cataracts) (de Albuquerque Alves, 2011; Thomas et al., 2012) have been associated with UVR exposures, along with some benefits (e.g. production of vitamin D) (Dixon et al., 2012). It was estimated that 81 000 cases of non-melanoma and 5 800 new cases of melanoma skin cancer would occur in Canada in 2012 (Canadian Cancer Society, 2012).

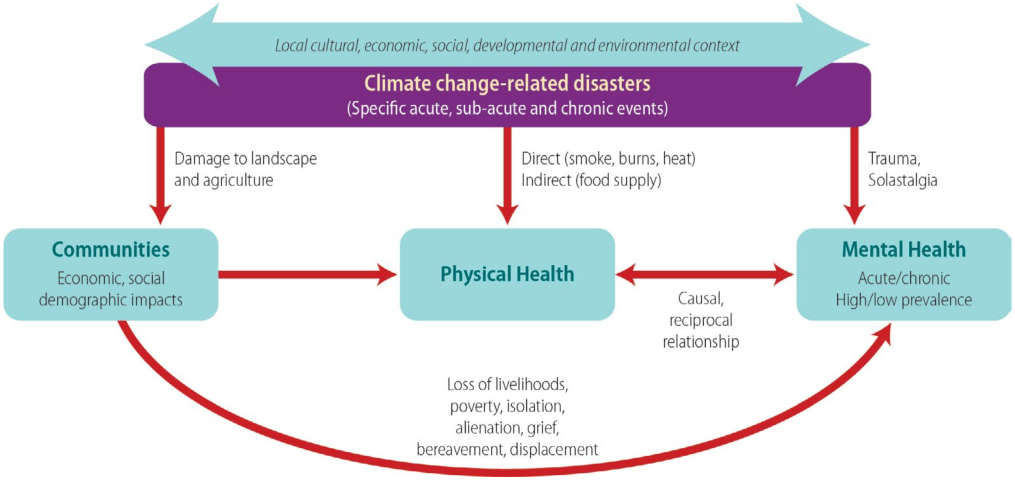


**FIGURE 8:** Framework showing the causal pathway linking climate change and mental health *(Source: Berry et al., 2009)*.

CASE STUDY 3

## MANITOBA FLOOD 2011: IMPETUS FOR A PROVINCIAL APPROACH TO PSYCHOSOCIAL ADAPTATION TO NATURAL HAZARDS

The 2011 flood in Manitoba lasted roughly four months, and many small communities, including a large number of First Nations, were evacuated for varying lengths of time. Some 1932 people remained displaced eighteen months later, and a proportion of evacuees are unlikely to ever return to their homes. Psychosocial impacts identified among individuals and families included increases in alcohol and drug use and family violence, along with other general symptoms of high levels of stress such as depression, anxiety, sleep disruption, and an increase in physical ailments (pers. comms., Gerry Delorme).

Manitoba Health's Office of Disaster Management worked with provincial emergency social services to identify and map locations and communities where psychosocial impacts were anticipated to be greatest. Key organizations (e.g. Emergency Social Services, Emergency Measures Organization, Aboriginal Affairs and Northern Development Canada, Manitoba Agriculture, Food and Rural Initiatives, Manitoba Family and Rural Support Services, Conservation and Water Stewardship) quickly established a *Provincial Psychosocial 2011 Flood Recovery Table* which formalized a structure for planning and response, and provided the leadership and funding required to address the multiple scales of psychosocial impacts (individual, community and provincial). Four regional recovery teams of 3 to 4 staff members were deployed to the most severely impacted areas of the province. Through this experience, the following challenges and lessons learned were identified:

- *Leadership* – Effective responses to the flood event required both centralized coordinated leadership and community-based actions.
- *Building capacity to address psychosocial impacts* – Psychosocial considerations must be routinely included in risk assessment and disaster management planning and response.
- *Tailoring communication and messaging* – Communications staff should be cognizant of, and trained in, the psychosocial aspects of messaging to affected citizens so as to reduce, rather than attenuate distress.
- *At-risk populations* – The most vulnerable people suffered disproportionately from psychosocial and other health impacts (e.g. elderly people, children, those with chronic medical conditions, the poor, and First Nations communities). More specific planning is required to identify and enhance the capacity of these people.
- *Psychosocial impacts and response personnel* – Emergency responders, psychosocial recovery workers, and decision makers suffered from psychosocial impacts, ranging from fatigue to extreme stress reactions. Targeted psychosocial support is required for health care workers, emergency management and other responders during an event.
- *Evaluating responses* – Evaluating the success of psychosocial interventions was limited by the capacity to plan for and collect data in the midst of response and recovery activities.

The flood of 2011 highlighted the need to plan more effectively to address the psychosocial impacts of climate-related events and disasters. As a result of the flood, a *Provincial Interagency Psychosocial Planning Table* (per comms. Gerry Delorme) has been established to increase the provincial capacity to respond to future disasters.

Warmer temperatures associated with climate change may result in increased exposure by the population to UVR in Canada due to higher levels of ambient UVR along with changes in human behaviour (e.g. more outdoor activities, limited use of personal protective measures) (Thomas et al., 2012). The Canadian National Sun Survey conducted in 2006 revealed that children aged one to 12 years use regular sun protection infrequently and heavily rely on sunscreen, indicating that other measures such as seeking shade and wearing protective clothing need to be promoted (Pichora and Marrett, 2010).

Ozone depletion has stabilized and started to recover since the 1990s (Bais, 2011; WMO, 2011). Recent projections of erythemally-weighted solar irradiance (UV-Ery) – a widely used metric to describe "sunburning" properties of UVR that is directly proportional to the UV Index – suggest that by the 2090s UV-Ery will be approximately 12% lower at high altitudes, 3% lower at mid-latitudes and 1% higher at the tropics (Bais, 2011). The projected values take climate change into consideration and are dependent on an increase in cloud cover at high latitudes and full recovery of column ozone,[5] which absorbs the UV-B band known for its negative health effects. Other projections suggest that under a clear-sky scenario, by 2095 the UV Index will decrease by 9% in northern high latitudes, increase by 4% in the tropics, and increase by up to 20% in southern high latitudes in late spring and early summer (Hegglin and Shepherd, 2009). Many uncertainties exist about projected levels of UVR and its spectral composition because of uncertainties associated with future levels of precipitation, cloud cover, aerosols, and loss of snow and sea ice (Thomas et al., 2012). Recent animal models demonstrate that an increase in temperature could increase UVR-induced carcinogenesis (van der Leun et al., 2008). However, predicting how climatic changes will affect UVR-related health impacts remains a challenge.

---

[5] The effects of climate change on ground-level ozone are discussed in Section 2.1.

# 3. REGIONAL AND COMMUNITY VULNERABILITIES

Exposure to climatic events that can affect health is highly dependent on geography, topography, and land use. Health impacts resulting from climate and weather-related exposures are either modulated or compounded by population sensitivities and adaptive capacity at sub-regional, local, and individual levels (Berry, 2008). Canadian communities and regions differ greatly in terms of key vulnerability factors that underpin threats to health from climate change. Urban, rural, coastal and northern communities have unique attributes that make them differentially vulnerable to health impacts. The availability of health, weather, climate, and socio-economic data is not uniform across the country which makes measurement and comparison of regional climate change health risks and vulnerabilities challenging. Some examples of regional variations in health risks and vulnerabilities are presented in Table 4.

| Climate Risk Category | Examples of Regions At Highest Risk | Examples of Climate-related Risk Factors and Health Impacts |
|---|---|---|
| Extreme Temperatures | **Extreme Heat**<br>Windsor to Quebec corridor (e.g. Windsor, Hamilton, Toronto, Kingston, Montreal), regions along Lake Erie, Lake Ontario and St. Lawrence River, Prairies (e.g. Winnipeg), Atlantic Canada (e.g. Fredericton) and British Columbia (e.g. Vancouver)<br>**Extreme Cold**<br>Arctic, Prairies, Ontario, eastern Canada | More frequent and severe heat waves and longer periods of warmer weather, possible colder conditions in some locations<br>Increase in annual heat-related mortality in Quebec projected for 2020, 2050 and 2080 to be 150, 550, and 1400 excess annual deaths respectively, based on mean temperature increase[6] |
| Extreme Weather Events and Natural Hazards | **Thunderstorms, Lightning, Tornadoes, Hailstorms**<br>Canada wide, low-lying areas of southern Canada, Saskatchewan, Manitoba , Nova Scotia, Ontario, Quebec, Alberta<br>**Freezing Rain , Winter Storms**<br>Atlantic Canada, Ontario, southern Saskatchewan, southern and northwestern Alberta, southwestern interior British Columbia<br>**Hurricanes, Storm Surges, Sea-Level Rise**<br>Eastern Canada (particularly Atlantic Canada), Arctic, British Columbia<br>**Mud-Rock and Landslides, Debris Flows, Avalanches**<br>Rocky Mountains, Alberta, British Columbia, Yukon, southern and northeastern Quebec and Labrador, Atlantic coastline, Great Lakes, St. Lawrence shorelines<br>**Floods**<br>New Brunswick, southern Ontario, southern Quebec and Manitoba<br>**Drought**<br>Prairies, southern Canada<br>**Wildfires**<br>Ontario, Quebec, Manitoba, Saskatchewan, British Columbia, Northwest Territories, Yukon | More frequent and violent extreme weather events, land-shifts, rising sea levels, increased floods, drought and wildfires<br>In January 2012, a freezing rain event in Montreal resulted in 50 road accidents that included 1 fatality[7] and followed a similar event a few weeks earlier which led to several traffic accidents, hospitalizations and road closures[8]<br>Between 2003 and 2011, there were 60 extreme flood events in Canada which resulted in the evacuation of 44 255 people. A June 2012 flood event in British Columbia resulted in 1 fatality, at least 350 evacuations, treacherous travel conditions and road closures[9]<br>34 wildfires occurred from 2003-2011 resulting in 113 996 evacuations, and in one event, 2 fatalities[10]; wildfires in Kelowna BC in 2003 were implicated in increased physician visits for respiratory disease up to 78% relative to previous years[11] |

*Table 4 continued on next page*

---

[6] Gosselin, P., Belanger, D., and Doyan, B. (2008b): Health impacts of climate change in Quebec; *in* Human health in a changing climate: A Canadian assessment of vulnerabilities and adaptive capacity; Health Canada, Ottawa, Ontario.

[7] CBC News (2012). Snow, freezing rain causes accidents across Quebec. Accessed on August 21, 2012 from: <http://www.cbc.ca/news/canada/montreal/story/2012/01/13/weather-montreal.html>

[8] CBC News (2012). Freezing rain causes havoc on Montreal roads. Accessed on August 21, 2012 from: <http://www.cbc.ca/news/canada/montreal/story/2011/12/21/freezin-rain-causes-accidents-in-montreal.html>

[9] CBC News (2012). Deadly B.C. flooding prompts more evacuations, highway closures. Accessed on August 21, 2012 from: <http://www.theglobeandmail.com/news/british-columbia/deadly-bc-flooding-prompts-more-evacuations-highway-closures/article4368207/>

[10] Public Safety Canada (PSC) (2012). The Canadian Disaster Database. Retrieved August 19, 2012 from: <http://www.publicsafety.gc.ca/prg/em/cdd/index-eng.aspx>

[11] Ostry A. et al. (2010). Climate change and health in British Columbia: Projected impacts and a proposed agenda for adaptation research and policy. International Journal of Environmental Research and Public Health, v. 7, no. 3, p. 1018-1035

| | | |
|---|---|---|
| Air Quality | **Outdoor Air Pollutants (Ozone and Particulate Matter)**<br>Ontario (Great Lakes Region), particularly urban areas of southern Ontario (Toronto), southern Quebec (e.g. Montreal) British Columbia (Vancouver, Lower Fraser Valley), Alberta (Calgary, Edmonton, Fort McMurray) and Manitoba (Winnipeg)<br>**Aeroallergens (Ragweed) and Fungal Pathogens**<br>Southern Quebec and southern Ontario, central and southern Saskatchewan (e.g. Saskatoon) and Manitoba (e.g. Winnipeg), British Columbia | Higher ground-level ozone levels, airborne dust, increased production of pollens and spores by plants<br>Increased average temperature in Canada could lead to an increase in ozone concentration and could result in an overall increase of 312 premature deaths.[12]<br>On the Island of Montreal, nearly 40 000 children suffer from ragweed-related allergic reactions[13] |
| Contamination of Food and Water and Food Security | **Water Contamination**<br>Canada wide, marine or freshwater coastal regions or watersheds vulnerable to sea-level rise and/or exposure to toxic or pathogenic surface run-off (West Coast, East Coast, Arctic, Great Lakes), regions that are vulnerable to drought (e.g. Prairies), overland flow or flooding leading to surface or groundwater contamination (e.g. rural agricultural areas, urban centers)<br>**Food Contamination**<br>Canada wide, agricultural regions (e.g. Prairies, Ontario, Quebec), regions with communities that are vulnerable to power outages and heat waves (e.g. urban centers such as Toronto), are exposed to toxic marine biota (coastal regions of British Columbia and Atlantic Provinces), are reliant on outdoor cold temperatures for food storage (e.g. Arctic)<br>**Food Security**<br>Arctic and agricultural regions | Contamination of drinking and recreational water due to run-off from heavy rainfall, and coastal algal blooms in coastal regions<br>4 million people suffer from food-related illnesses each year in Canada[14]; 7 provinces were implicated in the 2008 Canadian listeriosis outbreak that, of the 57 confirmed cases, lead to 23 deaths (75% occurring in Ontario)[15]<br>In 2006, 30% of Inuit children in Canada had experienced hunger at some point because the family had run out of food or money to buy food[16]. In 2007-2008, 9.7% of Canadian households with children experienced food insecurity[17] |
| Infectious Diseases Transmitted by Insects, Ticks and Rodents | **Lyme Disease**<br>Southern and southeastern Quebec, southern and eastern Ontario, and southeastern Manitoba, New Brunswick and Nova Scotia, southern British Columbia<br>**West Nile Virus**<br>Urban and semi urban areas of southern Quebec and southern Ontario, rural populations in the Prairies, rural and semi-urban areas of British Columbia<br>**Eastern Equine Encephalitis**<br>From Ontario to Nova Scotia<br>**Rodent-borne Diseases (e.g. Hantavirus)**<br>British Columbia, Alberta, Saskatchewan and Manitoba, Northwest Territories, Ontario, Quebec | Changes in the biology and ecology of various disease-carrying insects, ticks and rodents, faster maturation for pathogens within insect vectors and longer disease transmission season<br>Range expansion of the tick vector for Lyme disease is expected in the coming decade at an increased rate with climate change; this is expected to increase human Lyme disease risk, particularly in eastern Canada[18] |
| Stratospheric Ozone Depletion | Canada wide, in particular regions: at high altitudes; with highly reflective surfaces (e.g. Arctic); with limited natural or built-form shade or air particulates (i.e. smog) that may block UV radiation (e.g. rural areas), in southern Canada (i.e. lower latitude regions closer to the equator) | Increased human exposure to UV radiation owing to behavioural changes resulting from a warmer climate<br>In 2008, the estimated number of new cases of non-melanoma skin cancer among men was 40 000 and 33 000 among women. The estimated number of deaths was 160 among men and 100 among women in that year[19] |

**TABLE 4:** Regional variations in climate change health risks and impacts *(Sources: Lemmen et al., 2008; Seguin, 2008; ICLR, 2012; Public Safety Canada, 2013a)*.

---

[12] Lamy, S., and Bouchet, V. (2008): Air quality, climate change and health; in Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity; Health Canada, Ottawa, Ontario.

[13] See<http://www.santemontreal.qc.ca/en/healthy-living/healthy-environment/ragweed/>

[14] Thomas, M. K., Murray, R., Flockhart, L., Pintar, K., Pollari, F., Fazil, A., Nesbitt, A and Marshall, B. (2013). Estimates of the burden of foodborne illness in Canada for 30 specified pathogens and unspecified agents, Circa 2006. Foodborne Pathogens and Disease. July 2013, 10(7): 639-648 < http://www.phac-aspc.gc.ca/efwd-emoha/efbi-emoa-eng.php>

[15] Public Health Agency of Canada (2013): Evaluation of food-borne enteric illness prevention, detection and response activities at the Public Health Agency of Canada. <http://www.phac-aspc.gc.ca/about_apropos/evaluation/reports-rapports/2011-2012/feipdra-pdimeoa/app-ann-c-eng.php>

[16] Meakin, S. and Kurvits, T. (2009): Assessing the impacts of climate change on food security in the Canadian Arctic; <http://www.grida.no/files/publications/foodsec_updt_LA_lo.pdf>

[17] Health Canada (2013): Household Food Insecurity In Canada in 2007-2008: Key Statistics and Graphics; <http://www.hc-sc.gc.ca/fn-an/surveill/nutrition/commun/insecurit/key-stats-cles-2007-2008-eng.php#b>

[18] Leighton, P. et al. (2012): Predicting the speed of tick invasion: an empirical model of range expansion for the Lyme disease vector Ixodes scapularis in Canada, v. 49, no. 2, p 457-464.

[19] Public Health Agency of Canada (2013): Non Melanoma Skin Cancer; <http://www.phac-aspc.gc.ca/cd-mc/cancer/non_melanoma_skin_cancer-cancer_peau_non_melanique-eng.php>

The following sections discuss populations at higher risk to the health impacts of climate change and regional-level vulnerability factors important for planning and implementing adaptations to protect health.

## 3.1 VULNERABLE POPULATIONS

All Canadians are at risk from the health impacts of climate change. However, seniors, children and infants, the socially and economically disadvantaged, those with chronic diseases and compromised immune systems, Aboriginal people, and residents of northern and remote communities have been identified as being more vulnerable (Lemmen et al., 2008; Seguin, 2008; Bernstein and Myers, 2011). Evidence supports earlier findings that people with existing respiratory conditions are more vulnerable to air pollution and that seniors (Frumkin et al., 2008; Balbus and Malina, 2009) and children (Frumkin et al., 2008; Ebi and Paulson, 2010) are at higher risk from extreme heat events. Individuals who rely on untreated water systems may also be at higher risk from extreme weather events (both heavy rainfall and drought).

Climate change also poses special challenges to the health of Aboriginal populations and residents of northern and remote communities due to impacts on traditional food sources and diets, their dependence on the land, reliance on reasonably predictable and stable weather patterns and cultural impacts (Furgal and Seguin, 2006; Furgal, 2008; Ford et al., 2010a). Aboriginal Canadians living in the North, on reserve in southern communities and off reserve may be differently impacted by climate change. Research on the vulnerabilities faced by Aboriginal people in southern communities is sparse and further research is needed to inform adaptation actions.

Studies of the health impacts of extreme weather events (*see* Section 2.4) confirm that some groups are more impacted by these events and expand knowledge on the nature of existing vulnerabilities (Costello et al., 2009; IPCC, 2012; WHO, 2012b). For example, recent evidence suggests that seniors are more vulnerable to storms and floods because they are less likely to leave their homes in an emergency due to prior experience with false alarms, fear that their homes will be looted, or of the possible disruption of medical or other routines (Brunkard et al., 2008). In addition, people with lower socioeconomic standing who have poor quality housing, an inability to replace damaged property (e.g. lack insurance), and less access to legal and other services often suffer greater impacts from floods (English et al., 2009; Carroll et al., 2010). Home renters are less likely to be prepared for emergencies and have been found to be more vulnerable to flood events (Coulston and Deeny, 2010). There is also growing recognition of the heightened vulnerability of people whose job it is to help those in distress during emergencies, including support workers (Carroll et al., 2010), police and first responders (Neria et al., 2008), and health care and social service providers (Hess et al., 2009; Health Canada, 2011b).

Protecting the most vulnerable in society from climate change requires understanding individual sensitivity and exposure to current hazards, adaptation challenges (*see* Table 5) and knowledge of, and ability to communicate with, the most vulnerable populations (Maibach et al., 2011).

Innovative ways have been developed to locate vulnerable populations before and during emergencies and disasters so that they can be assisted. Bernier et al. (2009) used spatial online analytical processing (SOLAP) to investigate climate change and health vulnerability data in Québec City. SOLAP allows decision makers to combine the spatial views of geographic information systems (GIS) with complex and temporal analysis needed to understand and adapt to climate change impacts on health (Bernier et al., 2009). The City of Toronto has developed heat vulnerability maps (*see* Figure 9) to assist in the implementation of their heat alert and response system by, for example, providing information to ambulance services to prepare for heat alert days, supporting targeted door-to-door outreach to assist people in need, informing the creation of heat registries and identifying the best locations for cooling centres (Toronto Public Health, 2011a).

| Heat-Vulnerable Groups | Examples of Challenges |
|---|---|
| Older adults | • Physiological characteristics that may contribute to increased vulnerability to heat:<br>  • reduced thirst sensation<br>  • reduced fitness level<br>  • reduced sweating ability<br>  • increased susceptibility to chronic dehydration<br>• Visual, cognitive, and hearing impairments<br>• Agility and mobility challenges<br>• Differing perceptions of risks and vulnerabilities based on life experiences<br>• Reduced literacy<br>• Social isolation |
| Infants and young children | • Physiological and behavioural characteristics that may contribute to increased vulnerability to heat:<br>  • increased body heat production during physical activity<br>  • faster heat gain from the environment if air temperature is greater than skin temperature due to greater surface-area-to-body-weight ratio<br>  • inability to increase cardiac output<br>  • reduced sweating<br>• Dependence on caregiver to recognize heat impacts and take recommended actions |
| Socially disadvantaged individuals and communities:<br>• Low income<br>• Homeless<br>• Living alone | • Limited financial resources to adequately take protective actions<br>• Reduced access to clean water and cool places<br>• Limited access to health care and social services<br>• More environmental exposures (e.g. homeless, living on higher floors with no air conditioning)<br>• Higher rates of alcohol and drug dependency<br>• Social isolation |

**TABLE 5:** Examples of heat-vulnerable groups and challenges they may face in adapting to extreme heat events *(Source: Adapted from Health Canada, 2012c)*.

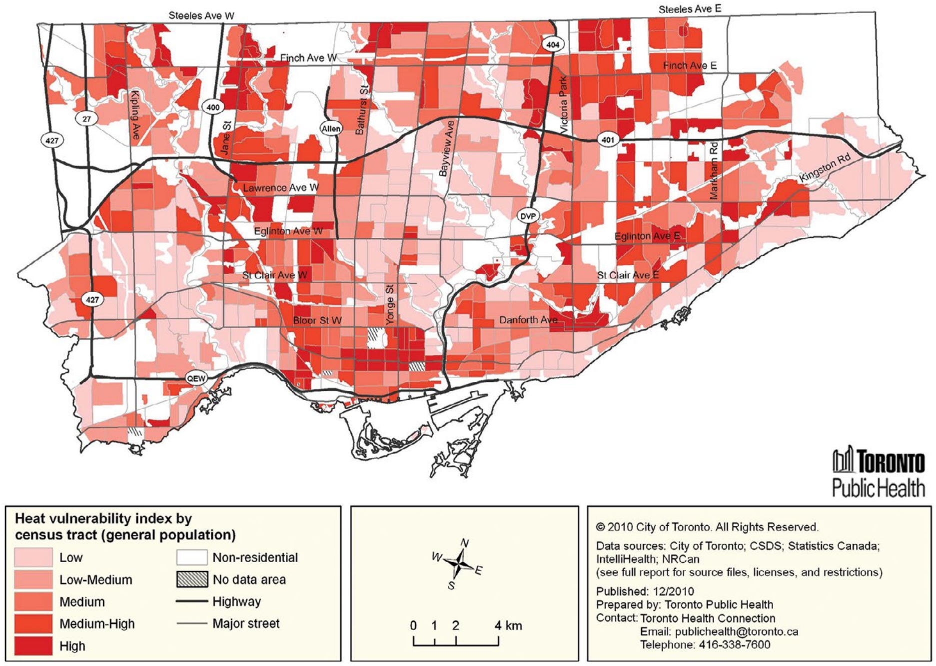


**FIGURE 9:** Vulnerability to heat in Toronto *(Source: Toronto Public Health, 2011a)*.

## 3.2 URBAN AND RURAL COMMUNITIES

Urban Canada has unique vulnerability attributes that predispose residents to health impacts from specific climate-related hazards; for example, large-scale population exposure to extreme heat and air pollution due to high population densities and the nature of the built environment. Cities have a high proportion of heat-retaining asphalt, high density living, tall towers, and limited green-space, which makes urban centres vulnerable to extreme heat events (Hess et al., 2009; Ostry et al., 2010; Bambrick et al., 2011; Gabriel and Endlicher, 2011; Huang et al., 2011a; Toronto Public Health, 2011a). Some Canadian cities are taking action to reduce climate-related health risks. For example, Montreal has implemented measures to reduce the urban heat island through regulations for newly constructed and renovated roofs and by developing green spaces to reduce solar reflectivity and heat retention in urban areas (Marsden, 2011).

Flood risks are increased in cities because water flows more rapidly on land that has been built over. Storms can lead to damaged or flooded roadways, combined sewer system overflows and floods in buildings, all of which can result in unsafe transport conditions, compromised critical infrastructure, and poor indoor air quality (Rosenzweig et al., 2011). Risks are higher in cities with drainage systems (e.g. combined sewer overflow systems) that are not adapted accordingly (McGranahan et al., 2007). Exposure to multiple extreme weather events occurring at the same time and in the same location may result in cumulative impacts that increase risks to health. During the summer of 2012 in the United States, very hot temperatures, drought conditions and stormy weather buckled highways, softened airport runways, kinked railway tracks, affected nuclear facilities due to warming of cooling water, and downed power lines, knocking out power to millions of people (Wald and Schwartz, 2012).

In rural regions where livelihoods are closely tied to natural resources, climate change may contribute to economic decline, social disruption, population displacement and/or similar challenges (Battisti and Naylor, 2009; Friel et al., 2009; Holden, 2009; McLeman et al., 2011; Clarke, 2012). Rural communities may be more exposed to certain types of extreme weather events and/or have more limited response capacity or access to services that help protect people (Berry, 2008; Ostry et al., 2010). For example, there is an increased risk of wildfires and floods in parts of western Canada affected by the Mountain Pine Beetle, which could have significant health implications for people living in these rural areas (Ostry et al., 2010). Evidence also suggests that flooded farmlands and surface run-off can contaminate local water sources and create health risks for populations located around or downstream of agriculture feedlots (Haines et al., 2006; Acharya et al., 2007). Fecal-oral cycling in such situations poses health risks to farmers, farm workers, farm families, and outdoor workers (Acharya et al., 2007; Du et al., 2010). In general, communities dependent on small and private drinking water systems that service populations of 5000 or less may be more vulnerable to water-borne disease outbreaks (Moffatt and Struck, 2011).

The capacity of rural populations to respond to climate change is influenced by unique sensitivities related to reductions in public services, changing demographics and dependency on natural resources (Wall and Marzall, 2006). Relative strengths relating to capacity include the social capital, networks and diverse skill sets of rural communities (Clarke, 2012). Table 6 highlights some of the health vulnerability risk factors stemming from climate change and climate-related impacts that can be prevalent in rural and urban communities.

| Key Vulnerability Factors | Examples of Urban Characteristics | Examples of Rural Characteristics |
|---|---|---|
| Exposure<br>• Geography<br>• Land use<br>• Climate | • Complex infrastructure, high density buildings and landscape dominated by impervious surfaces<br>• Higher population density<br>• Higher air pollutant levels | • Increased health risks from water contamination due to a high reliance on small drinking water systems<br>• More people employed in outdoor occupations<br>• Higher risk of exposure to land-shifts, wildfires, vector borne diseases and floods |
| Individual Sensitivity<br>• Age and Gender<br>• Health status | • Ageing population<br>• Cardiovascular and respiratory conditions in large urban centers from air pollution and extreme heat | • High elderly population and high incidence of chronic illnesses, smoking and obesity |
| Key Adaptive Capacity Factors<br>• Socio-economic status<br>• Public services and risk communication programs<br>• Employment | • Greater prevalence of high risk population groups, with limited adaptive capacity (e.g. low socio-economic status)<br>• Higher prevalence of social isolation and limited access to services (e.g. immigrants, First Nations, homeless or persons of low income or with mental illnesses)<br>• High reliance on critical infrastructure for health care and emergency service provision that are vulnerable to extreme weather | • Limited access to services during extreme events (e.g. power, water, food, medical)<br>• Limited availability and accessibility of public services and programs and communication venues to deliver health and emergency messages<br>• High dependency on natural resources that are vulnerable to disruption from extreme weather<br>• Lower proportion of population highly educated<br>• Limited livelihood and economic diversification<br>• Limited resources and services to respond to extreme weather events and associated health burdens<br>• Limited service access in remote communities |

**TABLE 6:** Urban and rural characteristics that increase vulnerability to climate change and climate-related impacts.

## 3.3 ABORIGINAL AND NORTHERN COMMUNITIES

Climate change impacts contribute to transformative social, ecological, and economic changes in Canada's north and present significant health risks to Aboriginal communities (Parkinson 2010a,b; Downing and Ceurrier, 2011; Rylander et al., 2011; The Aspen Institute, 2011; Health Canada, 2012a). Exposure to rapid climate change means that northern communities face increasing risks related to reduced duration and thickness of sea and lake ice, thawing permafrost, sea level rise and storm surges, erosion and landslides, more unpredictable weather, freezing rain and wildfires, shorter winter conditions, and hotter summers (Ford et al., 2009; Boulton et al., 2011). Such impacts create health risks by threatening food safety and security, drinking water supplies, water and ice safety, the availability of traditional medicine and the stability of infrastructure (Health Canada, 2012a). Northern residents report that environmental changes are impacting their livelihoods, their relationship with the land, their culture, and their mental health and well-being (Ford et al., 2010b; Lemelin et al., 2010; Morse and Zakrison, 2010; Downing and Cuerrier, 2011; Andrachuk and Smit, 2012; McClymont and Myers, 2012).

Traditional food practices such as hunting and gathering are threatened by climate change. For example, the shifting abundance and distribution of resources, threats to transportation safety when accessing resources and warmer temperatures are compromising the safety of food storage practices (Ford, 2009). In the Ross River First Nations (Yukon Territory), earlier spring thaw, warmer and extended summers, and increasing wildfires are affecting the feeding grounds, distribution and abundance of caribou populations, which are a vital traditional food source (Health Canada, 2012f). Impacts to caribou herds are also exacerbated by resource development, which is also influenced by climate change (*see* Chapter 3 – Natural Resources). These cumulative impacts can affect habitat suitability and lead to bioaccumulation of contaminants, ultimately threatening food safety (Health Canada, 2012a). One investigation of food security in Northern Manitoba found that weaker ice conditions related to winter warming have affected the transportation of goods, resulting in a shorter supply of healthy groceries for many of the province's 25 northern communities (Centre for Indigenous Environmental Resources, 2006). In Iqaluit, Nunavut, many people prefer traditional methods of collecting drinking water from rivers, streams, ponds, lakes, icebergs and sea ice versus relying on tap water. However, freshwater resources are at risk of possible contamination from thawing permafrost that could contain toxins, as well as from the northward migration of plants and animals harbouring water-borne pathogens (Health Canada, 2012d).

Characteristics that increase the vulnerability of Aboriginal health systems to climate change include the reliance on subsistence food supply, high rates of poverty, limited surveillance and early warning capacity, less access to health information, diagnosis and treatment of climate-sensitive diseases, jurisdictional and resource constraints and inequality (Ford et al., 2010a). Adaptive capacity challenges relate to the young population (the median age of Inuit is 22 years) and their relatively lower education levels, as only 25% of students graduate from high school (Statistics Canada, 2011). Furthermore, increased housing availability has not accommodated population growth in parts of the North (Owens et al., 2012) and unstable land from permafrost degradation and coastal erosion contributes to deterioration of a wide range of infrastructure in this region (Allard and Lemay, 2012).

## 3.4 COASTAL COMMUNITIES

Despite one third of Canada's coastline being moderately to highly vulnerable to sea-level rise (Shaw et al., 1998), relatively little research has been done on health-related impacts and adaptation to climate change in coastal areas in Canada (Dolan et al., 2005; Dolan and Walker, 2006). Unique health hazards and vulnerabilities exist in coastal areas; the combined effects of sea level rise, more severe and frequent storm surges, changing sea ice conditions and thawing permafrost are anticipated to cause a series of socioeconomic and environmental stresses that can impact health. Some coastal communities reside in the North or are small and isolated, and so share some of the specific factors that make these other types of communities vulnerable.

Climate change affects health in coastal regions through population displacement and social disruption due to land loss from sea-level rise, flooding and erosion, as well as changes in biodiversity, which affect use of natural resources and cultures. Storms and changing ice conditions that affect water security, occupational safety and economic opportunities, and landscape changes that affect the distribution and amounts of biotic and abiotic pollution in the environment can also threaten the health and safety of populations (Dolan and Walker, 2006; Hess et al., 2008; Rosenzweig et al., 2011; Government of British Columbia, 2012).

Exposure to extreme weather increases the vulnerability of coastal communities to climate change (Dolan and Ommer, 2008). For example, in 2010, Hurricane Igor stressed emergency response and acute health care services and displaced families in Newfoundland and Labrador (Public Safety Canada, 2013b). Ninety communities were isolated, 22 declared states of emergency, 300 families were evacuated, and 1 person died (Public Safety Canada, 2013b). High tides coupled with heavy rains have increased flood risk in communities in delta regions; as was seen on Vancouver Island in 2009 when extensive flooding resulted in a local state of emergency, with 50 homes destroyed and approximately 900 residents (300 homes) evacuated (Public Safety Canada, 2013c).

Environmental resource dependence and changing socio-economic conditions may make some coastal communities more vulnerable to the health impacts of climate change (Dolan and Ommer, 2008). For example, production of Fraser River sockeye salmon appears to be declining due to trends in water temperatures (*see* Chapter 4 – Food Production). This may have significant economic and cultural implications for Canadians, especially in British Columbia (Hinch and Martins, 2011)[20].

Some west coast towns that were previously dependent on forestry and fisheries have grown more dependent on tourism and aquaculture to provide employment and tax revenues. Others have endured population declines as people move away to find work (Dolan and Ommer, 2008). In remote coastal communities, vulnerability is further increased by social isolation and shrinking human capital, resulting in part from trends toward urban migration (Frumkin et al, 2008). Future impacts may be exacerbated by pressures linked to migration and coastal development (McGranahan et al., 2007; Rosenzweig et al., 2011; IPCC, 2012). Climate change may also bring benefits for coastal communities if changes related to access and use of natural resources create new economic opportunities in fisheries, tourism, and agriculture (Bigano et al., 2008; Lemmen et al., 2008; World Tourism Organization, 2008; Sumaila et al., 2011; *see also* Chapter 4 – Food Production and Chapter 5 – Industry).

Specific adaptation plans for coastal regions that are being considered, implemented and/or researched are typically led by Ministries or organizations outside of public health (e.g. Ministries of Environment). Such initiatives tend to lack a health lens, but exceptions exist, such as in northern Canada where programs dealing with country food security and health have been implemented (Government of Northwest Territories, 2008).

---

[20] Between 1988 and 1998 the total landed value of the commercial salmon fishery in British Columbia declined from $410 million to $55 million which impacted the standard of living of some people reliant on this resource (Dolan and Ommer, 2008).

# 4. ADDRESSING CLIMATE CHANGE RISKS TO HEALTH

***"Much of the potential health impact of climate change can [...] be avoided through a combination of strengthening key health system functions and improved management of the risks presented by a changing climate."*** *(WHO, 2012b, page V)*

As the climate continues to change and impacts on health are increasingly evident (Costello et al., 2009), adaptation is needed to reduce growing risks to vulnerable populations and communities (McMichael et al., 2008; WHO, 2008; Ebi, 2009; Paterson et al., 2012). The Canadian Medical Association (2010) called for action by health authorities to address climate change in Canada in five main areas:

- education and capacity building;
- surveillance and research;
- reducing the burden of disease to mitigate climate change impacts;
- preparing for climate emergencies; and
- advocacy to combat climate change.

Successful adaptation requires intersectoral collaboration (e.g. health, environment, planning, transport, infrastructure) on monitoring and surveillance of climate change health outcomes, addressing root causes that limit preparedness (e.g. poverty), identification of vulnerable populations, reducing uncertainty through increased research on impacts, educating the public and decision makers about potential disasters and the benefits of preparedness, and the financing of needed measures (Seguin, 2008; WHO, 2010; Ebi, 2011; Frumkin, 2011). Adaptations are most effective when they maximize co-benefits (e.g. increase social capital, improve urban design) (Cheng and Berry, 2012) that address related health concerns, and when they are mainstreamed into existing programs and planning.

## 4.1 ADAPTATION MEASURES AND STRATEGIES TO PROTECT HEALTH

Understanding of adaptation options that can be taken by public health and emergency management officials to build resilience has increased (Ebi et al., 2012; Paterson et al., 2012) although information about adaptation success is limited (Lesnikowski et al., 2011). Table 7 highlights measures identified in recent literature that are available to address climate change risks to health, and builds upon the list of public health adaptations presented by Seguin (2008)[21]. New adaptation areas of focus by public health officials and researchers include:

- vulnerability assessments of high risk populations (*see* Section 4.2.1);
- actions to address secondary health effects of climate hazards such as psychosocial impacts (*see* Case Study 3);
- use of new technologies to facilitate adoption of individual adaptive behaviours (e.g. use of automated devices in cars to warn of water depth (Fitzgerald et al., 2010) or landslide early detection systems);
- advice to health care providers about actions they can take to reduce climate-related health risks;
- emergency management planning measures tailored to increase the resiliency of health care facilities from climate change; and
- identification of preventative measures to reduce harmful exposures before negative health outcomes occur (e.g. infrastructure development such as green roofs to reduce the urban heat island).

---

[21] See pages 426-427 in "Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity" (Seguin, 2008) available at <http://publications.gc.ca/collections/collection_2008/hc-sc/H128-1-08-528E.pdf>

| Extreme Heat and Air Pollution | |
|---|---|
| Impact | Adaptation Measures |
| Health impacts from higher temperatures, increased frequency and severity of heat waves, increased air pollution | • Air conditioning (Frumkin et al., 2008; Balbus and Malina, 2009; Bedsworth and Hanak, 2010; Bambrick et al., 2011), with the caveat that other solutions should be explored first, as air conditioning may contribute to climate change and air pollution through greater use of fossil fuels (Ayres et al., 2009; Maller and Strengers, 2011; Health Canada, 2012c)<br>• Better quality housing stock, appropriate infrastructure (Frumkin et al., 2008; Ayres et al., 2009; English et al., 2009) with the ability to capture energy and recycle water (Bambrick et al., 2011)<br>• Infrastructure development such as green roofs, reflective road and building surfaces, urban green spaces, interior air sealing, use of elastomeric roof coating (Huang et al., 2011a; Maller and Strengers, 2011; Health Canada, 2012c)<br>• Public awareness and education campaigns to promote personal protection from air pollution (e.g. Air Quality Health Index – AQHI) (Haines et al., 2006; Seguin, 2008; Bedsworth and Hanak, 2010)<br>• Vulnerability assessments of high risk regions/populations (Ostry et al., 2010; Health Canada, 2011a; Health Canada, 2012c)<br>• Physician attention to vulnerable patients, pre-summer vulnerability assessments, advice on routine care, education of health risks and appropriate behaviours (Ayres et al., 2009; Ebi and Paulson, 2010; Health Canada, 2011b)<br>• Development and use of vulnerability maps to allow targeting of vulnerable populations (Hess et al., 2009; Health Canada, 2011a)<br>• Promotion of social capital development (Bambrick et al., 2011; Huang et al., 2011b) |

| Wildfires | |
|---|---|
| Impact | Adaptation Measures |
| Increased contact with fire/fire front and evacuations | • Avoid building in vulnerable locations (Bedsworth and Hanak, 2010)<br>• Access to appropriate clothing, fire shelters (e.g. bunkers), and equipment (e.g. particle filtering masks) for high risk areas (Künzli et al., 2006; Johnston, 2009)<br>• Infection control, disease surveillance and appropriate emergency accommodation (Johnston, 2009) |
| Increase in air pollution | • Relocation to clean air locations such as office, libraries, etc. (Johnston, 2009)<br>• Use of air conditioners (Künzli et al., 2006), especially reverse cycle air conditioners set to recycle mode to filter air particles (Johnston, 2009) (*see caveat above*)<br>• Avoidance of exercise in affected environments (Johnston, 2009)<br>• Spending less time outdoors (Künzli et al., 2006)<br>• Use of air masks (Künzli et al., 2006) |

| Drought | |
|---|---|
| Impact | Adaptation Measures |
| Decreased availability and quality of water | • Distribution of public awareness materials/public service announcements, public education programs (Morrissey and Reser, 2007; Wheaton et al., 2008; Bonsal et al., 2011; Wittrock et al., 2011)<br>• Physical relocation of individuals/families to non-drought affected areas (Wittrock et al., 2011)<br>• School-based mental health programs in rural areas, participation of trusted adults who understand drought, early identification of mental health problems and referral (Carnie et al., 2011; Hart et al., 2011)<br>• Training in coping mechanisms (Morrissey and Reser, 2007) |
| Decreased availability and higher costs for fresh fruits and vegetables (for consumers) | • Technological advances to increase production in new climate conditions (Frumkin et al., 2008)<br>• Improved food delivery systems (Frumkin et al., 2008) |
| Increase in water-borne pathogens and water contamination | • Boil water advisories (Wittrock et al., 2011)<br>• Monitoring of gastroenteritis (Horton et al., 2010) |
| Increase in drought and temperature enabled vector-borne disease | • Public education (Frumkin et al., 2008)<br>• Vector control (e.g. mosquito spraying) (Frumkin et al., 2008)<br>• Medical prophylaxis and treatment (Frumkin et al., 2008)<br>• Vaccination (Frumkin et al., 2008) |

*Table 7 continued on next page*

| Floods | |
|---|---|
| **Impact** | **Adaptation Measures** |
| Physical and mental health impacts from increased flood incidence rates and severity | • Flood-appropriate building and infrastructure construction standards for vulnerable areas (e.g. higher level bridges and causeways, water resistant emergency power) (Fundter et al., 2008; Du et al., 2010; Fitzgerald et al., 2010)<br>• Early warning systems based upon weather predictions of flooding, landslides, river flooding and coastal flooding (Alfieri et al., 2012)<br>• Flood evacuation plans, especially for nursing homes, hospitals, schools (Hayes et al., 2009; Jonkman et al., 2009; Bedsworth and Hanak, 2010)<br>• Proper design and siting of health infrastructure (Du et al., 2010)<br>• Assessment of the resiliency of health care facilities to climate change (Paterson et al., 2013)<br>• Education of health risks and appropriate behaviours by physicians (Ebi and Paulson, 2010)<br>• Mapping of high risk populations with 100- and 500-year flood zones (English et al., 2009)<br>• Post-flood disease surveillance (Fewtrell and Kay, 2008)<br>• Use of automated devices in cars to warn of water depth (FitzGerald et al., 2010), landslide early detection systems<br>• Disaster mental health services that are sensitive to socioeconomic status, livelihood patterns, local traditions, cultures and languages (Du et al., 2010)<br>• Immediate family reunion and support (for families that have been separated) (Ebi and Paulson, 2010) |
| Increased mold and respiratory contaminants from mold, bacteria, fungal growth on damp structures | • Inspection of heating, ventilating and air conditioning system (HVAC) by a professional after a flood (US, CDC, 2012)<br>• Drying out homes using fans or dehumidifiers when safe to do so, or by opening doors and windows (US CDC, 2012) |

| Zoonoses and Vector-borne Diseases | |
|---|---|
| **Impact** | **Adaptation Measures** |
| Spread of vector-borne and zoonotic diseases including exotic diseases | • Development of new surveillance methods (e.g. Ogden et al., 2011; Koffi et al., 2012)<br>• Dissemination of information for public health officials and the public (Public Health Agency of Canada, 2013a)<br>• Tools for risk-based decision making on management (i.e. surveillance, prevention and control) of emerging/re-emerging zoonoses/VBDs (e.g. Multi-Criteria Decision Analysis) (e.g. Hongoh et al., 2011), prioritization of zoonoses/VBDs for public health action (Cox et al., 2012; Ng and Sargeant, 2012), and weather-based forecasting of West Nile Virus (Wang et al., 2011) |

| Food and Water Quality | |
|---|---|
| **Impact** | **Adaptation Measures** |
| Increased water contamination and water-borne diseases, contamination of food | • Protocols for chemical and contaminant risk management (Du et al., 2010)<br>• Monitoring of harmful algae bloom outbreaks (Haines et al., 2006; English et al., 2009)<br>• Boil water advisories (Haines et al., 2006)<br>• Expanding water reuse systems to offset reduced supply, increased demand, or both (Water Research Foundation, 2013)<br>• Improving or expanding water treatment regimes (Water Research Foundation, 2013)<br>• Adopting alternative energy sources at treatment plants (e.g. diversifying power sources, adding energy-efficient water pumps) (Water Research Foundation, 2013)<br>• Establishing collaborative management regimes with power suppliers (Water Research Foundation, 2013)<br>• Abandoning or enhancing water infrastructure at risk (Water Research Foundation, 2013) |

**TABLE 7:** Adaptation measures to reduce health risks from climate change impacts.

## 4.2 HEALTH ADAPTATION IN CANADA

An international comparison of health adaptation activities among developed countries[22] listed in Annex 1 of the United Nations Framework Convention on Climate Change (UNFCCC) reported that Canada is further ahead of many countries in efforts to protect health from climate change. Specifically, it is one of the leading countries with respect to the depth of research being led on vulnerability to the impacts of climate change and adaptation options within the health sector. It is also one of the few countries to recognize and develop specific adaptation options around vulnerabilities of Indigenous groups (Lesnikowski et al., 2011). For development of this chapter, health adaptation efforts at federal, provincial, territorial and local levels related to assessing vulnerabilities, preparing for the impacts and communicating health risks to Canadians were examined. This review did not provide a comprehensive inventory of all local and regional adaptations (e.g. infectious disease surveillance, emergency management programs), nor did it comprehensively assess the state of health adaptation in Canada. However, it did highlight information that communities can draw from in order to set priorities, select appropriate strategies and implement them in a sustainable manner as a complement to existing programs, to protect and enhance health in their respective jurisdictions. The remainder of this section describes key findings of this review.

### 4.2.1 ASSESSING IMPACTS AND VULNERABILITIES

Climate change and health vulnerability assessments help public health officials to identify populations in their community or region who are vulnerable to the impacts, gauge the effectiveness of existing interventions and programs, identify additional measures necessary to respond to climate change, strengthen capacity to take action, and provide a baseline of information to monitor adaptation progress (Clarke and Berry, 2011; Health Canada, 2011a; WHO, 2012b). The World Health Organization recently released new guidelines for assessing health vulnerabilities to climate change and adaptation options (WHO, 2012b) and Health Canada released guidelines for assessing the vulnerability of communities and individuals to extreme heat (Health Canada, 2011a) (*see* Figure 10).

Such assessments rely on monitoring and surveillance data illustrating health impact trends associated with climate variability and change. Gaps in data exist for many climate change impacts of concern to Canadians (*see* Section 2.0). Cheng and Berry (2013) have identified a key basket of climate change and health indicators that can be used by health authorities to track impacts on health over time.

At present, few health authorities at regional and local levels have conducted full climate change and health vulnerability assessments. Analysis of possible health impacts from climate change have been undertaken in British Columbia (Ostry et

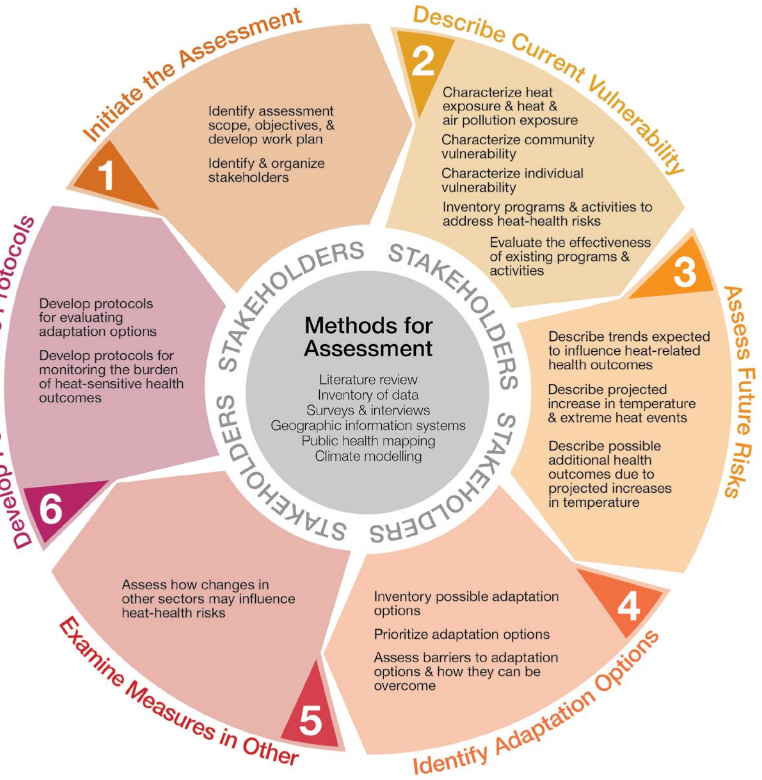


**FIGURE 10:** Steps for conducting an extreme heat and health vulnerability assessment *(Source: Health Canada, 2011a)*.

---

[22] For a list of UNFCCC Annex 1 countries see: http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php

al., 2010) and Quebec (Gosselin, 2010). Ontario's Adaptation Strategy and Action Plan 2011-2014 recognized extreme heat events as a key health concern and committed to the creation of a heat vulnerability assessment tool (Government of Ontario, 2011). At the local level, Peel Public Health (Ontario) used the new WHO guidelines to conduct a health vulnerability assessment (Pajot and Aubin, 2012) that will contribute to implementation of the Region of Peel Climate Change Strategy (Region of Peel, 2011). In addition, some public health authorities and their partners are currently undertaking or have undertaken research projects that contribute to knowledge of local vulnerability to specific health impacts (e.g. Gosselin, 2010; Kosatsky, 2010; Toronto Public Health, 2011a; Toronto Public Health, 2011b). Expertise on climate change and health issues is growing and many universities and organizations across Canada are undertaking research in this area.

## 4.2.2 PREPARING FOR THE IMPACTS

Protecting health from climate change impacts requires "mainstreaming" climate change considerations into existing risk assessment and management activities (Kovats et al., 2009; Clarke and Berry, 2011). Mainstreaming is based on "flexible" adaptation and institutional learning, which is responsive to changing risks to health, climate surprises, and individual- and community-level vulnerabilities (New York Panel on Climate Change, 2010; Ebi, 2011; Hess et al., 2011). Mainstreaming aims to reduce duplication and contradictions between existing public health interventions and new adaptations developed in response to climate change (Haq et al., 2008).

Evidence of mainstreaming in provincial and territorial policies, regulatory instruments and planning tools includes Strategic Direction 1 in the *"Quebec In Action – Greener by 2020: Government Strategy for Climate Change Adaptation"* that integrates climate change adaptation into government administration by modifying, where needed, the content of laws, regulations, strategies, policies, and planning tools (Government of Quebec, 2012). In Nunavut, the climate change adaptation plan requires all departments and agencies to "[…] integrate climate change projections, impacts, and best practices in all levels of their decision-making in order to implement a comprehensive response to climate change" (Government of Nunavut, 2011). One study in Ontario found evidence of adaptation through the mainstreaming of climate change into existing public health programs (Paterson et al., 2012). Outside of government, the Insurance Bureau of Canada is developing a municipal risk assessment tool that can help community decision makers use climate change information to address infrastructure vulnerabilities to projected flood events (IBC, 2013; *see also* Case Study 2, Chapter 5).

Other initiatives also contribute to reducing health risks from climate change. Many health authorities utilize HARS (heat alert response systems), air pollution monitoring activities, and programs to raise awareness of vector-borne diseases, which helps to manage a range of climate-related impacts (Berry, 2008). For example, the provinces of Manitoba, Quebec, and Nova Scotia have provincial HARS systems in place while Alberta is initiating one, and health authorities in Ontario are collaborating to maximize the effectiveness and integration of local systems. In addition, some activities that were not developed with the primary purpose of protecting health – for example, the development of a Drought Response Plan by the British Columbia Inter-Agency Drought Working Group (Government of British Columbia, 2010) – can indirectly help to improve health and well-being and thereby reduce the impacts of climate change.

New approaches and tools have been developed that could facilitate efforts to assist vulnerable groups in Canada and improve understanding of adaptation options at the individual and community levels. One example is the *"Building Community Resilience to Disasters: A Roadmap to Guide Local Planning"* (*see* Table 8). It provides examples of activities that public health and emergency management officials can undertake to help communities recover from disasters more quickly and withstand more severe events in the future.

| Lever | Activities |
|---|---|
| Wellness | Ensure pre-health incident access to health services and post-health incident continuity of care |
| Access | Provide "psychological first aid" or other early post-disaster psychological or behavioural health interventions |
| Education | Bolster coping skills and psychological wellness by developing public health campaigns focused on these messages |
| Engagement | Build the capacity of social and volunteer organizations (i.e. nongovernmental organizations) to engage citizens in collective action to address an issue or problem (e.g. a community development or service project) |
| Self-sufficiency | Develop programs that recognize the vital role citizens can and must play as "first responders" to help their own families and neighbours in the first hours and days of a major disaster |
| Partnership | Engage established and local organizations (e.g. cultural, civic, and faith-based groups, schools, and businesses) and social networks to develop and disseminate preparedness information and supplies |
| Quality | Ensure that all disaster plans have identified common data elements (e.g. benchmarks for disaster operations) to facilitate seamless monitoring and evaluation of health, behavioural health, and social services before, during and after an incident |
| Efficiency | Develop policies for effective donation management and provide the public with clear guidance on donations |

**TABLE 8:** Examples of activities for building community resilience to disasters *(Source: Rand, 2011).*

Warming temperatures in some areas may contribute to air pollution, thereby hindering efforts to improve air quality (Kleeman et al., 2010; Union of Concerned Scientists, 2011). Findings in this chapter suggest this could be the case for Canada (*see* Section 2.1.2). Significant "health co-benefits" can be achieved through properly designed efforts to both reduce GHG emissions (Frumkin and McMichael, 2008; Haines et al., 2009; Kjellstrom and Weaver, 2009) and adapt to climate change impacts (Rosenzweig et al., 2011). For example, immediate health benefits can be achieved through the adoption of active transport and rapid public transit measures that reduce GHG emissions, air contaminants and the urban heat island effect, which helps to reduce a range of diseases associated with physical inactivity and exposure to air pollution in a population (Environment Canada, 2002; Frumkin and McMichael, 2008; Haines et al., 2009; Cheng and Berry, 2012; WHO, 2012b).

Several provinces and territories are linking efforts to mitigate GHGs with efforts to adapt to climate change by improving air quality. For example, the New Brunswick Climate Change Action Plan 2007-2012 sets out actions to reduce GHGs through public education efforts aimed at reducing vehicle idling to protect health and the environment (Government of New Brunswick, 2007). Nova Scotia's climate change action plan highlights actions to reduce and monitor GHGs and includes the Air Quality Health Index (AQHI) to help protect human health from air pollution (Government of Nova Scotia, 2009). Some efforts to reduce GHGs in Canada are being driven explicitly, at least in part, to maximize co-benefits to health (e.g. City of Calgary, 2011).

Many interventions that have been implemented and may help reduce risks to health from climate change have not had their effectiveness evaluated (CMA, 2010; WHO, 2012b). A review by the Canadian Institute for Health Information (CIHI) of interventions in the urban environment to mitigate health inequalities that can be exacerbated by extreme heat and air pollution found that 86% had not been evaluated (CIHI, 2012). Building evaluation measures into adaptation planning to reduce climate change-related health risks is important (Kovats et al., 2009).

### 4.2.3 COMMUNICATING HEALTH RISKS TO THE PUBLIC

Individuals have a primary role to play in adapting to the health impacts of climate change. Psychological factors such as risk perception and perceived adaptive capacity may be important influences in determining levels of climate change adaptation (Grothmann and Patt, 2005; Osberghaus et al., 2010). Appropriate and targeted climate change and health education and awareness activities can encourage people to adopt protective behaviours (Maibach et al., 2011). A survey of Canadians in 2008 revealed that while most people are aware and concerned about climate change, they have little knowledge of specific risks to health (Berry et al., 2011b). Public health and emergency management authorities are providing the public with more information about how to reduce existing health risks from specific climate-related impacts, including those examined in this chapter (*see* Case Study 4).

There are few formal evaluations of public education efforts to reduce health risks associated with climate change (National Collaborating Centre for Environmental Health, 2008). Those that have been completed show mixed results. A study of the education campaign in Montreal, Quebec indicated that people who have been exposed to education materials were more likely to take protective measures against heat through, for example, the use of lightweight clothing, avoiding strenuous exercise, taking a shower or bath to cool down, and hydration (Gosselin et al., 2008a). However, other studies suggest that while knowledge of heat warnings is very broad (>90%), protective actions taken by individuals are inadequate (Sheridan, 2006) or that perceptions of health risks are generally low and the adoption of preventative actions is not widespread (Gower and Mee, 2011). Research on levels of public awareness and the effectiveness of health promotion campaigns related to air quality advisories (Heart and Stroke Foundation, 2008; The Lung Association, 2008), food safety (Mancini, 2008) and reducing risks from vector-borne diseases (Region of Peel, 2006) show similarly mixed results. Public awareness messaging on climate-related risks can be contradictory (e.g. exercising later in the day to avoid extreme heat versus not going outdoors at night to avoid contracting West Nile Virus). To maximize effectiveness, health promotion programs should develop consistent messaging across health issue areas (Hill, 2012).

**CASE STUDY 4**

#### MANAGING RISKS TO HEALTH FROM POOR AIR QUALITY WITH THE AIR QUALITY HEALTH INDEX (AQHI)

Climate change is expected to increase risks to the health of Canadians from poor air quality (*see* Section 2.1). Local AQHI data is now available and used in over 60 communities in all 10 provinces. The AQHI is a health management tool that provides information via the Internet (www.airhealth.ca) that allows people to make informed decisions about reducing their exposure to air pollution. Health messages are provided to the general public and are also tailored for vulnerable groups – parents with children and infants, seniors and those with cardiovascular and respiratory diseases (Environment Canada, 2013a). Local AQHI values are also available through The Weather Network, both on-line and through local television weather forecasts. The Asthma Society also makes local, real-time AQHI values available through their desktop widget, which can be downloaded from their website.

This review of health adaptation activities in Canada suggests that a range of actions are being taken from local to national levels to reduce health risks from climate change, including many of the activities highlighted in previous Government of Canada assessments (Lemmen et al., 2008; Seguin, 2008) and by the WHO (2010) and international experts. Some Canadian health authorities have assessed potential health vulnerabilities. Efforts, programs, and actions to mainstream climate change considerations into existing policies are underway to increase the public's understanding of climate-related health risks. However, adaptation activities are not consistent across Canada, leaving some communities and individuals more vulnerable than others. Efforts to protect Canadians from climate change will benefit from actions to strengthen effective health adaptation. The impacts of climate change on the health system or on the resiliency of individuals may reduce the ability of communities and regions to take such actions in the future.

### 4.2.4 RESEARCH NEEDS

Over the last 15 years, calls for expanded research efforts on climate-related health risks (Duncan et al., 1997; Riedel, 2004; Seguin, 2008) have resulted in a growing body of research to help guide actions to protect the health of Canadians (Berrang-Ford et al., 2011; Gosselin et al., 2011). Strides have been made in the areas of air quality, extreme heat, and the understanding of some climate-related infectious diseases. Although it is important to understand and recognize how far Canada has come, knowledge development has not been uniform among issue areas nor across regions of Canada (Berrang-Ford et al., 2011). Research needs identified in this chapter to better inform adaptation to climate change impacts on health are presented in Table 9.

| Health Concern | Research Needs |
|---|---|
| **Air Quality** | • Estimates of the contribution of black carbon emissions in Canada originating from sources such as open biomass burning and wood stove burning<br>• Identification of the extent of proliferation, impact and allergenicity of aeroallergen-producing plants as warming continues<br>• Identification and monitoring of potentially invasive fungal diseases that could establish with climate change<br>• Understanding of the effects of various GHG mitigation and adaptation activities (e.g. energy efficiency trade-offs, green roofs) on ambient and indoor air quality and associated health impacts<br>• Understanding of how heat and poor air quality interact to impact health and adaptive strategies to reduce health risks<br>• Identification of how dampness and temperature affect degradation of materials in buildings and how indoor material product design may affect human exposure to chemicals |
| **Food and Water Quality** | • Understanding of the impact of water contaminants on human health and monitoring of illnesses<br>• Monitoring of food-borne illness cases to reduce underreporting, including attention to emergence or re-emergence of specific diseases<br>• Knowledge of the impacts of climate change on food and water security in northern and southern Canada<br>• Understanding of the capacity and preparedness of water utilities to adapt to climate change<br>• Defining the characteristics of resilient water and food management systems |
| **Zoonoses and VBDs** | • Surveillance for zoonoses, vectors and vector-borne diseases, including attention to emergence of novel diseases<br>• Basic and applied research studies to inform the development of surveillance, prevention and control methods, vaccines and licensed products for vector control<br>• Enhanced capacity to train highly qualified personnel for both research and public health activities |
| **Natural Hazards** | • Improved projections of extreme weather events due to climate change and modelling of possible health impacts<br>• Surveillance of direct and indirect health impacts from extreme weather-related events<br>• Interdisciplinary (psychology, social work, community development, health promotion, emergency management) research on the effects of natural hazards on psychosocial health<br>• Understanding of climate-resilient infrastructure that is protective of human health |
| **Vulnerable Populations** | • Definition of robust environmental health indicators of climate change to monitor impacts on individuals and communities and develop adaptive measures<br>• Understanding of how the nature of vulnerabilities to the health impacts of climate change for specific groups are changing in order to inform new protective measures for such populations<br>• Understanding how current perceptions and attitudes about climate change and health risks influence the adoption of adaptations<br>• Longitudinal studies across different demographic groups (children, elderly, urban, rural and outdoor workers) to identify health impacts from slow developing hazards (e.g. drought) and cumulative effects of climate change (e.g. extreme heat, drought and wild fires) |

**TABLE 9:** Climate change and health research needs in Canada.

# 5. CONCLUSIONS

Since 2008, stronger evidence has emerged that health risks related to weather variability and climate change are increasing in Canada. For example, further evidence has emerged of the effects of air pollution and extreme heat events on health. Recent studies suggest impacts on ambient air pollution associated with increases in aeroallergens, $O_3$, PM, and wildfires will increase as the climate continues to change. Projections of future air quality in 2050 suggest that without further reductions in anthropogenic air contaminants, air pollution in many Canadian communities will worsen due to increased concentrations of $O_3$ and PM. Indoor air quality may be affected because of more extreme weather events affecting indoor environments (e.g. mold growth after floods).

Climate change is expected to increase risks from food-borne diseases as temperatures rise and extreme precipitation events increase. How the food security of Canadians will be affected is less certain, although evidence suggests Aboriginal populations in the North are already being impacted and would benefit from early adaptation measures. There is also evidence of a link between climate change and impacts on water quality in Canada through microbial contamination, the introduction of hazardous materials (e.g. pesticides) via extreme weather and the growth of cyanobacteria.

Projections in 2008 suggesting the expansion in Canada of the tick vector that causes Lyme Disease have been validated in the field and human cases are on the rise. The spread of Eastern Equine Encephalitis virus into Canada is also evidence of the expansion of a vector-borne disease that could be due, at least in part, to a changing climate. In addition, researchers are beginning to examine the vulnerability of Canadians to 'exotic' zoonoses/vector borne diseases (e.g. malaria, chikungunya, dengue, Japanese encephalitis, Rift Valley fever) imported from countries further afield than the U.S., noting that a warming southern Canada will become increasingly suitable for malaria transmission.

An increase in the number of extreme weather events continues to affect the health of Canadians, although the extent and severity of the impacts on health is difficult to determine from existing surveillance systems. Expanded monitoring of the health impacts from extreme weather events will benefit future adaptation efforts. Improved understanding of health risks from floods, extreme heat and other extreme weather events highlights the need to build resiliency among vulnerable populations to these events, particularly given the expected impacts of climate change in most parts of the country. Analysis of recent natural disasters in Canada and the U.S. has increased knowledge of the psychosocial impacts on health that may result from these events and of the measures that can be taken to protect health.

Canadians across the country are affected by the health impacts of current climate and weather variability, but vulnerability factors that predispose people to increased risks differ significantly by region and population. Greater exposure to rapid climate change and more limited capacity to adapt makes Canada's North one of the most vulnerable regions to health impacts. Important differences in infrastructure, community design, health care and social service delivery, community resources, and demographic and health trends require the adoption of local or regionally planned public health adaptation strategies for urban, rural, northern, and coastal communities (e.g. mitigating the urban heat island effect in cities, improving access to traditional foods in the North, protecting drinking water from sea level rise on the coast).

Government authorities at the federal, provincial, territorial, and local levels in Canada are taking action to prepare for climate change health impacts by including health risks in climate change plans and by mainstreaming climate change considerations into a range of policies and programs that help protect health. However, adaptation efforts need strengthening as growing risks from climate change leave some individuals and communities highly vulnerable to associated impacts. An expanded range of measures and tools to adapt to the health impacts of climate change, including vulnerability assessment guidelines, vulnerability mapping, and decision support tools are now available to public health and emergency management officials in Canada. Increased collaboration and information sharing among governmental, non-governmental, and academic partners will enhance efforts to protect Canadians from the health impacts of climate change.

# REFERENCES

Acharya, M. P., Kalischuk, R. G., Klein, K. K., and Bjornlund, H. (2007): Health impacts of the 2005 flood events on feedlot farm families in Southern Alberta, Canada; Water Resources Management IV, p. 253-262; WIT Press.

Adhern, M. M., Kovats, R. S., Wilkinson, P., Few, R., and Matthies, F. (2005): Global health impacts of floods: epidemiologic evidence; Epidemiologic Reviews, v. 27, no. 1, p. 36-46.

Allard, M. and M. Lemay (2012). Nunavik and Nunatsiavut: From science to policy. An Integrated Regional Impact Study (IRIS) of climate change and modernization. ArcticNet Inc., Quebec City, Canada, 303p.

Alfieri, L., Salamon, P., Pappenberger, F., Wetterhall, F., and Thielen, J. (2012): Operational early warning systems for water-related hazards in Europe; Environmental Science and Policy, no. 21, p. 35-49.

Alves, L.F., Fernandes, B.F., Burnier, J.V., Zoroquiain, P., Eskenazi, D.T., and Burnier Jr., M.N. (2011): Incidence of epithelial lesions of the conjunctiva in a review of 12,102 specimens in Canada (Quebec); Arq. Bras. Oftalmol., v. 74, no. 1, p. 21-23.

Anderson, G. B., Dominici, F., Wang, Y., McCormack, M.C., Bell, M.L. and Peng, R.D. (2013): Heat-related emergency hospitalizations for respiratory diseases in the Medicare population. American Journal of Respiratory and Critical Care Medicine, AJRCCM, Articles in Press.

Andrachuk, M. and Smit, B. (2012): Community-based vulnerability assessment of Tuktoyaktuk, NWT, Canada to environmental and socio-economic changes; Regional Environmental Change, p. 1-19.

Anenberg, S., Schwartz, J., Shindell, D., Amann, M., Faluvegi, G., Klimont, Z., Janssens-Maenhout, G., Pozzoli, L., Van Dingenen, R., Vignati, E., Emberson, L., Muller, N.Z., West, J., Williams, M., Demkine, V., Hicks, W.K., Kuylenstierna, J., Raes, F., and Ramanathan, V. (2012): Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls; Environmental Health Perspectives, v. 120, no. 6, p. 831–839.

Angelini, P., Macini, P., Finarelli, A. C., Pol, C., Venturelli, C., Bellini, R., and Dottori, M. (2008): Chikungunya epidemic outbreak in Emilia-Romagna (Italy) during summer 2007; Parassitologia, v. 50 no. 1-2, p. 97-98.

Auger, N., Kuehne, R., Goneau, M., and Daniel, M. (2011): Preterm birth during an extreme weather event in Quebec, Canada: a natural experiment; Maternal and Child Health Journal, v. 15 no. 7, p. 1088-1096.

Ayres, J. G., Forsberg, B., Annesi-Maesano, I., Dey, R., Ebi, K. L., Helms, P. J., Medina-Ramòn, M., Windt, M., and Forastiere, F. (2009): Climate change and respiratory disease: European respiratory society position statement; European Respiratory Journal, v. 34, no. 2, p. 295-302.

Bais, A. F., Tourpali, K., Kazantzidis, A., Akiyoshi, H., Bekki, S., Braesicke, P., Eyring, V., Garny, H., Iachetti, D., Jöckel, P., Kubin, A., Langematz, U., Mancini, E., Michou, M., Morgenstern, O., Nakamura, T., Newman, P.A., Pitari, G., Plummer, D.A., Rozanov, E., Shepherd, T.G., Shibata, K., Tian, W., Yamashita, Y. (2011): Projections of UV radiation changes in the 21st century: impact of ozone recovery and cloud effects; Atmospheric Chemistry and Physics, no. 11, p. 7533-7545.

Balbus, J. M., and Malina, C. (2009): Identifying vulnerable subpopulations for climate change health effects in the United States; Journal of Occupational and Environmental Medicine / American College of Occupational and Environmental Medicine, v. 51, no.1, p. 33-37.

Bambrick, H. J., Capon, A., Barnett, G., Beaty, R., and Burton, A. (2011): Climate change and health in the urban environment: adaptation opportunities in Australian cities; Asia-Pacific Journal of Public Health, v. 23, no. 2, p. 67S-79S.

Barbeau, B., Carrière, A., Prévost, M., Zamyadi, A., and Chevalier, P. (2009): Climate change in Southern Quebec: an analysis of the vulnerability of Québec drinking water facilities to toxic cyanobacteria – Summary; Government of Quebec.

Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M., and García-Herrera, R. (2011): The hot summer of 2010: Redrawing the temperature record map of Europe; Science, v. 332, no. 6026, p. 220-224.

Bassil, K. (2012): The association between heat, air pollution and emergency medical service calls in Toronto, 2009-2011; Technical Report.

Battisti, D. S. and Naylor, R. L. (2009): Historical warnings of future food insecurity with unprecedented seasonal heat; Science, v. 323, no. 5911, p. 240-244. doi:10.1126/science.1164363.

Bedsworth, L. W. and Hanak, E. (2010): Adaptation to climate change: a review of challengers and tradeoffs in six areas; Journal of the American Planning Association, v. 76, no. 4, p. 477-495.

Bernier, E., Gosselin, P., Badard, T., and Bédard, Y. (2009): Easier surveillance of climate-related health vulnerabilities through a web based spatial OLAP application; International Journal of Health Geographics, v. 8. no. 18, p. 1-18.

Bernstein, A. S. and Myers, S. S. (2011): Climate change and children's health; Current Opinion in Pediatrics, v. 23, no. 2, p. 221-226.

Berrang-Ford, L., MacLean, D., Gyorkos, T., Ford, J., and Ogden, N. H. (2009): Climate change and malaria in Canada: a systems approach; Interdisciplinary Journal of Infectious Diseases, 2009, 13 p.

Berrang-Ford, L., Ford, J., and Paterson, J. (2011): Are we adapting to climate change?; Global Environmental Change, no. 21, p. 25-33.

Berry, H. L., Bowen, K., and Kjellstrom, T. (2009): Climate change and mental health: a causal pathways framework; International Journal of Public Health, v. 55, no. 2, p.123-132.

Berry, H. L., Kelly, B., Hanigan, I., Coates, J., McMichael, A., Welsh, J., and Kjellstrom, T. (2008a): Rural mental health impacts of climate change; The Australian National University, Canberra, Australia.

Berry, P. (2008): Chapter 8 - Vulnerabilities, adaptation and adaptive capacity; in Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity; Health Canada, Ottawa, Ontario.

Berry, P., Clarke, K. L., Brisbois, M., and Brisbois, M. (2011a): Assessment of vulnerability to the health impacts of extreme heat in the city of Winnipeg.

Berry, P., Clarke, K. L., Pajot, M. and Hutton, D. (2011b): Chapter 14 - risk, perception, health communication and adaptation to the health impacts of climate change in Canada; in Climate Change Adaptation in Developed Nations: From Theory to Practice; (ed.) J. D. Ford and L. Berrang-Ford.

Berry, P., McBean, G., and Seguin, J. (2008b): Chapter 3 - vulnerabilities to natural hazards and extreme weather; in Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity; Health Canada, Ottawa, Ontario.

Bethel, J. W., Foreman, A. N., and Burke, S. C. (2011): Disaster preparedness among medically vulnerable populations; American Journal of Preventive Medicine, v. 40, no. 2, p.139-143.

Bigano, A., Bosello, F., Roson, R., and Tol, R. S. J. (2008): Economy-wide impacts of climate change: A joint analysis for sea level rise and tourism; Mitigation and Adaptation Strategies for Global Change, v. 13, no. 8, p. 765-791.

Bonsal, B. R., Wheaton, E. E., Chipanshi, A. C., Lin, C., Sauchyn, D. J., and Wen, L. (2011): Drought research in Canada: a review; Atmosphere - Ocean, v. 49, no. 4, p. 303-319.

Boon, H. J., Brown, L. H., Tsey, K., Speare, R., Pagliano, P., Usher, K., and Brenton, C. (2011): School disaster planning for children with disabilities a critical review of the literature; International Journal of Special Education, v. 26, no. 3, p. 223-237.

Bouchard, C., Beauchamp, G., Nguon, S., Trudel, L., Milord, F., Lindsay, L. R., Bélanger, D. and Ogden, N. H. (2011): Associations between Ixodesscapularis ticks and small mammal hosts in a newly endemic zone in southeastern Canada: implications for Borreliaburgdorferi transmission; Ticks and Tick-Borne Diseases, v. 2, no. 4, p. 183-190.

Boulton, K., Lougheed, M., Ford, J., Nickels, S., and Shirley, J. (2011): What we know, don't know and need to know about climate change in Inuit Nunangat: A systematic literature review and gap analysis of the Canadian Arctic.

Bouri, N., Sell, T. K., Franco, C., Adalja, A. A., Henderson, D. A., and Hynes, N. A. (2012): Return of epidemic dengue in the United States: implications for the public health practitioner; Public Health Reports, v. 127, no. 3, p. 259-266.

Brettle, M., Berry, P., Paterson, J., Yasvinski, G. and Kertland, P. (2013): Determining the preparedness of Canadian water utilities for the impacts of climate change; Report prepared for Health Canada, Ottawa, Ontario.

British Columbia Centers for Disease Control (2012): Cryptococcus gattii. <http://www.bccdc.ca/dis-cond/a-z/_c/CryptococcalDisease/overview/default.htm>.

Brunkard, J., Namulanda, G., and Ratard, R. (2008): Hurricane Katrina deaths, Louisiana, 2005; Disaster Medicine and Public Health Preparedness, v. 2, no. 4, p. 215-223.

Bustinza, R., Lebel, G., Gosselin, P., Belanger, D., and Chebana, F. (2013): Health impacts of the July 2010 heat wave in Quebec, Canada; BMC Public Health, v. 13, no. 56.

Campagna, S., Lévesque, B., Anassour-Laouan-Sidi, E., Côté, S., Serhir, B., Ward, B. J., Libman, M. D., Drebot, M. A., Makowski, K., Andonova, M., Ndao, M., and Dewailly, É. (2011): Seroprevalence of 10 zoonotic infections in 2 Canadian Cree communities; Diagnostic Microbiology and Infectious Disease, v. 70, no. 2, p. 191-199.

Canadian Cancer Society (2012): Canadian Cancer Statistics 2012; Canadian Cancer Society, Toronto, Ontario.

Carnie, T. L., Berry, H. L., Blinkhorn, S. A., and Hart, C. R. (2011): In their own words: young people's mental health in drought-affected rural and remote NSW; Australian Journal of Rural Health, v. 19, no. 5, p. 244-248.

Carroll, B., Morbey, H., Balogh, R., and Araoz, G. (2009): Flooded homes, broken bonds, the meaning of home, psychological processes and their impact on psychological health in a disaster; Health and Place, no. 15, p. 543-547.

Carroll, B., Balogh, R., Morbey, H., and Araoz, G. (2010): Health and social impacts of a flood disaster: responding to needs and implications for practice; Disasters, v. 34, no. 4, p.1045-1063.

Casati, B. and Yagouti, A. (2010): Analysis of extreme temperature indices in nine Canadian communities using the Canadian Regional Climate Model projections for public health planning; Ouranos.

Casati, B., Yagouti, A., and Chaumont, D. (In press): Analysis of extreme temperature indices in 9 Canadian communities using the Canadian Regional Climate Model projections for public health planning; Paper accepted by the Journal of Applied Meteorology and Climatology.

Centre for Indigenous Environmental Resources. (2006): Climate change impacts on ice, winter roads, access trails, and Manitoba First Nations study.

CESD [Commissioner of the Environment and Sustainable Development] (2010): 2010 Fall Report of the Commissioner of the Environment and Sustainable Development (CESD); Chapter 3 - Adapting to Climate Impacts.

Cheng, C. S., Auld, H., Li, Q., and Li, G. (2011): Possible impacts of climate change on extreme weather events at local scale in south-central Canada; Climatic Change, v. 112, no. 3-4, p. 1-17.

Cheng, J. and Berry, P. (2012): Health co-benefits and risks of public health adaptation strategies to climate change: a review of current literature; International Journal of Public Health, no. 58, p. 305-311.

Cheng. J. and Berry, P. (2013): Development of key indicators to track the health impacts of climate change on Canadians; Ottawa.

Chew, G.L., Wilson, J., Rabito, F.A., Grimsley, F., Iqbal, S., Reponen, T., Muilenberg, M.L., Thorne, P.S., Dearborn, D.G., and Morley, R.L. (2006): Mold and endotoxin levels in the aftermath of Hurricane Katrina: a pilot project of homes in New Orleans undergoing renovation; Environmental Health Perspectives, no. 114, p. 1883-1889.

Chiovarou, E. D., and Siewicki, T. C. (2007). Comparison of storm intensity and application timing on modeled transport and fate of six contaminants; Science of the Total Environment, v. 389, no. 1, p. 87-100.

CIHI [Canadian Institute for Health Information] (2011): Urban physical environments and health inequalities; Canadian Institute for Health Information, Ottawa, Ontario.

CIHI [Canadian Institute for Health Information] (2012): Urban physical environments and health inequalities: a scoping review of interventions; Canadian Institute for Health Information, Ottawa, Ontario.

City of Calgary (2011): Calgary Community GHG Reduction Plan; Calgary. <http://www.calgary.ca/UEP/ESM/Documents/ESM-Documents/Calgary_GHG_Plan_Nov_2011.pdf>.

City of Toronto (2011): Map-based heat vulnerability assessment: Implementation of a map-based heat vulnerability assessment and decision support system <http://www.climateontario.ca/doc/ORAC_Products/TPH/Mapping%20Tool%20-%20User%20Manual%20for%20Heat%20Vulnerability%20Mapping%20Tool.pdf>.

City of Toronto (2012): Toronto's future weather and climate driver study: outcomes report; Toronto. <http://www.toronto.ca/legdocs/mmis/2012/pe/bgrd/backgroundfile-51653.pdf>.

Clarke, K.L. (2009): Critical health infrastructures during disasters: lessons learned; in Emergency management: Taking the health perspective; Health Policy Research Bulletin, Health Canada, Issue 15, April 2009. <http://www.hc-sc.gc.ca/sr-sr/pubs/hpr-rpms/bull/2009-emergency-urgence/index-eng.php>.

Clarke, K.L. and Berry, P. (2011): From theory to practice: a Canadian case study of the utility of climate change adaptation frameworks to address health impacts; International Journal of Public Health, v. 57, no. 1, p.167-174.

Clarke, K.L. (2012): Climate-related stresses on human health in a remote and rural region of Ontario, Canada; Thesis Submission to the Department of Geography, University of Ottawa.

CMA [Canadian Medical Association] (2008): No breathing room: national illness costs of air pollution – summary report; Canadian Medical Association, Ontario. <http://www.cma.ca/multimedia/CMA/Content_Images/Inside_cma/Office_Public_Health/ICAP/CMA_ICAP_sum_e.pdf>.

CMA [Canadian Medical Association] (2010): Climate change and human health; Canadian Medical Association, Ottawa, Ontario.

Cockwill, K. R., Taylor, S. M., Snead, E. C., Dickinson, R., Cosford, K., Malek, S., Robbin, L., Vissotto, P. P., and Diniz, P. P. (2009): Granulocytic anaplasmosis in three dogs from Saskatoon, Saskatchewan; Canadian Veterinary Journal, v. 50, no. 8, p. 835-840.

Committee on the Significance of International Transport of Air Pollutants (2009): Global sources of local pollution: An assessment of long-range transport of key air pollutants to and from the United States. National Research Council. <http://www.nap.edu/catalog.php?record_id=12743>.

Costello, A., Abbas, M., Allen, A., Ball, S., Bell, S., Bellamy, R., Friel, S., Groce, N., Johnson, A., Kett, M., Lee, M., Levy, C., Maslin, M., McCoy, D., McGuire, B., Montgomery, H., Napier, D., Pagel, C., Patel, J., Puppim de Oliveira, J. A., Redclift, N., Rees, H., Rogger, D., Scott, J., Stephenson, J., Twigg, J., Wolff, J., and Patterson, C. (2009): Managing the health effects of climate change; Lancet and University College London Institute for Global Health Commission; The Lancet, v. 373, no. 9676, p.1693-1733.

Coulston, J. E. and Deeny, P. (2010): Prior exposure to major flooding increases individual preparedness in high-risk populations; Prehospital and Disaster Medicine, v. 25, no. 4, p. 289-295.

Cox, R., Revie, C. W., and Sanchez, J. (2012): The use of expert opinion to assess the risk of emergence or re-emergence of infectious diseases in Canada associated with climate change; PLoS ONE, v. 7, no. 7.

Cretikos, M. A., Merritt, T. D., Main, K., Eastwood, K., Winn, L., Moran, L., and Durrheim, D. N. (2007): Mitigating the health impacts of a natural disaster - the June 2007 long-weekend storm in the hunter region of new South Wales; Medical Journal of Australia, v. 187, no. 11-12, p. 670-673.

Cunderlik, J. M. and Ouarda, T. B. M. J. (2009): Trends in the timing and magnitude of floods in Canada; Journal of Hydrology, v. 375, no. 3-4, p. 471-480.

CWWA [Canadian Water and Wastewater Association] (2012): Understanding the preparedness of Canadian water utilities for the impacts of climate change; report prepared for Health Canada, Ottawa, Ontario.

Dixon, K. M., Sequeira, V. B., Camp, A. J., and Mason, R. S. (2012): Vitamin D and skin cancer; in Handbook of Diet, nutrition and the skin, (ed.) V. Preedy; Wageningen Academic Publishers, no. 2, p. 394-411.

Değer L, Plante, C., Goudreau, S., Smargiassi, A., Perron, S., Thivierge, R.L., and Jacques, L. (2010): Home environmental factors associated with poor asthma control in Montreal children: a population-based study; J Asthma, v. 47, no. 5, p. 513-520.

DesJarlais, C. and Blondlot, A. (2010): Learning to adapt to climate change; Ouranos, Montreal, <http://www.ouranos.ca/en/publications/documents/sscc_anglais_br-V22Dec2011.pdf>.

Dolan, A. H. and Walker, I. J. (2006): Understanding vulnerability of coastal communities to climate change related risks; Itajai, SC - Brazil. (SI 39).

Dolan, H., and Ommer, R. (2008): Climate change and community health: lessons from Canada's east and west Coasts; Journal of Rural and Community Development, v. 3, no. 2, p. 27-46.

Dolan, A. H., Taylor, M., Neis, B., Ommer, R., Eyles, J., Schneider, D., and Montevecchi, B. (2005): Restructuring and health in Canadian coastal communities; EcoHealth, v. 2, no. 3, p. 195-208.

Downing, A. and Cuerrier, A. (2011): A synthesis of the impacts of climate change on the First Nations and Inuit of Canada; Indian Journal of Traditional Knowledge, v. 10, no. 1, p. 57-70.

Drowning Prevention Research Centre Canada (2011): National Drowning Report - 2011 Edition, Lifesaving Society.

Du, W., FitzGerald, G. J., Clark, M., and Hou, X. Y. (2010): Health impacts of floods; Prehospital and Disaster Medicine; The Official Journal of the National Association of EMS Physicians and the World Association for Emergency and Disaster Medicine in Association with the Acute Care Foundation, v. 25, no. 3, p. 265-272.

Duncan, K., Guidotti, T., Cheng, W., Naidoo, K., Gibson, G., Kalkstein, L., Sheridan, S., Waltner-Toews, D., MacEachern, S. and Last, J. (1997): Canada Country Study: impacts and adaptation - health sector; in Responding to Global Climate Change: National Sectoral Issue, (ed.) G. Koshida and W. Avis; Environment Canada, Canada Country Study: Climate Impacts and Adaptation, v. VII, p. 501-620.

Ebi, K. L. (2011): Resilience to the health risks of extreme weather events in a changing climate in the United States; International Journal of Environmental Research and Public Health, v. 8, no. 12, p. 4582-4595.

Ebi, K. L. and Paulson, J. A. (2010): Climate change and child health in the United States; current problems in pediatric and adolescent health care, v. 40, no. 1, p. 2-18.

Ebi, K. L. (2009): Managing the changing health risks of climate change; Current Opinion in Environmental Sustainability, v. 1, no. 1, p. 107-110.

Ebi, K., Lindgren, E., Suk, J.E., and Semenza, J.C. (2012): Adaptation to the infectious disease impacts of climate change; Climatic Change, v. 118, no. 2, p. 355-365.

Ebi, K.L. and Mills, D. (2013): Winter mortality in a warming climate: a reassessment; Willey Interdisciplinary Reviews: Climate Change, v. 4, no. 3, p. 203-2012.

Eckhardt, R., Berrang-Ford, L., Ross, N. A., Pillai, D. R., and Buckeridge, D. L. (2012): A spatial analysis of individual and neighborhood-level determinants of Malaria incidence in adults, Ontario, Canada; Emerging Infectious Diseases, v. 18, no. 5, p. 775-782.

English, P. B., Sinclair, A. H., Ross, Z., Anderson, H., Boothe, V., Davis, C., Ebi, K., Malecki, J., Shultz, R., and Simms, E. (2009): Environmental health indicators of climate change for the United States: findings from the State Environmental Health Indicator Collaborative; Environmental Health Perspectives, v. 117, no. 11, p. 1673-1681.

Environment Canada (2002): Making transportation sustainable: a case study of the Quebec City – Windsor corridor; Environment Canada, Ottawa, Ontario; <http://publications.gc.ca/site/eng/109358/publication.html>.

Environment Canada (2007): Changing weather patterns, uncertainty and infrastructure risks: emerging adaptation requirements; Occasional Paper 9. Toronto, Ontario. <http://www.ec.gc.ca/Publications/6544796D-66EB-4A64-B2E7-88A8911D0439%5CChangingWeatherPatternsUncertaintyOccasionalPaper9.pdf>.

Environment Canada (2012a): Ambient levels of ground-level ozone; <http://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=9EBBCA88-1>.

Environment Canada (2012b): Ambient levels of fine particulate matter; <http://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=029BB000-1>.

Environment Canada (2013a): About the Air Quality Health Index; <http://www.ec.gc.ca/cas-aqhi/default.asp?lang=En&n=065BE995-1>.

Environment Canada (2013b): National air pollution surveillance program. <http://www.ec.gc.ca/rnspa-naps/>.

Ermert, V., Fink, A. H., Morse, A. P., and Paeth, H. (2012): The impact of regional climate change on malaria risk due to greenhouse forcing and land-use changes in tropical Africa; Environmental Health Perspectives, v. 120, no. 1, p. 77-84.

Febriani, Y., Levallois, P., Gingras, S., Gosselin, P., Majowicz, S. E., and Fleury, M. D. (2010): The association between farming activities, precipitation, and the risk of acute gastrointestinal illness in rural municipalities of Quebec, Canada: a cross-sectional study; BMC Public Health, v. 10, no. 48.

Fewtrell, L. and Kay, D. (ed.) (2008) A guide to the health impact assessment for sustainable water management; International Water Association, Amsterdam. 320 p., <http://www.iwapublishing.com/template.cfm?name=isbn1843391333> ISBN 9781843391333.

FitzGerald, G., Du, W., Jamal, A., Clark, M., and Hou, X-Y. (2010): Flood fatalities in contemporary Australia (1997-2008); Emergency Medicine Australasia, no. 22, p. 180-186.

Flannigan, M.D., Krawchuk, M.A., de Groot, W.J., Wotton, B.M. and Gowman, L.M. (2009): Implications of changing climate for global wildland fire; International Journal of Wildland Fire no. 18, p. 483-507.

Flannigan, M. and Wotton, M. (2010): Forest fire activity in Canada during 2030s-2050s.; Wildland Fire Canada, <http://www.ualberta.ca/~wildfire/Wildland_Fire_Canada/2010%20PDF/Mike%20Flannigan.pdf>.

Ford, J. D. (2009): Dangerous climate change and the importance of adaptation for the Arctic's Inuit population; Environmental Research Letters, v. 4, no. 2.

Ford, J. D., Berrang-Ford, L., King, M., and Furgal, C. (2010a): Vulnerability of Aboriginal health systems in Canada to climate change; Global Environmental Change, v. 20, no. 4, p. 668-680.

Ford, J. D., Gough, W. A., Laidler, G. J., MacDonald, J., Irngaut, C., and Qrunnut, K. (2009): Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada; Climate Research, v. 38, no. 2, p. 137-154.

Ford, J. D., Pearce, T., Duerden, F., Furgal, C., and Smit, B. (2010b): Climate change policy responses for Canada's Inuit population: the importance of and opportunities for adaptation; Global Environmental Change, v. 20, no. 1, p. 177-191.

Friel, S., Dangour, A. D., Garnett, T., Lock, K., Chalabi, Z., Roberts, I., Butler, A., Butler, C., Waage, J., McMichael, A., and Haines, A. (2009): Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture; The Lancet, v. 374, no. 9706, p. 2016-2025.

Fritze, J. C., Blashki, G. A., Burke, S., and Wiseman, J. (2008): Hope, despair and transformation: climate change and the promotion of mental health and wellbeing; International Journal of Mental Health Systems, v. 2, no. 16.

Frumkin, H. (2011): Bumps on the road to preparedness; American Journal of Preventive Medicine, v. 40, no. 2, p. 272-273.

Frumkin, H. and McMichael, A. J. (2008): Climate change and public health: thinking, communicating, acting; American Journal of Preventive Medicine, v. 35, no. 5, p. 403-410.

Frumkin, H., Hess, J., Luber, G., Malilay, J., and McGeehin, M. (2008): Climate change: The public health response; American Journal of Public Health, v. 98, no. 3, p. 435-445.

Fundter, D. Q., Jonkman, B., Beerman, S., Goemans, C. L., Briggs, R., Coumans, F., Lahaye, J. W., and Bierens, J. (2008): Health impacts of large-scale floods: Governmental decision-making and resilience of the citizens; Prehospital and Disaster Medicine; The Official Journal of the National Association of EMS Physicians and the World Association for Emergency and Disaster Medicine in Association with the Acute Care Foundation, v. 23, no. 4, s70-73.

Furgal, C. (2008): Chapter 7 – Health impacts of climate change in Canada's North; in Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity; Health Canada, Ottawa, Ontario.

Furgal, C. and Seguin, J. (2006): Climate change, health, and vulnerability in Canadian Northern Aboriginal communities; Environmental Health Perspectives, v. 114, no. 12, p. 1964-1970.

Gabriel, K. M. and Endlicher, W. R. (2011): Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany; Environmental Pollution, v. 159, no. 8-9, p. 2044-2050.

Gauderman, W.J., Avol, E., Gilliland, F., Vora, H., Thomas, D., Berhane, K., McConnell, R., Kuenzli, N., Lurmann, F., Rappaport, E., Margolis, H., Bates, D., and Peters, J. (2004): The effect of air pollution on lung development from 10 to 18 Years of Age; New England Journal of Medicine, no. 351, p. 1057-1067.

Gilbert, N. L., Dare, O. K., Libman, M. D., Muchaal, P. K., and Ogden, N. H. (2010): Hospitalization for trichinellosis and echinococcosis in Canada, 2001-2005: the tip of the iceberg?; Canadian Journal of Public Health, v. 101, no. 1, p. 337-340.

Gomez, D., Haas, B., Ahmed, N., Tien, H., Nathens, A. (2011): Disaster preparedness of Canadian trauma centres: the perspective of medical directors of trauma; Canadian Journal of Surgery, v. 54, no. 1, p. 9-15.

Gosselin, C., Kosatsky, T., Fournier, M., Richard, L., Pinard, M., King, N., Bonney, D., and Gaudet, J. (2008a): Evaluation of the "It's Summer. Be Cool!" Education Campaign; Natural Resources Canada.

Gosselin, P., Belanger, D., and Doyan, B. (2008b): Health impacts of climate change in Quebec; in Human health in a changing climate: A Canadian assessment of vulnerabilities and adaptive capacity; Health Canada, Ottawa, Ontario.

Gosselin, P. (2010): Health of populations; in Learning to Adapt to Climate Change; Ouranos, Montreal, Quebec.

Gosselin, P., Belanger, D., Lapaige, V., and Labbe, Y. (2011): The burgeoning field of transdisciplinary adaptation research in Quebec (1998–): a climate change-related public health narrative; Journal of Multidisciplinary Healthcare, no. 4, p. 337–348.

Government of British Columbia (2010): Preparing for climate change: British Columbia's adaptation strategy.

Government of British Columbia (2012): BC Climate Action Toolkit; <http://www.toolkit.bc.ca/adaptation-challenges-and-opportunities>.

Government of Canada (2012): Canadian smog science assessment: highlights and key messages; Government of Canada, Ottawa, Ontario.

Government of New Brunswick (2007): Climate Change Action Plan 2007-2012. Take Action!

Government of Northwest Territories (2008): NWT climate change impacts and adaptation report 2008.

Government of Nova Scotia (2009): Toward a greener future: Nova Scotia's climate change action plan; <http://climatechange.gov.ns.ca/content/WhatNSIsDoing>.

Government of Nunavut (2011): Upagiaqtavut setting the course: climate change impacts and adaptation in Nunavut; Government of Nunavut, Iqaluit, Nunavut; <http://env.gov.nu.ca/sites/default/files/3154-315_climate_english_sm.pdf >.

Government of Ontario (2011): Climate ready: Ontario's adaptation strategy and action plan 2011-2014.

Government of Quebec (2012): Quebec in action - greener by 2020: government strategy for climate change adaptation.

Gower, S. and Mee, C. (2011): Hot weather protection: public knowledge and perceptions leading to public action in Toronto.

Greer, A., Ng, V., and Fisman, D. (2008): Climate change and infectious diseases in North America: the road ahead; Canadian Medical Association Journal, v. 178, no. 6, p. 715-722.

Grothmann, T. and Patt, A. (2005): Adaptive capacity and human cognition: the process of individual adaptation to climate change; Global Environmental Change, v. 15, no. 3, p. 199-213.

Haines, A., Kovats, R. S., Campbell-Lendrum, D., and Corvalan, C. (2006): Climate change and human health: impacts, vulnerability and mitigation; The Lancet, v. 367, no. 9528, p. 2101-2109.

Haines, A., McMichael, A. J., Smith, K. R., Roberts, I., Woodcock, J., Markandya, A., Armstrong, B. G., Campbell-Lendrum, D., Dangour, A. D., Davies, M., Bruce, N., Tonne, C., Barrett, M., and Wilkinson, P. (2009): Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers; The Lancet, v. 374, no. 9707, p. 2104-2114.

Hajat, S. and Kosatky, T. (2010): Heat-related mortality: a review and exploration of heterogeneity; Journal of Epidemiology and Community Health, v. 64 no. 9, p. 753-760.

Hanson, A., Bi, P., Nitschke, M., Ryan, P., Pisaniello, D., and Tucker, G. (2008): The effect of heat waves on mental health in a temperate Australian city; Environmental Health Perspectives, no. 116, p. 1369-1375.

Haq, G., Whitelegg, J., and Kohler, M. (2008): Growing old in a changing climate: meeting the challenges of an ageing population and climate change; Stockholm Environment Institute, Stockholm.

Harmon, S. M. and Wyatt, D. E. (2008): Evaluation of post-Katrina flooded soils for contaminants and toxicity to the soil invertebrates Eisenia fetida and Caenorhabditis elegans; Chemosphere, v. 70, no. 10, p. 1857-1864.

Harper, S. L., Edge, V. L., Schuster-Wallave, C. J., Berke, O., and McEwen, S. A. (2011): Comparison of trends in weather, water quality and infectious gastrointestinal illness in two Inuit communities in Nunatsiavut, Canada: Potential implications for climate change; EcoHealth, no. 8, p. 93-108.

Hart, C. R., Berry, H. L., and Tonna, A. M. (2011): Improving the mental health of rural New South Wales communities facing drought and other adversities; Australian Journal of Rural Health, v. 19, no. 5, p. 231-238.

Hayes, J., Mason, J., Brown, F., and Mather, R. (2009): Floods in 2007 and older adult services: lessons learnt; Psychiatric Bulletin, v. 33, no. 9, p. 332-336.

Health Canada (2011a): Adapting to extreme heat events: guidelines for assessing health vulnerability; Health Canada, Ottawa, Ontario.

Health Canada (2011b): Extreme heat events guidelines: technical guide for health care workers; Health Canada, Ottawa, Ontario.

Health Canada (2012a): Climate telling. <http://climatetelling.ca>.

Health Canada (2012b): Guidelines for Canadian drinking water quality - technical documents. <http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/index-eng.php#tech_doc>.

Health Canada (2012c): Heat alert and response systems to protect health: best practices guidebook. Ottawa, Ontario.

Health Canada (2012d): Iqaluit (NRI): building local capacity to monitor microbiological water quality in the streams and rivers of Iqaluit Nunavut: towards protecting drinking water resources in a changing climate. <http://climatetelling.ca/community/iqaluit-nri/>.

Health Canada (2012e): Our health, our environment: a snapshot of environmental health in Canada; Ottawa: Health Canada, <http://www.hc-sc.gc.ca/ewh-semt/pubs/contaminants/sehc-asec/index-eng.php>.

Health Canada (2012f): Ross River First Nation Yukon: caribou culture and climate change. < http://climatetelling.ca/community/ross-river-caribou>.

Health Canada (2000): Blue-Green Algae (Cyanobacteria) and their toxins. <http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/cyanobacter-eng.php>.

Health Canada (2013a): Health risks and benefits associated with the use of 10% ethanol-blended gasoline in Canada; Health Canada, Ottawa, Ontario. <http://www.hc-sc.gc.ca/ewh-semt/pubs/air/ethanol-eng.php>.

Health Canada (2013b): Human health risk assessment for biodiesel production, distribution and use in Canada - executive summary; Health Canada, Ottawa, Ontario. <http://www.hc-sc.gc.ca/ewh-semt/pubs/air/biodiesel-eng.php>.

Heart and Stroke Foundation (2008): Canada's heart health up in the air, says the 2008 Heart and Stroke Foundation Report Card on Canadians' Health.

Hegglin, M. I. and Shepherd, T. G. (2009): Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux; Nature Geoscience, no. 2, p. 687-691.

Heisler, J., Glibert, P. M., Burkholder, J. M., Anderson, D. M., Cochlan, W., Dennison, W. C., Dortch, Q., Gobler, C. J., Heil, C. A., Humphries, E., Lewitus, A., Magnien, R., Marshall, H. G., Sellner, K., Stockwell, D. A., Stoeker, D. K., and Suddleson, M. (2008): Eutrophication and harmful algal blooms: a scientific consensus; Harmful Algae, v. 8, no. 1, p. 3-13.

Henderson, S. B., Brauer, M., MacNab, Y. C., and Kennedy, S. M. (2011): Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort. Environmental Health Perspectives, v. 119, no. 9, p. 1266-1271.

Hess, J., Heilpern, K. L., Davis, T., and Frumkin, H. (2009): Climate change and emergency medicine: Impacts and opportunities; Academic Emergency Medecine, v. 16, no. 8, p. 782-794.

Hess, J., McDowell, J. Z., and Luber, G. (2011): Integrating climate change adaptation into public health practice: using adaptive management to increase adaptive capacity and build resilience; Environmental Health Perspectives, v. 120, no. 2, p. 171-190.

Hess, J. J., Malilay, J. N., and Parkinson, A. J. (2008): Climate change: the importance of place; American Journal of Preventive Medicine, v. 35, no. 5, p. 468-478.

Higginbotham, N., Connor, L., Albrecht, G., Freeman, S., and Agho, K. (2007): Validation of the environmental distress scale; EcoHealth, no. 3, p. 245-254.

Hill, J. (2012): Analysis of climate change and health promotion campaigns in relation to heat health messages; report Prepared for Health Canada, Ottawa, Ontario.

Hilscherova, K., Dusek, L., Kubik, V., Cupr, P., Hofman, J., Klanova, J., and Holoubek, I. (2007): Redistribution of organic pollutants in river sediments and alluvial soils related to major floods; Journal of Soils and Sediments, v. 7, no. 3, p. 167-177.

Himsworth, C. G., Jenkins, E., Hill, J. E., Nsungu, M., Ndao, M., Thompson, R. C. A., Covacin, C., Ash, A., Wagner, B. A., McConnell, A., Leighton, F. A., and Skinner, S. (2010a): Short report: emergence of sylvatic echinococcus granulosus as a parasitic zoonosis of public health concern in an indigenous community in Canada; American Journal of Tropical Medicine and Hygiene, v. 82, no. 4, p. 643-645.

Himsworth, C. G., Skinner, S., Chaban, B., Jenkins, E., Wagner, B. A., Harms, N. J., Leighton, F. A., Thompson, R. C. A., and Hill, J. E. (2010b): Short report: multiple zoonotic pathogens identified in canine feces collected from a remote Canadian indigenous community; American Journal of Tropical Medicine and Hygiene, v. 83, no. 2, p. 338-341.

Hinch, S.G. and Martins, E.G (2011): A review of potential climate change effects on survival of Fraser River sockeye salmon and an analysis of interannual trends in en route loss and pre-spawn mortality; The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River, Technical Report 9. <http://www.watershed-watch.org/wordpress/wp-content/uploads/2011/06/Exh-553-NonRT.pdf>.

Holden, C. (2009): Climate change: higher temperatures seen reducing global harvests; Science, v. 323, no. 5911, p. 193.

Hongoh, V., Berrang-Ford, L., Ogden, N. H., Lindsay, R., Scott, M. E., and Artsob, H. (2009): A review of environmental determinants and risk factors for avian-associated mosquito arboviruses in Canada; Biodiversity, v. 10, no. 2-3, p. 83-91.

Hongoh, V., Berrang-Ford, L., Scott, M. E., and Lindsay, L. R. (2012): Expanding geographical distribution of the mosquito, Culexpipiens, in Canada under climate change; Applied Geography, v. 33, no. 1, p. 53-62.

Hongoh, V., Hoen, A. G., Aenishaenslin, C., Waaub, J., Bélanger, D., and Michel, P. (2011): Spatially explicit multi-criteria decision analysis for managing vector-borne diseases; International Journal of Health Geographics, v. 10.

Horton, G., Hanna, L., and Kelly, B. (2010): Drought, drying and climate change: emerging health issues for ageing Australians in rural areas; Australasian Journal on Ageing, v. 29, no. 1, p. 2-7.

Huang, C., Barnett, A. G., Wang, X., Vaneckova, P., Fitzgerald, G., and Tong, S. (2011a): Projecting future heat-related mortality under climate change scenarios: a systematic review; Environmental Health Perspectives, v. 119, no.12, p. 1681-1690.

Huang, C., Vaneckova, P., Wang, X., FitzGerald, G., Guo, Y., and Tong, S. (2011b): Constraints and barriers to public health adaptation to climate change: a review of the literature; American Journal of Preventive Medicine, v. 40, no. 2, p. 183–190.

IBC [Insurance Bureau of Canada] (2013): Municipal Risk Assessment Tool. <http://www.ibc.ca/en/Natural_Disasters/Municipal_Risk_Assessment_Tool.asp>.

ICLR [Institute for Catastrophic Loss Reduction] (2012): Telling the weather story. <http://iclr.org/images/Telling_the_weather_story.pdf>.

IOM [Institute of Medicine] 2011: Climate change, the indoor environment and health; The National Academies Press, Washington DC.

IPCC [Intergovernmental Panel on Climate Change] (2007): Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007; Cambridge University Press, Cambridge, United Kingdom; New York, New York.

IPCC [Intergovernmental Panel on Climate Change] (2012): Summary for policymakers; in Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation; Cambridge University Press, Cambridge, United Kingdom. <http://www.ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf>.

Iranpour, M., Turell, M. J., and Lindsay, L. R. (2011): Potential for Canadian mosquitoes to transmit Rift Valley fever virus; Journal of the American Mosquito Control Association, v. 27, no. 4, p. 363-369.

Isaacs, S., LeBer, C., and Michel, P. (1998): The distribution of foodborne disease by risk setting - Ontario; Canada Communicable Disease Report, v. 24, no. 8, p. 61-64.

Islam, T., Berhane, K., McConnell, R., Gauderman, W. J., Avol, E., Peters, J. M., and Gilliland, F. D. (2009): Glutathione-S-transferase (GST) P1, GSTM1, exercise, ozone and asthma incidence in school 5 children; Thorax, no. 64, p.197-202.

Jaakkola, J. J. and Knight, T.L. (2008): The role of exposure to phthalates from polyvinyl chloride products in the development of asthma and allergies: a systematic review and meta-analysis; Environmental Health Perspectives, v. 116, no.7, p. 845-853.

Jackson, Y., Gétaz, L., Wolff, H., Holst, M., Mauris, A., Tardin, A., Sztajzel, J., Besse, V., Loutan, L., Gaspoz, J. M., Jannin, J., Vinas, P. A., Luquetti, A., and Chappuis, F. (2010): Prevalence, clinical staging and risk for blood-borne transmission of Chagas disease among latin American migrants in Geneva, Switzerland; PLoS Neglected Tropical Diseases, v. 4, no. 2.

Jardine, C., Lindsay, L. R., Nicholson, V. M., Ojkic, D., and Prescott, J. F. (2011): Longitudinal study on the seroprevalence of avian influenza, leptospirosis, and tularemia in an urban population of raccoons (Procyonlotor) in Ontario, Canada; Vector-Borne and Zoonotic Diseases, v. 11, no. 1, p. 37-42.

Jenkins, E. J., Schurer, J. M., and Gesy, K. M. (2011): Old problems on a new playing field: Helminth zoonoses transmitted among dogs, wildlife, and people in a changing northern climate; Veterinary Parasitology, v. 182, no. 1, p. 54-69.

Jerrett M., Burnett R.T., Pope, C.A. 3rd, Ito, K., Thurston, G., Krewski, D., Shi, Y., Calle, E., and Thun, M. (2009): Long-term ozone exposure and mortality. New England Journal of Medicine, v. 360, no. 11, p.1085-95.

Johnston, F. H. (2009): Bushfires and human health in a changing environment; Australian Family Physician, v. 38, no. 9, p. 720-724.

Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., Defries, R. S., Kinney, P., Bowman, D. M. J. S., and Brauer, M. (2012): Estimated global mortality attributable to smoke from landscape fires; Environmental Health Perspectives, v.120, no. 5, p. 695-701.

Jonkman, S. N., Maaskant, B., Boyd, E., and Levitan, M. L. (2009): Loss of life caused by the flooding of New Orleans after Hurricane Katrina: analysis of the relationship between flood characteristics and mortality; Risk Analysis, v. 29, no. 5, p. 676-698.

Kelly, J., Makar, P. A., and Plummer, D. A. (2012): Projections of mid-century summer air-quality for North America: effects of changes in climate and precursor emissions; Atmospheric Chemistry and Physics, no. 12, p. 3875-3940.

Kenny, G. P., Yardley, J., Brown, C., Sigal, R. J., and Jay, O. (2010): Heat stress in older individuals and patients with common chronic diseases; CMAJ, v. 182, no.10, p. 1053-1060.

Kidd, S. E., Chow, Y., Mak, S., Bach, P. J., Chen, H., Hingston, A. O., Kronstad, J.W., and Bartlett, K. H. (2007): Characterization of environmental sources of the human and animal pathogen Cryptococcus gattii in British Columbia, Canada, and the Pacific Northwest of the United States; Applied and Environmental Microbiology, v. 73, no. 5, p. 1433-1443.

Kjellstrom, T. and Weaver, H. J. (2009): Climate change and health: impacts, vulnerability, adaptation and mitigation; New South Wales Public Health Bulletin, v. 20, no. 1-2, p. 5-9.

Kleeman, M. J., Chen, S., and Harley, R. A. (2010): Climate change impact on air quality in California, no. 04-349.

Koffi, J. K., Leighton, P. A., Pelcat, Y., Trudel, L., Lindsay, L. R., Milord, F., and Ogden, N. H. (2012): Passive surveillance for Ixodesscapularis ticks: enhanced analysis for early detection of emerging Lyme disease risk; Journal of Medical Entomology, v. 49, no. 2, p. 400-409.

Kosatsky, T. (2010): Hot day deaths, summer 2009: what happened and how to prevent a recurrence; British Columbia Medical Journal, v. 52, no. 5, p. 261.

Kovats, S., Toelupe, P. T., Alam, M., and Mohamed, A. J. (2009): Chapter 3: Developing effective adaptation strategies, *in* Commonwealth Health Ministers' Update 2009, p. 49-54.

Kovats, R.S., and Hajat, S. (2008): Heat stress and public health: a critical review, Annual Review of Public Health; v. 29, p. 41-55.

Kravchenko, J., Abernethy, A.P., Fawzy, M. and Lyerly, H.K. (2013): Minimization of heat wave morbidity and mortality; American Journal of Preventive Medicine, v. 44, no. 3, p. 274-282.

Krewski, D., Burnett, R., Jerrett, M., Pope, C. A., Ranham, D., Calle, E., Thurston, G., and Thun, M. (2005): Mortality and long-term exposure to ambient air pollution: ongoing analyses based on the American Cancer Society cohort; Journal of Toxicology and Environmental Health - Part A, no. 68, p. 1093-1109.

Künzli, N., Avol, E., Wu, J., Gauderman, W. J., Rappaport, E., Millstein, J., Bennion, J., McConnel, R., Gilliland, F. D., Berhane, K., Lurmann, F., Winer, A., and Peters, J. M. (2006): Health effects of the 2003 southern California wildfires on children; American Journal of Respiratory and Critical Care Medicine, v. 174, no. 11, p. 1221-1228.

Laforce, S., Simard, M., Leconte, R., and Brissette, F. (2011): Climate change and floodplain delineation in two southern Quebec river basins; Journal of the American Water Resources Association, v. 47, no. 4, p. 785-799.

Lake, I. R., Gillespie, I. A., Bentham, G., Nichols, G. L., Lane, C., Adak, G. K., and Threlfall, E. J. (2009): A re-evaluation of the impact of temperature and climate change on foodborne illness; Epidemiology and Infection, v. 137, no. 11, p. 1538-1547.

Lamy, S., and Bouchet, V. (2008): Air quality, climate change and health; in Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity; Health Canada, Ottawa, Ontario.

Larson T., Su J., Baribeau A.M., Buzzelli M., Setton E., and Brauer M. (2007): A spatial model of urban winter woodsmoke concentrations in Vancouver, B.C; Environmental Science & Technology, no. 41, p. 2429-2436.

Leighton, P. A., Koffi, J. K., Pelcat, Y., Lindsay, L. R., and Ogden, N. H. (2012): Predicting the speed of tick invasion: An empirical model of range expansion for the Lyme disease vector Ixodes scapularis in Canada; Journal of Applied Ecology, v. 49, no. 2, 457-464.

Lemelin, H., Matthews, D., Mattina, C., McIntyre, N., Johnston, M., Koster, R., and Weenusk First Nation at Peawanuck (2010): Climate change, wellbeing and resilience in the Weenusk First Nation at Peawanuck: the Moccasin Telegraph goes global; Rural and Remote Health, v. 10, no. 2, p. 1333.

Lemmen, D. S., Warren, F. J., Lacroix, J., and Bush, E. (2008): From impacts to adaptation: Canada in a changing climate 2007; Government of Canada, Ottawa, Ontario.

Lesnikowski, A. C., Ford, J. D., Berrang-Ford, L., Paterson, J. A., Barrera, M., and Heymann, S. J. (2011): Adapting to health impacts of climate change: a study of UNFCCC Annex I parties; Environmental Research Letters, v. 6, no. 4.

Lowe, D., Ebi, K.L., and Forsberg, B. (2011): Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves; International Journal of Environmental Research and Public Health, no. 8, p. 4623-4648.

Maibach, E., Nisbet, M., and Weathers, M. (2011): Conveying the human implications of climate change: a climate change communication primer for public health professionals; George Mason University Center for Climate Change Communication, Fairfax, VA.

Mak, S., Morshed, M., and Henry, B. (2010): Ecological niche modeling of Lyme disease in British Columbia, Canada; Journal of Medical Entomology, v. 47, no. 1, p. 99-105.

Maller, C. J. and Strengers, Y. (2011): Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward; Health Promotion International, v. 26, no. 4, p. 492-498.

Mancini, R. (2008): Kitchen violations: doing the right thing at home; The Canadian Journal of Canadian Medical Education, v. 20, no. 1, p. 47-48.

Marcheggiani, S., Puccinelli, C., Ciadamidaro, S., Bella, V. D., Carere, M., Blasi, M. F., Pacini, N., Funari, E., and Mancini, L. (2010): Risks of water-borne disease outbreaks after extreme events; Toxicological and Environmental Chemistry, v. 92, no. 3, 593-599.

Marsden, W. (2011): Cities feeling the heat; Montreal Gazette, January 29.

Martel, B., Giroux, J., Gosselin, P., Chebana, F., Ouarda, T., and Charron, C. (2010): Indicateurs et seuils météorologiques pour les systèmes de veille-avertissement lors de vagues de chaleur au Québec; Institut National de Santé Publique du Québec; INRS-ETE.

McClymont Peace, D. and Myers, E. (2012): Community-based participatory process - Climate change and health adaptation program for Northern First Nations and Inuit in Canada; International Journal of Circumpolar Health, no. 71, p. 18412.

McGranahan, G., Balk, D., and Anderson, B. (2007): The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones; Environment & Urbanization, v. 19, no. 1, p. 17-37.

McLeman, R., Brcklacich, M., Woodrow, M., Vodden, K., Gallaugher, P., and Sander-Regier, R. (2011): Opportunities and barriers for adaptation and local adaptation planning in Canadian rural and resource-based communities; Climate Change Adaptation in Developed Nations, p. 449-459.

McMichael, C., Barnett, K. M., and McMichael, A. J. (2012): An ill wind? Climate change, migration and health; Environmental Health Perspectives, v. 120, no. 5, p. 646-654.

McMichael, A. J., Neira, M., and Heymann, D. L. (2008): World Health Assembly 2008: climate change and health; The Lancet, v. 371, no. 9628, no. 1895-1896.

McMichael, A.J., Woodruff, A.R., and Hales, S. (2006): Climate change and human health: Present and future risks; The Lancet, v. 367, no. 9513, p. 842.

Meakin, S. and Kurvits, T. (2009): Assessing the impacts of climate change on food security in the Canadian Arctic; <http://www.grida.no/files/publications/foodsec_updt_LA_lo.pdf>.

Medlock, J. M., Hansford, K. M., Schaffner, F., Versteirt, V., Hendrickx, G., Zeller, H., and Bortel, W. V. (2012): A review of the invasive mosquitoes in Europe: ecology, public health risks and control options; Vector-Borne and Zoonotic Diseases, v. 12, no. 6.

Meier-Stephenson, V., Langley, J. M., Drebot, M., and Artsob, H. (2007): Encephalitis in the summer: a case of snowshoe hare (California serogroup) virus infection in Nova Scotia; Canada Communicable Disease Report - Relevé Des Maladies Transmissibles Au Canada, v. 33, no. 11, p. 23-26.

Messier, V., Lévesque, B., Proulx, J., Rochette, L., Libman, M. D., Ward, B. J., Serhir, B., Couillard, M., Ogden, N. H., Dewailly, E., Hubert, B., Déry, S., Barthe, C., Murphym D., and Dixon, B. (2009): Seroprevalence of toxoplasma gondii among Nunavik Inuit (Canada); Zoonoses and Public Health, v. 56, no. 4, p.188-197.

Millins, C., Reid, A., Curry, P., Drebot, M. A., Andonova, M., Buck, P., and Leighton, F. A. (2011): Evaluating the use of house sparrow nestlings as sentinels for West Nile Virus in Saskatchewan; Vector-Borne and Zoonotic Diseases, v. 11, no. 1, p. 53-58.

Moffatt, H. and Struck, S. (2011): Water-borne disease outbreaks in Canadian Small Drinking Water Systems.

Moore, D., Copes, R., Fisk, R., Joy, R., Chan, K., and Brauer, M. (2006): Population health effects of air quality changes due to forest fires in British Columbia in 2003: estimates from physician-visit billing data; Canadian Journal of Public Health, v. 97, no. 2, p. 105-108.

Morrissey, S. A. and Reser, J. P. (2007): Natural disasters, climate change and mental health considerations for rural Australia; Australian Journal of Rural Health, v. 15, no. 2, p. 120-125.

Morse, B.W. and Zakrison, M. (2010): The Impact on the Inuit of Environmental Degradation to the Canadian Arctic; Common Law World Review, v. 39, no. 1, p. 48-68.

Nakazawa, Y., Williams, R., Peterson, A. T., Mead, P., Staples, E., and Gage, K. L. (2007): Climate change effects on plague and tularemia in the United States; Vector-Borne and Zoonotic Diseases, v. 7, no. 4, p. 529-540.

National Collaborating Centre for Environmental Health (2008): Current evidence on the effectiveness of interventions during heat episodes; Vancouver, <http://www.ncceh.ca/sites/default/files/Heat_Interventions_Sept_2008.pdf>.

Neria, Y., Nandi, A., and Galea, S. (2008): Post-traumatic stress disorder following disasters: a systematic review; Psychological Medicine, v. 38, no. 4, p. 467-480.

New York Panel on Climate Change (2010): Climate change adaptation in New York City: Building at risk management response; Annals of the New York Academy of Sciences, no. 1196, p. 1-3.

Ng, V. and Sargeant, J. M. (2012): A stakeholder-informed approach to the identification of criteria for the prioritization of zoonoses in Canada; PLoS ONE, v. 7, no. 1.

Nitschke, M., Tucker, G. R., and Bi, P. (2007): Morbidity and mortality during heat waves in Metropolitan Adelaide; Medical Journal of Australia, v. 187, no. 11-12, p. 662-665.

Norval, M., and Halliday, G. M. (2011): The consequences of UV-induced immunosuppression for human health; Hotochemistry and Photobiology, v. 87, no. 5, p. 965-977.

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., Erwin, K. N., and Levin, E. D. (2009): The toxicology of climate change: environmental contaminants in a warming world; Environment International, v. 35, no. 6, p. 971-986.

NRTEE [National Round Table on the Environment and the Economy] (2011): Paying the price: the economic impacts of climate change for Canada.

OCFP [Ontario College of Family Physicians] (2011): Health effects of climate change: An information brochure for family physicians from the Ontario College of Family Physicians; Toronto, Ontario.

Ogden, N. H., Lindsay, L. R., Hanincová, K., Barker, I. K., Bigras-Poulin, M., Charron, D. F., Heagy, A., Francis, C. M., O'Callaghan, C. J., Schwartz, I., and Thompson, R. A. (2008b): Role of migratory birds in introduction and range expansion of Ixodes scapularis ticks and of Borrelia burgdorferi and Anaplasma phagocytophilum in Canada; Applied and Environmental Microbiology, no. 74, p. 1780-1790.

Ogden, N.H., Bouchard, C., Kurtenbach, K., Margos, G., Lindsay L.R., Trudel, L., Nguon, S., and Milford, F. (2010): Active and passive surveillance and phylogenetic analysis of Borrelia burgdorferi elucidate the process of Lyme disease risk emergence in Canada; Environmental Health Perspectives, v. 118, no. 7, p. 909-14.

Ogden, N. H., Margos, G., Aanensen, D. M., Drebot, M. A., Feil, E. J., Hanincová, K., Schwartz, I., Tyler, S., and Lindsay, L. R. (2011): Investigation of genotypes of Borrelia burgdorferi in Ixodes scapularis ticks collected during surveillance in Canada; Applied and Environmental Microbiology, v. 77, no. 10, p. 3244-3254.

Ogden, N. H., St.-Onge, L., Barker, I. K., Brazeau, S., Bigras-Poulin, M., Charron, D. F., Francis, C. M., Heagy, A., Lindsay, L. R., Maarouf, A., Michel, P., Milord, F., O'Callaghan, C. J., Trudel, L., and Thompson, R. A. (2008a): Risk maps for range expansion of the Lyme disease vector, Ixodes Scapularis, in Canada now and with climate change; International Journal of Health Geographics, v. 7, no. 24.

Orihel, D. M., Bird, D. F., Brylinsky, M., Chen, H., Donald, D. B., Huang, D. Y., Giani, A., Kinniburgh, D., Kling, H., Kotak, B. G., Leavitt, P. R., Nielson, C. C., Reedyk, S., Rooney, R. C., Watson, S. B., Zurawell, R. W., and Vinebrooke, R. D. (2012): High microcystin concentrations occur only at low nitrogen-to-phosphorus ratios in nutrient-rich Canadian lakes; Canadian Journal of Fisheries and Aquatic Sciences, v. 69, no. 9, p. 1457-1462.

Osberghaus, D., Finkel, E., and Pohl, M. (2010): (Individual adaptation to climate change: the role of information and perceived risk; Discussion Paper No. 10-061, Centre for European Economic Research.

Ostry, A., Ogborn, M., Bassil, K. L., Takaro, T. K., and Allen, D. M. (2010): Climate change and health in British Columbia: projected impacts and a proposed agenda for adaptation research and policy; International Journal of Environmental Research and Public Health, v. 7, no. 3, p. 1018-1035.

Owens et al. 2012. Public health in the Canadian Arctic: contributions from International Polar Year research. <http://link.springer.com/article/10.1007%2Fs10584-012-0569-3>.

Pabbaraju, K., Ho, K. C. F., Wong, S., Fox, J. D., Kaplen, B., Tyler, S., Drebot, M., and Tilley, P. A. G. (2009): Surveillance of mosquito-borne viruses in Alberta using reverse transcription polymerase chain reaction with generic primers; Journal of Medical Entomology, v. 46, no. 3, p. 640-648.

Paerl, H. W. and Huisman, J. (2009): Climate change: a catalyst for global expansion of harmful cyanobacterial blooms; Environmental Microbiology Reports, v. 1, no. 1, p. 27-37.

Paerl, H. W. and Huisman, J. (2008): Climate: blooms like it hot - a link exists between global warming and the worldwide proliferation of harmful cyanobacterial blooms; Science, v. 320, no. 5872, p. 57-58.

Pajot, M. and Aubin, L. (2012): Assessing health vulnerability to climate change in the region of Peel – summary; Region of Peel, Ontario.

Parkinson, A. J. (2010a): Sustainable development, climate change and human health in the Arctic; International Journal of Circumpolar Health, v. 69, no. 1, p. 99-105.

Parkinson, A. J. (2010b): Arctic human health initiative: a contribution to the International Polar Year; Circumpolar Health Supplements, no. 6, p. 1-46.

Parkinson, A. J. and Evengard, B. (2009): Climate change, its impact on human health in the Arctic and the public health response to threats of emerging infectious diseases; Global Health Action, no. 2, p. 1-3.

Paterson, J. A., Ford, J. D., Berrang Ford, L., Lesnikowski, A., Berry, P., Henderson, J., and Heymann, J. (2012): Adaptation to climate change in the Ontario public health sector; BMC Public Health, v. 12, p. 452.

Paterson J.A., Berry, P., Varangu, L., and Waddington, K. (2013): Preparing health care facilities in Canada for climate change; report submitted to the Nova Scotia Department of the Environment, Climate Change Adaptation Fund.

Pichora, E. C., and Marrett, L. D. (2010): Sun behaviour in Canadian children: results of the 2006 National Sun Survey; Canadian Journal of Public Health, v. 101, no. 4, p. 14-18.

Polain, J. D., Berry, H. L., and Hoskin, J. O. (2011): Rapid change, climate adversity and the next 'big dry': Older farmers' mental health; Australian Journal of Rural Health, v. 19, no. 5, p. 239-243.

Potera, C. (2011): Indoor air quality: climate change impacts indoor environment; Environmental Health Perspectives, v. 119, no. 9, p. A382.

Poutiainen, C., Berrang-Ford, L., Ford, J., and Heymann, J. (2013): Civil society organizations and adaptation to the health effects of climate change in Canada; Public Health, <http://www.sciencedirect.com/science/article/pii/S0033350613000711>.

PSC [Public Safety Canada] (2013a): Lyme disease fact sheet. <http://www.phac-aspc.gc.ca/id-mi/lyme-fs-eng.php>.

PSC [Public Safety Canada] (2013b): Maps and stats – West Nile Virus monitor; <http://www.phac-aspc.gc.ca/wnv-vwn/index-eng.php>.

PSC [Public Safety Canada] (2013a): Canadian Disaster Database (CDD); <http://cdd.publicsafety.gc.ca/dtpg-eng.aspx?cultureCode=en-Ca&provinces=9&eventTypes=%27WF%27&eventStartDate=%2720110101%27%2c%2720111231%27&normalizedCostYear=1&dynamic=false&eventId=1025>.

PSC [Public Safety Canada] (2013b): Canadian Disaster Database (CDD); <http://cdd.publicsafety.gc.ca/dtpg-eng.aspx?cultureCode=en-Ca&provinces=2&eventTypes=%27FL%27&eventStartDate=%2720090101%27%2c%2720091231%27&normalizedCostYear=1&eventId=1030>.

PSC [Public Safety Canada] (2013c): Canadian Disaster Database (CDD) <http://cdd.publicsafety.gc.ca/dtpg-eng.aspx?cultureCode=en-Ca&provinces=5&eventTypes=%27HU%27&eventStartDate=%2720100101%27%2c%2720101231%27&normalizedCostYear=1&dynamic=false&eventId=555>.

Public Health Agency of Canada (2014): Lyme disease and other tick-borne diseases: Information for healthcare professionals; <http://www.phac-aspc.gc.ca/id-mi/tickinfo-eng.php>.

RAND (2011): Building community resilience to disasters: a roadmap to guide local planning; Research Highlights, RAND Health.

Ravel, A., Smolina, E., Sargeant, J. M., Cook, A., Marshall, B., Fleury, M. D., and Pollari, F. (2010): Seasonality in human salmonellosis: Assessment of human activities and chicken contamination as driving factors; Foodborne Pathogens and Disease, v. 7, no. 7, p. 785-794.

Region of Peel (2006): West Nile Virus in the region of Peel; Region of Peel, Ontario.

Region of Peel (2011): Peel climate change strategy: a strategic plan for climate change for the Geographic region of Peel.

Riedel, D. (2004): Human health and well-being; in (ed.) Lemmen, D.S. and Warren, F.J.; Climate change impacts and adaptation: A Canadian perspective. Natural Resources Canada, Ottawa.

Robine, J. M., Cheung, S. L., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J. P., and Herrmann, F. R. (2008): Death toll exceeded 70,000 in Europe during the summer of 2003; Comptes Rendus Biologies, v. 331, no. 2, p. 171-178.

Robinson, B., Alatas, M. F., Robertson, A., and Steer, H. (2011): Natural disasters and the lung; Respirology, v. 16, no. 3, p. 386-395.

Rosenzweig, C., Solecki, W. D., Hammer, S. A., and Mehrotra, S. (2011): Climate change and cities: first assessment report of the urban climate change research network; Cambridge University Press, Cambridge, United Kingdom.

Rylander, C., Odland, J. O., and Sandanger, T. M. (2011): Climate change and environmental impacts on maternal and newborn health with focus on Arctic populations; Global Health Action, v. 4.

Safronetz, D., Drebot, M. A., Artsob, H., Cote, T., Makowski, K., and Lindsay, L. R. (2008): Sin Nombre virus shedding patterns in naturally infected deer mice (Peromyscus maniculatus) in relation to duration of infection; Vector-Borne and Zoonotic Diseases, v. 8, no. 1, p. 97-100.

Salam, M.T., Islam, T., Gauderman, J., and Gilliland, F.D. (2009): Roles of arginase variants, atopy, and ozone in childhood asthma; Journal of Allergy and Clinical Immunology, no. 123, p. 596–602.
Item 1 - <http://www.sciencedirect.com/science/article/pii/S0091674908024354>
Item 2 - <http://www.sciencedirect.com/science/article/pii/S0091674908024354>.

Salb, A. L., Barema, H. W., Elkin, B. T., Thompson, R. C., Whiteside, D. P., Black, S. R., Dubey, J. P., and Kutz, S. J. (2008): Dogs as sources and sentinels of parasites in humans and wildlife, northern Canada; Emerging Infectious Diseases, v. 14, no. 1, p. 60-63.

Salcioglu, E., Basoglu, M., and Livanou, M. (2007): Post-traumatic stress disorder and comorbid depression among survivors of the 1999 earthquake in Turkey; Disasters, v. 31, no. 2, p. 115-129.

Sampasa-Kanyinga, H., Lévesque, B., Anassour-Laouan-Sidi, E., Côté, S., Serhir, B., Ward, B. J., Libman, M. D., Drebot, M. A., Ndao, M., and Dewailly, E. (2012): Zoonotic Infections in Native Communities of James Bay, Canada; Vector-Borne and Zoonotic Diseases, v. 12, no. 6, p. 473-481.

Schenck, P., Ahmed, K. A., Bracker, A., and DeBernardo, R. (2010): Climate change, indoor air quality and health; U.S. Environmental Protection Agency.

Schmidt, C. W. (2011): Black carbon: the dark horse of climate change drivers; Environmental Health Perspectives, v. 119, no. 4, p. A172-175.

Seguin, J. (2008): Human health in a changing climate: a Canadian assessment of vulnerabilities and adaptive capacity; Health Canada, Ottawa, Ontario.

Seguin, J. and Berry, P. (2008): Synthesis Report; in Human Health and a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity; Health Canada, Ottawa, Ontario.

Shaw, J., Taylor, R.B., Forbes, D.L., Solomon, S., and Ruz, M.H. (1998): Sensitivity of the coasts of Canada to sea-level rise; Geological Survey of Canada; Ottawa, Ontario, 79 p.

Sheridan, S. C. (2006): A survey of public perception and response to heat warnings across four North American cities: an evaluation of municipal effectiveness; International Journal of Biometeorology, v. 52, no. 1, p. 3-15.

Shindell, D., Kuylenstierna , J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S. C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V, Hicks, K, Oanh, N., Milly, G., Williams, M., Demkine, V., and Fowler, D. (2013): Simultaneously mitigating near-term climate change and improving human health and food security; Science, v. 335, no. 6065, p. 183-189.

Simon, A., Chambellant, M., Ward, B. J., Simard, M., Proulx, J. F., Levesque, B., Bigras-Poulin, M., Rousseau, A. N., and Ogden, N. H. (2011): Spatio-temporal variations and age effect on Toxoplasmagondii seroprevalence in seals from the Canadian Arctic; Parasitology, v. 138, no. 11, p. 1362-1368.

Smargiassi, A., Brand, A., Fournier, M., Tessier, F., Goudreau, S., Rousseau, J., and Benjamin, M.A. (2012): Spatiotemporal land-use regression model of winter fine particulate levels in residential neighbourhoods; Journal of Exposure Science and Environmental Epidemiology, v. 22, no. 4, p. 331-8.

Somasundaram, D. J. and Van De Put, W. A. (2006): Management of trauma in special populations after a disaster; Journal of Clinical Psychiatry, v. 67, Suppl. 2, p. 64-73.

Statistics Canada. (2011): Census; <http://www12.statcan.gc.ca/census-recensement/index-eng.cfm>.

Stern, N. (2006): The Stern review on the economics of climate change, Cambridge University Press, Cambridge, UK.

Sumaila, U. R., Cheung, W., Lam, V., Pauly, D., and Herrick, S. (2011): Climate change impacts on the biophysics and economics of world fisheries; Nature Climate Change; 1:449-456.

Tagaris, E., Manomaiphiboon, K., Liao, K. J., Leung, L.R., Woo, J. H., He, S., Amar, P., and Russell, A. G. (2007): Impacts of global climate change and emissions on regional ozone and fine particulate matter concentrations over the United States; Journal of Geophysical Research, v. 112, issue D14312.

Taylor, J., Lai, K. M., Davies, M., Clifton, D., Ridley, I., and Biddulph, P. (2011): Flood management: Prediction of microbial contamination in large-scale floods in urban environments; Environment International, v. 37, no. 5, p. 1019-1029.

ten Veldhuis, J. A. E., Clemens, F. H. L. R., Sterk, G., and Berends, B. R. (2010): Microbial risks associated with exposure to pathogens in contaminated urban flood water; Water Research, v. 44, no. 9, p. 2910-2918.

The Aspen Institute (2011): The shared future: a report of the Aspen Institute Commission on Arctic Climate Change; The Aspen Institute, Energy and Environment Program.

The Lung Association (2008): Majority of Canadians unfamiliar with Air Quality Index; Lung Association survey; <http://www.lung.ca/media-medias/news-nouvelles_e.php?id=114>.

Thielman, A. and Hunter, F. F. (2006): Establishment of Ochlerotatusjaponicus (Diptera: Culicidae) in Ontario, Canada; Journal of Medical Entomology, v. 43, no. 2, p. 138-142.

Thomas, M. K., Charron, D. F., Waltner-Toews, D., Schuster, C. J., Maarouf, A. R., and Holt, J. D. (2006): A role of high impact weather events in waterborne disease outbreaks in Canada; International Journal of Environmental Health Research, v. 16, no. 3, p. 167-180.

Thomas, M.K., Murray, R., Flockhart, L., Pintar, K., Pollari, F., Fazil, A., Nesbitt, A., and Marshall, B. (2013): Estimates of the burden of foodborne illness in Canada for 30 specified pathogens and unspecified agents, circa 2006; Foodborne Pathogens and Disease, v. 10, no. 7, p. 639-648.

Thomas, P., Swaminathan, A., and Lucas, R. M. (2012): Climate change and health with an emphasis on interactions with ultraviolet radiation: a review; Global Change Biology, v. 18, no. 8, p. 2392-2405.

Toronto Public Health (2011a): Implementation of a map-based heat vulnerability assessment and decision support system; Final Project Report and Map Series.

Toronto Public Health (July 2011b): Protecting vulnerable people from health impacts of extreme heat. <http://www.toronto.ca/legdocs/mmis/2011/hl/bgrd/backgroundfile-39468.pdf>.

Tuomainen, A., Markku, S., and Sieppi, A. (2004): Indoor air quality and health problems associated with damp floor coverings; International Archives of Occupational and Environmental Health, no. 77, p. 222–226.

Union of Concerned Scientists (2011): Climate change and your health: rising temperatures, worsening ozone pollution.

US CDC [United States Centers for Disease Control and Prevention], Environmental Protection Agency (EPA), National Oceanic and Atmospheric Agency (NOAA), and American Water Works Association (AWWA) (2010): When every drop counts: protecting public health during drought conditions— a guide for public health professionals; U.S. Department of Health and Human Services, Atlanta. <http://www.cdc.gov/nceh/ehs/Docs/When_Every_Drop_Counts.pdf>.

US CDC [United States Centers for Disease Control and Prevention] (2012): Reentering your flooded home; <http://emergency.cdc.gov/disasters/mold/reenter.asp>.

US EPA [United States, Environmental Protection Agency] (2008): Health Security through Healthy Environments; Briefing Note 01.

US EPA [United States, Environmental Protection Agency] (2012): Chapter 6 - Benefits of reducing BC emissions; in Report to Congress on Black Carbon; Department of the Interior, Environment and Related Agencies Appropriations Act, 2010. 388 p. <http://www.epa.gov/blackcarbon>.

van der Leun, J. C., Piacentini, R. D., and de Gruijl, F. R. (2008): Climate change and human skin cancer; Photochemical and Photobiology Science, no. 7, p. 730-733.

Vida, S., Durocher, M., Ouarda, T.B., and Gosselin, P. (2012): Relationship between ambient temperature and humidity and visits to mental health emergency departments in Quebec; Department of Psychiatry, McGill University and McGill University Health Centre, Montreal, Quebec; v. 63, no. 11, p. 1150-3; <http://www.ncbi.nlm.nih.gov/pubmed/23117515>.

Vrbova, L., Stephen, C., Kasman, N., Boehnke, R., Doyle-Waters, M., Chablitt-Clark, A., Gibson, B., FitzGerald, M., and Patrick, D. M. (2010): Systematic review of surveillance systems for emerging zoonoses; Transboundary and Emerging Diseases, v. 57, no. 3, p. 154-161.

Wald, M. L. and Schwartz, J. (2012): Weather extremes leave parts of U.S. grid buckling; The New York Times, July 25.

Wall, E., and Marzall, K. (2006): Adaptive capacity for climate change in Canadian rural communities; Local Environment, v.11, no. 4, p. 373-397.

Water Research Foundation (2013): Opportunities for managing climate change by applying adaptive management; Water Research Foundation, Denver, CO.

Wang, J., Ogden, N. H., and Zhu, H. (2011): The impact of weather conditions on Culex pipiens and Culex restuans (Diptera: Culicidae) abundance: A case study in Peel Region; Journal of Medical Entomology, v. 48, no. 2, p. 468-475.

Wheaton, E., Kulshreshtha, S., Wittrock, V., and Koshida, G. (2008): Dry times: hard lessons from the Canadian drought of 2001 and 2002; Canadian Geographer, v. 52, no. 2, p. 241-262.

Winter, J. G., DeSellas, A. M., Fletcher, R., Heintsch, L., Morley, A., Nakamoto, L., and Utsumi, K. (2011): Algal blooms in Ontario, Canada: Increases in report since 1994; Lake and Reservoir Management, no. 27, p. 105-112.

Wittrock, V., Kulshrestha, S. N., and Wheaton, E. (2011): Canadian prairie rural communities: their vulnerabilities and adaptive capacities to drought; Mitigation and Adaptation Strategies for Global Change, v. 16, no. 3, p. 267-290.

Wobeser, G., Campbell, G. D., Dallaire, A., and McBurney, S. (2009): Tularemia, plague, yersiniosis, and Tyzzer's disease in wild rodents and lagomorphs in Canada: a review; Canadian Veterinary Journal, v. 50, no. 12, p. 1251-1256.

WHO [World Health Organization] (2008): Protecting health from climate change; World Health Organization, Geneva, Switzerland.

WHO [World Health Organization (WHO) (2010): Protecting health in an environment challenged by climate change: European Regional Framework for Action; World Health Organization, Copenhagen, Denmark.

WHO [World Health Organization] (2012a): International agency for research on cancer; Press Release No. 213, Diesel Engine Exhaust Carcinogenic. <http://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf>.

WHO [World Health Organization] (2012b): Protecting health from climate change: vulnerability and adaptation assessment; World Health Organization, Geneva, Switzerland. <http://www.who.int/globalchange/publications/Final_Climate_Change.pdf>.

WMO [World Meteorological Organization] (2011): Scientific assessment of ozone depletion: 2010; Global Ozone Research and Monitoring Project-Report No. 52; Geneva, Switzerland.

WMO [World Meteorological Organization] (2013): Annual climate statement confirms 2012 as among top ten warmest years; Press Release No. 972; <http://www.wmo.int/pages/mediacentre/press_releases/pr_972_en.html>.

WTO [World Tourism Organization] (2008): Climate change and tourism: Responding to global challenges; World Tourism Organization, Madrid, Spain; <http://www.e-unwto.org/content/kk9027/?p=d7a22d4758ad49e08d57c5d0d0e8b956&pi=0>.

Zanobetti A. and Schwartz, J. (2011): Ozone and survival in four cohorts with potentially predisposing diseases; American Journal of Respiratory and Critical Care Medicine, v. 184, no. 7, p. 836-841.

Ziska, L., Knowlton, K., Rogers, C., Dalan, D., Tierney, N., Elder, M. A., Filley, W., Shropshire, J., Ford, L. B., Hedberg, C., Fleetwood, P., Hovanky, K. T., Kavanaugh, T., Fulford, G., Vrtis, R. F., Patz, J. A., Portnoy, J., Coates, F., Bielory, L., and Frenz, D. (2011): Recent warming by latitude associated with increased length of ragweed pollen season in central North America; Proceedings of the National Academy of Sciences of the United States of America, v. 108, no. 10, p. 4248-4251.

Ziska, L.H., Epstein, P.R., and Schlesinger, W.H. (2009): Rising CO2, climate change, and public health: exploring the links to plant biology; Environmental Health Perspectives, v. 117, no. 2, p. 155-158.

# CHAPTER 8:
# WATER AND TRANSPORTATION INFRASTRUCTURE

Lead Authors:

**Jean Andrey** *(University of Waterloo)*, **Pamela Kertland**
and **Fiona Warren** *(Natural Resources Canada)*

Contributing Authors:

**Linda Mortsch** *(Environment Canada)*, **Adam Garbo**
and **Julien Bourque** *(Natural Resources Canada)*

Recommended Citation:

Andrey, J., Kertland, P. and Warren, F.J. (2014): Water and Transportation Infrastructure; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, (ed.) F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 233-252.

# TABLE OF CONTENTS

# KEY FINDINGS

- Well-maintained infrastructure is more resilient to a changing climate. This is especially true with respect to gradual changes in temperature and precipitation patterns, which in many cases can be addressed through regular maintenance and normal upgrade cycles or adjustments to operation and maintenance policies and procedures. Key vulnerabilities relate to the impacts of extreme weather events, which can overwhelm the capacity of water infrastructure, leading to flooding and water contamination issues, and cause damage to transportation networks with resulting disruption of access and supply chains.

- The work of the PIEVC (Public Infrastructure Engineering Vulnerability Committee) has been an important driver of progress on understanding how to adapt Canada's infrastructure to climate change over the past five years. The broadly applicable, risk-based assessment protocol developed by the PIEVC allows engineers and planners to view and address climate change as one factor, among many, that affects system resiliency and plan accordingly.

- Consideration of climate change as an element of adaptive asset management encourages consideration of climate factors as part of ongoing system monitoring, and informs decisions regarding the most cost-effective approaches for infrastructure design, operation and maintenance.

- Codes, standards and related instruments (CSRI) are recognized as a potentially important driver of infrastructure adaptation, but there are few examples of CSRI in Canada that considered historic changes or projected future changes in climate when they were developed. Further assessment of current and future climate risks to infrastructure systems is required to inform appropriate adjustments to design codes and standards to address future climate.

# 1. INTRODUCTION

Infrastructure systems are a key area of concern for adaptation given their importance in supporting a wide range of social, economic and environmental goals, including public health, safety, economic development and environmental protection. Safe and reliable water supplies, protection from flooding, and dependable transportation networks are critical to all of the economic sectors discussed throughout the chapters of this report. In Canada, billions of dollars are spent annually on repairing, upgrading and expanding public infrastructure. For example, in 2011, $1.336 billion was spent to upgrade existing water treatment plants and commission new ones (Statistics Canada, 2013). Recent government budgets include significant and long-term investments in infrastructure funding, and needs for further infrastructure funding have been identified.

Infrastructure is designed to provide services over its lifetime, a period lasting anywhere from 10 to 100 years, and must be adapted over time to meet evolving circumstances, such as changes in technology, society and business (CCPE, 2008). Climate change presents a range of challenges for infrastructure design, construction, operation and maintenance, and is recognized as an additional factor that needs to be considered as Canada strives to maintain and improve existing infrastructure (Figure 1; Félio, 2012).

In the 2008 Canadian assessment, *From Impacts to Adaptation: Canada in a Changing Climate* (Lemmen et al., 2008), climate impacts on infrastructure were noted for all regions of Canada. Moreover, the synthesis of that report highlighted the vulnerability of communities and critical infrastructure to climate change. Since 2008, there has been a small but growing body of peer-reviewed literature focusing on adaptation and infrastructure in Canada, including analysis of the resilience of individual infrastructure systems (much of this work being conducted using the Public Infrastructure Engineering Vulnerability Committee (PIEVC) engineering protocol (Box 1)). In addition, information on climate change impacts and adaptive responses has been incorporated into various planning documents (e.g. the Region of Durham Community Climate Change Local Action Plan), has led to operational and structural changes (e.g. design of culverts for Transport Quebec's road infrastructure is required to account for increasing frequency and intensity of rain events likely under future climate conditions; Ouranos, 2010); and has contributed to development of policy guidance at the regional scale (*see* Case Study 2). However, little of this progress has been documented well within the scientific literature.

This chapter presents an introduction to this emerging field of study by focusing on water infrastructure (water supply, storm and waste water) and certain aspects of transportation. This chapter focuses on climate change impacts and adaptation in relation to physical infrastructure itself rather than the larger water resource or transportation systems of which it is a part[1]. Key sensitivities, impacts and adaptive responses are discussed using case studies to provide additional details on adaptation activities.

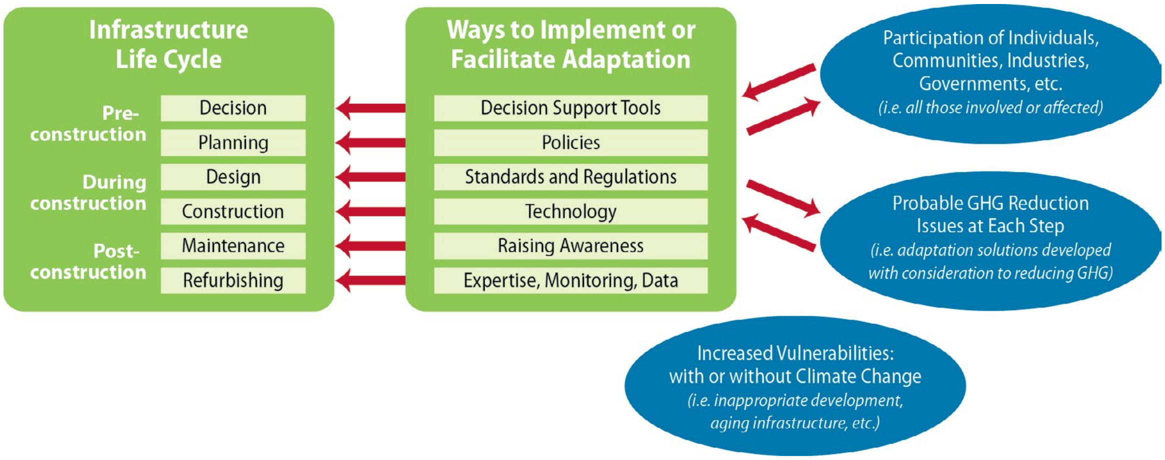


**FIGURE 1:** Adaptation in the infrastructure life cycle *(Source: Larrivée and Simonet, 2007)*.

---

[1] Note too, that a more comprehensive assessment of climate change impacts and adaptation in Canada's transportation sector is currently in development.

**BOX 1**

## CANADA'S PUBLIC INFRASTRUCTURE ENGINEERING VULNERABILITY COMMITTEE (PIEVC)

*(http://www.pievc.ca/e/index_.cfm)*

The Public Infrastructure Engineering Vulnerability Committee (PIEVC) is a national committee established to conduct an engineering assessment of the vulnerability of Canada's public infrastructure to the impacts of climate change. It involves all levels of government, engineering professionals, and non-governmental organizations. The goals of the PIEVC include ensuring the integration of climate change into the planning, design, construction, operation, maintenance and rehabilitation of public infrastructure in Canada.

The PIEVC initially focused on four aspects of public infrastructure in Canada: buildings, roads and associated structures, storm water and wastewater systems, and water resources. Products include the PIEVC Engineering Protocol, which is a formalized process that can be applied to any type of infrastructure to assess engineering vulnerability and risk from current and future climate impacts (Figure 2). As of September 2013, nearly 30 case studies using the protocol had been completed across the country (Table 1), and more are in progress. Results of using the PIEVC Protocol are also incorporated into a national knowledge base maintained by Engineers Canada, and have been used in a review of infrastructure codes, standards and design.

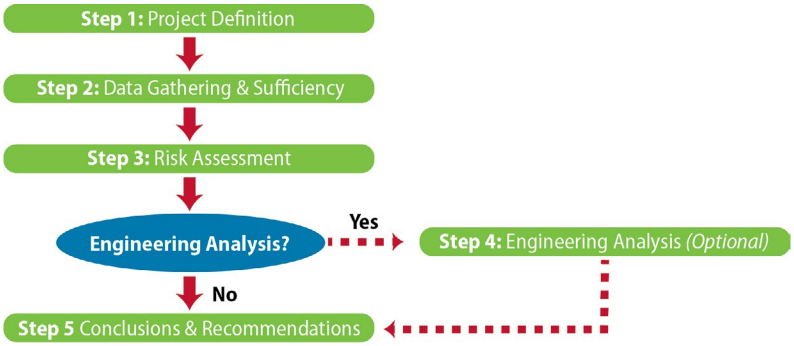


**FIGURE 2:** An overview of the PIEVC five step process to analyze the engineering vulnerability of an individual infrastructure to current and future climate *(Source: PIEVC, 2007)*.

| Case Study Topic | Host/ Partner |
|---|---|
| Buildings | |
| Thermosyphon Foundations in Warm Permafrost | Government of Northwest Territories |
| Government of Canada Tunney's Pasture Campus | Public Works and Government Services Canada |
| Three Public Buildings in Southwestern Ontario | Infrastructure Ontario |
| Current Engineering Building and New Addition | University of Saskatoon |
| Toronto Community Housing Building: 285 Shuter Street | Toronto Community Housing Corporation |
| Energy | |
| Toronto Hydro Electrical Supply and Delivery Infrastructure | Toronto Hydro |
| Transportation | |
| Quesnell Bridge | City of Edmonton |
| City of Sudbury Road Infrastructure | City of Sudbury |
| Coquihalla Highway – Hope to Merritt Section | BC Ministry of Transportation and Infrastructure |
| Highway 3 West of Yellowknife | Government of Northwest Territories |
| Culverts | City of Toronto Transportation Department |
| B.C. Yellowhead Highway 16 Between Vanderhoof and Priestly Hill | BC Ministry of Transportation and Infrastructure |
| Toronto Pearson Airport Infrastructure | Greater Toronto Airport Authority |

*Box 1 continued on next page*

| Case Study Topic | Host/ Partner |
|---|---|
| **Stormwater and Wastewater** | |
| Placentia Breakwater and Seawall Infrastructure | Town of Placentia and Government of Newfoundland and Labrador |
| Vancouver Sewerage Area Infrastructure | Metro Vancouver |
| Fraser Sewerage Area Infrastructure | Metro Vancouver |
| Claireville and G. Ross Lord Flood Control Dams | Toronto and Region Conservation Authority |
| Sandy Point Sewage Treatment Plan Upgrade | Municipality of the District of Shelburne |
| Stormwater Infrastructure | City of Castlegar |
| Sanitary Sewage System | Town on Prescott |
| Evaluation of Surface Water Drainage Systems in Trois-Rivières Centre | Trois-Rivières |
| Evaluation of City of Laval Rainwater Harvesting System | Ville de Laval |
| Stormwater and Wastewater Infrastructure | City of Welland |
| **Water Resources** | |
| Water Resources Infrastructure | City of Portage la Prairie |
| Water Supply Infrastructure | City of Calgary |

**TABLE 1:** Case studies completed using the PIEVC Engineering Protocol. Reports and summaries of each are available online at http://www.pievc.ca/e/doc_list.cfm?dsid=3.

## 2. WATER INFRASTRUCTURE

Some of the most significant and pervasive impacts of climate change in Canada will be related to water resources (Lemmen et al., 2008). Key threats to water infrastructure identified throughout the 2008 Assessment include extreme events (flooding, droughts and storms), permafrost degradation in northern regions, and lower water levels in many parts of the country, associated with higher temperatures. Reduced water quality and quantity will be experienced on a seasonal basis in every region of Canada, with remote and First Nations communities being especially vulnerable (e.g. Bourque and Simonet, 2008; Walker and Sydneysmith, 2008). The fundamental importance of water resources to a wide range of activities, including agriculture, energy production, transportation, community and recreation is also reflected throughout Lemmen et al. (2008), as well as in the preceding chapters of this report.

Recent case studies have more precisely identified the nature of potential vulnerabilities of water infrastructure to changing climate and have suggested approaches to enable adaptation (CCPE, 2008; Associated Engineering, 2011). Water infrastructure is essential for supplying water for community, industrial and agricultural use, storm water management, and control of inland and coastal flooding. Although the inaugural Canadian Infrastructure Report Card (Félio, 2012), did not analyze the implications of future climate change, it provided a self-reported snapshot of the state of current infrastructure systems. Stormwater management systems were the best of the infrastructure classes covered, being ranked "very good" in general. However, 12.5% of the systems fell below good conditions, largely due to concerns about pipes (Table 2). Drinking water systems, which include plants, reservoirs and pumping stations as well as transmission and distribution pipes, were rated good overall, with roughly 15% of drinking water systems rated fair to very poor based on the condition of specific components of the infrastructure system (Table 2). Wastewater infrastructure was also rated good overall, though the percentage ranked fair to very poor was considerably higher (e.g. ~30-40%) than for drinking water or stormwater systems (Félio, 2012). These results were based on voluntary input to the project from 123 municipalities across all provinces, representing 40.7% to 59.1% of the Canadian population (depending on infrastructure type).

|  | Rating |  |  |  |  |
|---|---|---|---|---|---|
| Type of System | Very Good | Good | Fair | Poor | Very Poor |
| Drinking water |  |  |  |  |  |
| • Plants, pumping stations & reservoirs | 12.6% | 73.1% | 9.8% | 4.3% | 0.3% |
| • Transmission & distribution pipes | 4.2% | 80.5% | 14.4% | 0.3% | 0.7% |
| Stormwater |  |  |  |  |  |
| • Pumping stations & stormwater facilities | 56.8% | 30.7% | 6.9% | 5.0% | 0.6% |
| • Collection systems | 40.5% | 36.2% | 17.7% | 4.9% | 0.8% |
| Wastewater |  |  |  |  |  |
| • Plants, pumping stations & storage | 16.0% | 43.7% | 34.5% | 5.7% | 0.1% |
| • Collection systems | 33.7% | 36.1% | 22.4% | 6.5% | 1.2% |

**TABLE 2:** Summary of Infrastructure Report Card ratings for drinking water, stormwater and wastewater *(from Félio, 2012).*

Adapting infrastructure involves several different approaches, often in combination, ranging from structural changes to non-structural or "soft" measures such as changes in policies and procedures that can be undertaken at different stages of the infrastructure life cycle as it is planned, rehabilitated or replaced (Figure 1). These measures can involve addressing issues directly by redesigning and upgrading infrastructure to deal with specific changes in climate (e.g. upsizing culverts to handle more intense precipitation events), and/or by enhancing the resilience of the system to climate change in general (e.g. regular maintenance of pipes, reducing stormwater runoff).

**BOX 2**

### CODES, STANDARDS AND RELATED INSTRUMENTS (CSRI)

The PIEVC project reviewed its water resource infrastructure case studies to identify recommendations for changes to Codes, Standards and Related Instruments (CSRI). Water resource infrastructure is subject to many types of CSRI, including regulations, codes and standards, local government by-laws and national guidelines. The PIEVC found the climate information used in the development of CSRI was not always readily available or identified, meaning that updating CSRI is not just a matter of updating the climate information contained within them. Recommendations for action on CSRI reflect the loss of stationarity in climate and enabling adaptation related to: 1) improving climate data; 2) the need for CSRI to address incremental options over the life cycle of infrastructure; 3) the need to expand the scope of CSRI to cover physical, functional and operational performance; and 4) the need for flexibility in design to adapt to climate change (PIEVC, 2012).

## 2.1 WATER AVAILABILITY AND SUPPLY

Robust and reliable water infrastructure is critical for the delivery of clean water. A changing climate can affect water availability through seasonal shifts in river flows (e.g. from earlier snowmelt and spring runoff), more intense precipitation events, longer dry spells and more frequent droughts, and lower lake levels (CCPE, 2008; *see also* Chapter 2). Changing ice conditions are also important to consider; for example more periods of frazil ice (accumulation of ice crystals in water) can block intake pipes (Associated Engineering, 2011).

Key concerns for supply commonly relate to competing demands for water, particularly in the context of climate-related reductions in availability at the same time that population, agricultural and industry needs are growing. Several studies across Canada have shown reduced water availability due to climate change (e.g. Forbes et al., 2011; Tanzeeba and Gan, 2012; *see also* Chapter 2 – An Overview of Canada's Changing Climate), with some regions, including the southern interior of British Columbia, the southern Prairies and southern Ontario being particularly vulnerable. Water supply systems may be limited by the quantity allowed in water withdrawal licenses and priorities of water rights, particularly during periods of drought (Genivar, 2007; Associated Engineering, 2011). In such cases, the focus of adaptation may be on water conservation measures by household and industrial consumers. The City of Calgary has set a goal to increase water-use efficiency, and thus reduce demands on the water system, by 30 percent over 30 years so that they can accommodate future growth while maintaining the amount of water removed from the river at 2003 levels (City of Calgary, 2007). Using multiple sources of water and multiple intake points may also increase resilience by allowing water operators to shift production from one intake to another if one source becomes compromised (Associated Engineering, 2011), by ice blockage or low water levels, for example.

## 2.2 WATER QUALITY

Water quality can be affected by climate and extreme weather in a number of ways. Key climate change concerns include: flooding, with immediate and longer-term effects on water quality; increased water turbidity and contamination from more intense precipitation events and drought, which could lead to lower water levels providing less dilution; and salinization of groundwater in coastal regions due to sea level rise.

Floods can not only change the quality of water at the water treatment system intake, but also pose risks to physical infrastructure and materials, such as water treatment chemicals stored on site (Genivar, 2007). Intense precipitation events can introduce more contaminants from rural and urban sources into intake water. Heavy rainfall events and subsequent erosion can also increase turbidity of intake water. This may be less of a concern in regions such as the Prairies, which already experience periods of high turbidity, because the water treatment systems usually include settling tanks. However, even in these regions, changes to the operation of the system and additional treatment technologies may be needed over time (Associated Engineering, 2011; Genivar, 2007).

Higher temperatures can result in taste and odour events requiring additional treatment (Associated Engineering, 2011). Wildfires can also negatively affect the quality of source water, with impacts lasting many years. For example, in the four years after the 2003 Lost Creek fire in Alberta, turbidity, total organic carbon and nitrogen in runoff increased, particularly during peak flows after rainstorms and during spring melt (Emelko et al., 2011). Such changes can result in increased water treatment costs (e.g. for chemicals) in systems already equipped to handle the impacts, or may require upgrading of infrastructure where water treatment systems are not sufficient (Associated Engineering, 2011; Emelko et al., 2011). While reservoirs may currently be capable of handling demands during an individual high demand period (e.g. a drought or a heat wave), vulnerabilities may occur when there are repeated periods of high demand (such as back-to-back extreme weather events), as the systems may not be able to replace depleted storage in the reservoir (Associated Engineering, 2011).

In systems that use chlorine, increased amounts may be required because chlorine decays more quickly in warmer water temperatures. While analysis of water treatment plants in Quebec found that most (80%) were able to treat the maximum historical levels of *microsystin-LR*, and that an increase in this toxin due to climate change would not represent a serious threat, other toxins may present challenges if current treatment methods are not efficient (Carrière et al., 2010). In such cases, different chemical treatment methods or other technologies would be needed.

The Portage La Prairie (Genivar, 2007) and Placentia (NFLD), PIEVC case studies identified risks to elements of the water treatment systems due to a changing climate. These included vulnerabilities associated with pre-treatment, softening and clarification, disinfection, storage, chemical storage, and valves and pipes – related to several climatic factors, including flooding, high temperatures, intense rain, drought, ice storms and intense wind (CCPE, 2008). The case studies note that some investment in infrastructure will be required to avoid loss of reputation or more severe future impacts. A similar study in Calgary, AB focused on key climate risks to water supply infrastructure, and concluded that the system was generally resilient to changing climate conditions (*see* Case Study 1).

For groundwater-dependent communities, including all of Prince Edward Island and approximately 90% of the rural population in Ontario, Manitoba and Saskatchewan, previous assessments have noted that changes in precipitation patterns may result in a decrease in recharge, particularly in shallow aquifers (e.g. Lemmen et al., 2008). For coastal communities, saltwater intrusion is expected to increase as a result of sea level rise (e.g. Vasseur and Catto, 2008). Recent analysis of groundwater supplies in several locations in Nova Scotia and Prince Edward Island found that, to date, salinity was due to geologic and anthropogenic factors such as water demand and over-extraction, rather than climatic changes and sea level rise (Ferguson and Beebe, 2012; ACASA, n.d.). In a study of Richibucto, New Brunswick, rising sea levels did play a role in lateral seawater intrusion in shallow- to intermediate-depth aquifers, but the effects were less significant than climate change effects on groundwater recharge and increased pumping (MacQuarrie et al., 2012). Enhanced mapping and assessment of groundwater resources would better enable water system managers to accurately detect the impact of human activity, geologic factors and climate change on water availability and quality.

### CASE STUDY 1

## CITY OF CALGARY WATER SUPPLY INFRASTRUCTURE VULNERABILITY ASSESSMENT

*(Source: Associated Engineering, 2011)*

In 2011, the City of Calgary, together with Engineers Canada, conducted a vulnerability risk assessment of its water supply infrastructure. The purpose of the study was to identify those components of its potable water supply system that were vulnerable to future climate change and extreme climate events. The PIEVC protocol was used to estimate the levels of exposure that the infrastructure will face under future climate change, with focus placed on the years 2020 and 2050. The assessment considered the entire water supply infrastructure owned and operated by the City within its boundaries, as well as the Elbow and Bow River watersheds.

Using historic climate data and climate change projections from an ensemble of global climate models, the team determined which climatic conditions pose the greatest risks to the design, construction, operation and management of the water supply infrastructure, as well as impacts on the watersheds with respect to water quality and quantity. Those climate variables expected to impact both the capacity and integrity of the water supply infrastructure are outlined in Table 3.

| Infrastructure components | Environmental Variables |
|---|---|
| **Water source** | |
| • Watersheds<br>• Glenmore Dam and Reservoir<br>• Ghost and Bearspaw Dams and Reservoirs | • Increase in minimum temperature<br>• Flooding<br>• Drought<br>• River flow changes<br>• Decreased snow pack<br>• Compounding events – forest fires |
| **Raw Water Intakes and Raw Water Pump Stations** | |
| • Glenmore Intake and Raw Water Pump Station<br>• Bearspaw Intakes and Raw Water Lift Stations | • Flooding<br>• Increase in freeze/thaw |
| **Treatment Processes** | |
| • Pre-treatment Facility<br>• Filtration<br>• Disinfection<br>• Storage<br>• Chemical Feed Systems<br>• Residuals Treatment | • Compounding events – forest fires<br>• Increase in minimum temperature<br>• Flooding<br>• Drought |
| **Storage and Distribution** | |
| • Linear Infrastructure<br>• Valves/Pipelines | • Increase in freeze/thaw |
| **Supporting Systems** | |
| • Supporting Physical Infrastructure<br>• Administration/Operations<br>• Electrical Power and Communications<br>• Transportation | • Increase in extreme temperature<br>• Flooding |

**TABLE 3:** City of Calgary water supply infrastructure components and negatively impacting climate variables.

Assessment results showed that, overall, the City of Calgary's water supply infrastructure is robust and adaptable to the gradual effects of future climate change, due in large part to the redundancies present within the City's water treatment plants, raw water sources and distribution systems that enhance the resiliency of the system. However, greater vulnerabilities were associated with extreme events such as flooding and drought, and compounding events were identified within these systems. The assessment team also highlighted areas requiring additional study.

Record flooding in Calgary in June 2013 provided a test to the resilience of the water supply infrastructure and its stormwater and wastewater systems. Published analysis of how the flooding impacted system performance was not available when this chapter was finalized. However, both water treatment plants in Calgary, Bearspaw and Glenmore, were able to continue to produce potable water throughout the event. This included a 1:500 peak flow event upstream of the Glenmore Plant on the Elbow River and a 1:100 year event on the Bow River. Some of the new treatment processes in place as a result of recent upgrades were severely tested with high turbidities from this event. Water restrictions were used to keep water demand at a lower level during the flood event (P. Fesko personal communication; City of Calgary, 2013).

## 2.3 STORMWATER AND WASTEWATER MANAGEMENT

Storm and wastewater management infrastructure represents the second largest category of capital investment in infrastructure in Canada (CCPE, 2008). These systems are often linked through their collection and transmission systems and both are affected by population growth, land use change and climate change.

Vulnerabilities in wastewater systems stem from a variety of sources. More frequent winter thaw events can increase the flow of cold surface runoff in combined sewer systems, reducing the water temperature. These shocks can affect the efficacy of biological nitrogen removal and secondary clarification processes (Plosz et al., 2009). More intense rainfall events and increased rain on frozen ground events are expected to increase the risk of stormwater infiltration into sanitary systems, creating more and larger combined sewer overflows (Urban Systems, 2010; Genivar, 2011). Increased heavy flows will also increase pumping requirements, thus increasing energy costs (Kerr Wood Leidal Associates Ltd, 2009) and in some cases, overwhelming pumping capacity. Pumping stations are also at risk of electrical failure during periods of extreme summer heat due to overheating of building electrical systems (Genivar, 2011). Direct physical impacts on systems from heavier rainfalls include the movement of debris that can block flows to culverts and catch basins, which in turn can result in localized flooding or erosion in surrounding areas, damaging the infrastructure.

There is increasing recognition that innovative solutions arising from interdisciplinary collaboration will be necessary to manage storm and waste water in a changing climate (Smith, 2009; Pyke et al., 2011). Urban flood events over the past two decades, combined with information about future climate change, have provided the impetus for better mapping of areas of risk, improved monitoring and maintenance of drainage systems, the separation of drainage systems from sanitary systems and the use of low-impact development (Marsalek and Schreier, 2009; Pyke et al., 2011).

Low-impact development is an approach to manage stormwater at its source, reduce contaminants in stormwater and slow runoff by changing the imperviousness of the surface and the materials through which water flows. One study found that an increase in rainfall intensities by 20% had the same impact on a combined sewer system as a 40% increase in impervious area (Kleindorfer et al., 2009). Another concluded that reducing impervious cover from 25 to 16 percent can significantly reduce stormwater runoff (Pyke et al., 2011).

Many cities have plans and programs such as downspout disconnection in place to separate storm and sanitary systems and reduce the flow of stormwater into the waste water system. The City of Toronto has increased monitoring and maintenance of its culvert system, while flood-prone communities, such as Cambridge and Milton, Ontario, are performing economic assessments of the implications of climate change for drainage infrastructure design (Scheckenberger et al., 2009). Actions may be more effective if done cooperatively at the basin scale (AMEC, 2012).

## 2.4 RESILIENCE AND CAPACITY TO ADAPT

While there is insufficient information available to undertake a full assessment of the resilience of water resource infrastructure to climate change across Canada, recent reports suggest that there is significant resilience in well-maintained systems. The PIEVC concluded that properly maintained infrastructure increases resilience to climate change by allowing the system to function as designed (CCPE, 2008). This finding was further confirmed in case studies completed since the 2008 report, and aligns with a broader assessment of the state of Canadian infrastructure, which highlights the importance of improving asset management (Félio, 2012). Several provinces in Canada have increased municipal requirements for asset management planning and have provided guidance to support this call (cf. Government of Ontario, 2012).

The PIEVC also identified the need to adjust engineering practices to adapt infrastructure design and operation to a changing climate. Engineers Canada prepared a draft set of principles of climate change adaptation for infrastructure engineers. This document is presently under consideration by the profession (David Lapp, personal communication). New guidance and tools to assist infrastructure owners are also emerging. For instance, a new guide for the assessment of hydrologic effects of climate change in Ontario was published (EBNFLO Environmental AquaResource Inc, 2010) and is complemented by on-line training.

Since conditions new to one region may already be experienced elsewhere, the exchange of information between owners/operators/engineers across regions can be helpful. In British Columbia, multi-year collaborative efforts on revising sea dyke guidelines in the province contributed to the development of a Sea Level Rise primer, which is applicable to other coastal regions as well (*see* Case Study 2).

Surveys provide an indication of current preparedness of system operators to address climate change. In 2012, the Canadian Water and Wastewater Association surveyed 100 Canadian water utilities representing a range of population sizes to determine their preparedness to manage projected impacts of climate change. They found that larger utilities (serving populations of 150 000 or more) were most advanced in terms of identifying risks of climate change.

CASE STUDY 2

## BRITISH COLUMBIA'S SEA DYKE GUIDELINES

Over the past six years, actions within British Columbia have facilitated the incorporation of new scientific information about changes in sea level into policy and planning processes. Analysis of regional vertical land motion (due to tectonics, glacial rebound, sediment loading and other factors) and global projections of sea level rise produced new estimates of future sea level changes (Bornhold, 2008; Thomson et al., 2008), with significant implications for the current system of sea dykes, which protect important infrastructure and property in the province. Subsequent analyses were undertaken by the BC Ministry of Forests, Lands, & Natural Resource Operations, the Association of Professional Engineers and Geoscientists of British Columbia, and others with the objective of helping policymakers and planners incorporate sea level rise into flood risk assessment, coastal floodplain mapping, sea dyke design and land use planning. Guidelines for sea dykes were established for the years 2050, 2100 and 2200, with provisions for regional sea level rises of 0.5 m, 1 m and 2 m, respectively.

Outputs from that analysis included:

- A recommended 'Sea Level Rise Planning Curve' indicating that coastal development should plan for SLR of 0.5 m by 2050, 1.0 m by 2100 and 2.0 m by 2200.
- Technical reports to guide calculation of sea dyke crest elevation and flood construction levels, considering sea level rise, wind set-up, storm surge and wave run-up (Figure 3).
- Guidance for sea level rise planning, including designation of 'sea level rise planning areas' by local governments.
- A report comparing the costs of a variety of adaptation options from dyke construction to flood proofing and managed retreat. The study estimated that the cost for upgrading infrastructure works required along 250 km of dyked shorelines and low-lying areas in Metro Vancouver to accommodate a 1 m rise in sea level, including necessary seismic upgrades, would be about $9.5 billion.
- Professional practice guidelines for engineers and geoscientists to incorporate climate change in flood risk assessments.
- Seismic design guidelines for dykes focusing on factors to be considered in the seismic design of high-consequence dykes located in Southwestern BC.

This regional analysis has spurred municipal action. For example, the City of Vancouver offered workshops to engineers, developers and municipal staff on adapting coastal infrastructure. In turn, these workshops led the city to review their flood-proofing policies and agree on interim measures. One of these measures is to encourage applicants with projects in identified flood-hazard areas to meet an interim Flood Construction Level (FCL) equal to the current applicable FCL plus 1 m (City of Vancouver, 2012).

Building on these outputs, a working group that included local, provincial and federal government representatives, industry, academia and practitioners worked to develop a national Sea Level Rise Primer (www.env.gov.bc.ca/cas/adaptation/pdf/SLR-Primer.pdf) with examples from British Columbia, Québec and the Atlantic provinces. The Primer helps communities to identify, evaluate and compare adaptation options, and showcases planning and regulatory tools, land use change or restriction tools, and structural and non-structural tools.

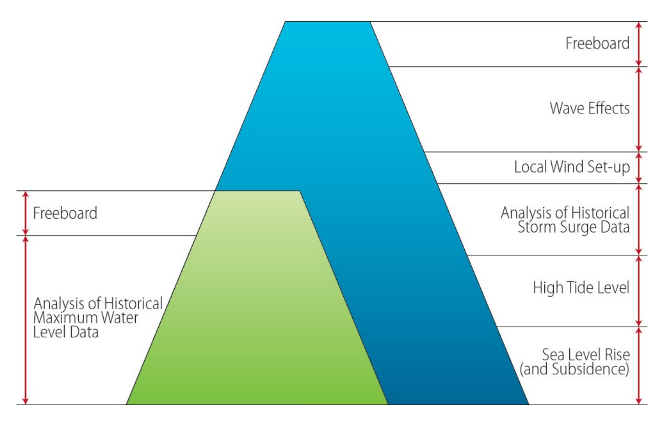


**FIGURE 3:** Conceptual differences between old and new sea dyke design approach *(Source: BC Ministry of Forest, Lands and Natural Resource Operations, 2012).*

Many respondents cited a lack of information about climate change impacts and risks to water systems as a gap that needed to be addressed. Also in 2012, a survey of 244 senior water utility executives from ten countries examined their preparedness to meet water supply challenges to 2030. While there were regional variations in concerns, most expected increased water stress by 2030 and identified demand management as a key action to address it (Economist Intelligence Unit, 2012). These surveys suggest that while there is growing awareness of climate change as a risk for water management infrastructure, the focus for action continues to be on issues such as replacement of aging infrastructure as well as dealing with increasing population and changing regulatory requirements. The role of changing codes, standards and related instruments (*see* Box 2) has received less attention.

There is also growing recognition of the importance that interdependencies among infrastructure systems, as well as management systems, play in adaptation planning (Zimmerman and Faris, 2010, PIEVC case studies). For example, water systems are often dependent on surface water sources that are also used for electrical generation or flood control. Operation of the system must therefore consider multiple and possibly conflicting needs. The availability of electrical power, including backup power, has emerged as a common and significant risk to systems that process and manage water. Several case studies identify the need to protect power supply systems to ensure the continued functioning of water treatment, management and control systems as part of an adaptation strategy (Genivar, 2007; Associated Engineering, 2011). Extreme weather and associated hazards can also prevent workers who operate water infrastructure from accessing facilities. Calgary has addressed this risk by implementing cross-training programs to ensure that trained staff/system operators are available at all times (Associated Engineering, 2011).

# 3. TRANSPORTATION INFRASTRUCTURE

Transport is inherently sensitive to climate, with numerous examples of transportation disruptions and delays related to weather events and seasonal conditions (Table 4). Such events were identified as key climate change-related concerns in many of the sectoral chapters of this report. Indeed, similar to water infrastructure, climate impacts on transportation systems have implications for most sectors in Canada, including natural resources, agriculture, fisheries, tourism, insurance and health, all of which depend upon a safe and reliable transportation network. In turn, Canada's transportation system, which includes four main components – air, marine, rail and roads – is sensitive to changes in other sectors with respect to demand and operations. Transportation services account for 4.2% of the Canadian GDP (Transport Canada, 2011), with the Canadian transportation system having an asset value in excess of $100 billion.

| Summary | Date | Reference |
|---|---|---|
| Winter roads in Manitoba turn into quagmires | 3-Jan-12 | CTV News (2012) |
| Flights cancelled due to low visibility and fog | 17-Jan-12 | Ptashnick and Hayes (2012) |
| Rainfall-induced underground slide creates sinkhole 200 m wide x 5 m deep on Hwy 83 in Manitoba | 3-Jul-12 | CBC News (2012c) |
| Ice build-up in E. Arctic damages ship and causes delay in unloading sealifts | 29-Jul-12 | CBC News (2012d). |
| Early winter storm in Alberta delays transit, cancels flights, and makes sidewalks and roads treacherous | 23-Oct-12 | Zickefoose.(2013) |
| Wawa in a state of emergency due to runoff from rain.Total damage > $10 million dollars | 27-Oct-12 | Metro News (2012) |
| Hurricane Sandy causes flight cancellations in Atlantic Canada | 29-Oct-12 | The Telegram (2012) |
| The Trans-Canada Hwy in Newfoundland closed due to damage from a landslide | 19-Nov-12 | CBC News (2012e) |
| Sailings from Vancouver Island cancelled due to winds, wave height and sea conditions | 19-Dec-12 | Lavoie (2013) |
| Record snowfall affects transport in southern Quebec | 27-Dec-12 | Radio Canada (2012) |
| VIA Rail uses the "snow fighter" to clear the train tracks during snowstorms | 24-Jan-13 | Pinsonneault (2013) |
| Roads closed in Northwestern Ontario as drifting and blowing snow impacted highways still affected by freezing rain | 30-Jan-13 | CBC News (2013a). |
| Road and marine travel delayed by winter weather | 18-Feb-13 | National Post (2013a) |
| Unusual warm days in Fort Chipewyan AB threaten to cut the northern community off from the rest of Alberta | 25-Feb-13 | CBC News (2013b) |
| Roads and highways were closed near Fort McLeod and many flights were cancelled due to limited visibility and icy roads | 4-Mar-13 | National Post (2013b) |
| Road floods after heavy rains | 3-Jun-13 | Radio Canada (2013) |
| Barge supply to western Arctic interrupted by ice | 3-Sep-13 | CBC News (2013c) |

**TABLE 4:** Examples of weather-transportation news stories from 2012-2013.

The climate sensitivity of transportation systems is reflected in design and construction standards, asset management expenditures, and mobility and safety outcomes. Impacts are associated with extreme weather events, such as heat waves and heavy rainfall, as well as more gradual changes such as permafrost thaw, higher temperatures, sea-level rise and declining water levels in freshwater systems. Previous analyses of climate change, including those in the various chapters of Lemmen et al. (2008), indicate that disruptions from extreme events, such as floods, fire and storms are the main climate concern for most regions with respect to transportation, and that some of the most vulnerable transport systems in Canada are integral to remote and resource-based community life, particularly in northern and coastal areas, and/or related to the transport of natural resource products (*see also* Chapter 3 – Natural Resources). More recent research also indicates that climate change has important implications for the operation and maintenance of transport systems in the most densely populated regions of Canada (*see* Section 3.1).

This section discusses key climate change vulnerabilities for transportation infrastructure in general, as well as some specific climate change issues for northern transportation systems, coastal regions and shipping in the Great Lakes (all with respect to the infrastructure, rather than the system as a whole). As such, it is not intended to present a comprehensive assessment of impacts and adaptation issues for the transportation sector. A more inclusive and in-depth perspective on these issues will be presented in the upcoming (2015-2016) Transportation Assessment, being co-led by Transport Canada and Natural Resources Canada.

## 3.1 KEY ISSUES FOR TRANSPORTATION INFRASTRUCTURE

Over the past six years, there has been a significant increase in the international engineering community's attention to climate change impacts. Much of the focus has been on future projections of heat waves, heavy rains, and other extremes including winds, given their implications for design standards and guidelines (Auld, 2008; Vajda et al., 2012), and on system-wide vulnerabilities to changing conditions (e.g. Capano, 2013; Dzikowski, 2013).

Projections of temperature extremes indicate that more frequent, longer and more intense heat spells are expected across much of North America (*see* Chapter 2). This can result in increased heat-related stresses, such as pavement rutting, rail buckling, and cargo overheating. Mills et al. (2007; 2009) confirm that projections of summer temperatures in parts of southern Canada (e.g. Windsor, Ontario) are expected to result in occasions/locations where there is pavement softening, rutting, bleeding and/or the need to specify a different asphalt cement oil grade. Municipalities and the engineering community are increasingly aware of these issues, especially in trucking corridors (Meyer et al., 2010), and agencies are beginning to reconsider road design/materials (e.g. culverts, asphalt binders) in light of the warming trend (Jacobs et al., 2013).

Heavy rainfalls can lead to flooding and washouts, cause slope failures and even trigger major landslides. Increases in heavy rainfall are expected across most of Canada, and in some cases could require revision of existing design and maintenance practices. For example, the Province of British Columbia has observed that "increased rainfall intensity could require updated policies and procedures regarding design and maintenance of highway infrastructure" (Nyland et al., 2011). Environment Canada (2013) provides intensity-duration-frequency curves for 563 locations across Canada—many of which have been recently updated; however, Peck et al. (2012) argue that such updates may not be sufficient to represent future rainfall patterns. While recent work has led to improved understanding of past rainfall extremes (e.g. Cheng et al., 2009), large uncertainties remain in representing extreme precipitation in future simulations (Maraun et al., 2010). There is also evidence that other weather conditions that are disruptive of transport networks and operations may become more frequent under climate change. For example, there is evidence that freezing rain events are likely to increase in south-central Canada (Cheng et al., 2007; 2011). Sequenced events (e.g. rain on freezing rain, or rain on snow), also pose risks to transportation. Researchers note that methods are needed to incorporate increasing trends in extreme weather events into infrastructure design standards (Cheng et al., 2012).

Most freight transporters and much of freight infrastructure (e.g. rail lines, airports and seaports) are managed by not-for-profit, non-share capital corporations or by private interests, and so risks and opportunities related to climate change are less frequently described in either the peer-reviewed or publicly accessible grey literature. Some insights can be gained through examination of Carbon Disclosure Project (CDP) questionnaires (both Canadian Pacific (CP) and Canadian National (CN) Railways have participated) and reports from meetings, such as a summit of key players involved in freight transportation in the U.S., including CN Railway (Camp et al., 2013). From the summit, many of the identified risks were associated with weather extremes that can close networks and delay shipments. CN specifically identified precipitation events as a major climate-related concern affecting the railroad industry because of associated risks of flooding, erosion and landslides, as well as wildfires because of service disruptions and damage to wooden bridges (Camp et al., 2013). Such events have impacted railway systems in the past, a recent example being the train derailment caused by a bridge failure associated with the spring 2013 floods in Calgary (Graveland and Krugel, 2013). High-temperatures are also a recognized risk for rail track integrity (e.g. Transportation Safety Board of Canada, 2013a,b), and heat waves have specifically been identified as a concern because of the potential for increased frequency of rail buckling/sun kinking and slow orders (CSIRO, n.d.; National Research Council, 2008; CBC News, 2012b).

## 3.2 ISSUES SPECIFIC TO NORTHERN REGIONS

There is widespread recognition that northern surface transport systems serving the Yukon, Northwest Territories and Nunavut, as well as the northern reaches of many provinces, are vulnerable to changing climate in a number of ways. Much of these regions are underlain by permafrost, have marine access during only a relatively short summer season, and often rely on a combination of ice roads, barge transport, air services, and limited rail access for commercial activities and community supply. In addition, the sparse nature of transportation infrastructure in the North means that service interruptions can have serious consequences. The Northern Transportation Systems Assessment (Prolog, 2011) provides an overview of the roles, usage and importance of certain elements of transportation systems in Canada's north, and identifies a range of strategies, such as alternate routes, to ensure access under changing climate conditions.

Considerable progress has been made in understanding cold regions processes and in exploring how transportation infrastructure designs might be adapted to withstand climate extremes and be more resilient in the face of changing thermal and moisture regimes (e.g. Doré and Zubeck, 2008; McGregor et al., 2010). There have also been several recent examples of northern vulnerability assessments and hazard mapping studies of relevance to transportation infrastructure (NRTEE, 2009; Champalle et al., 2013), and a number of site-specific assessments of permafrost conditions and degradation have been completed for existing transport infrastructure, ranging from northern Quebec airports (Fortier et al., 2011; L'Hérault et al., 2011) to roads in the Yukon (Lepage et al., 2010) and Northwest Territories (*see* Case Study 3).

### CASE STUDY 3

### NORTHWEST TERRITORIES TRANSPORTATION INFRASTRUCTURE

The Northwest Territories' (NWT) transportation system of 2200 km of all-weather roads and 1450 km of winter roads produces substantial benefits at local, regional and national levels. Roads improve connectivity between communities and provide residents with cheaper, easier and safer access to regional services such as health care, education and recreational activities.

The Government of Northwest Territories, Department of Transportation (GNWT-DOT), has acknowledged that its transportation infrastructure is vulnerable to the effects of climate change (GNWT-DOT, 2012). A PIEVC case study (*see* Box 1) of a 100 km section of Highway 3 located between Behchoko (Rae-Edzo) and Yellowknife was undertaken because it traverses highly variable terrain within an area of warm, discontinuous permafrost. Many sections of the highway exhibited various forms of embankment instabilities, ranging from differential settlements, shoulder rotations, and cracking of the pavement surface (Figure 4; Stevens et al., 2012). The case study examined more than 1100 highway climate event/infrastructure component combinations in order to identify potential vulnerabilities and to quantify the risk of future climate change impacts (GNWT-DOT, 2011).

The vulnerability assessment identified the sections of highway built on ice-rich permafrost as most vulnerable and recommended that additional baseline information be obtained for these sections (GNWT-DOT, 2011). Remote sensing techniques were subsequently used to analyze a 48 km section of the highway to detect changes to the highway corridor and identify sections that may require future remediation and adaption measures (Wolfe, 2012). The highway embankment was determined to be seasonally stable over 67% of the 48 kilometres analyzed, with moderate downward displacement (-3 to -6 cm per year) over 2% of its length. Many embankment side slopes were found to be steeper than the recommended grade as a result of surface displacement caused by the thawing of ice-rich permafrost terrain (Stevens et al., 2012).

Identifying areas most impacted by changing climate assists in the planning of annual road maintenance, evaluating the effectiveness of highway remediation projects and identifying areas where further data is required. For example, based on the vulnerability assessment, test sites were established along Highway 3, and are being monitored on an ongoing basis by the Government of the Northwest Territories. Such analysis will ultimately reduce the costs of constructing and maintaining the highways and help ensure safe driving conditions.

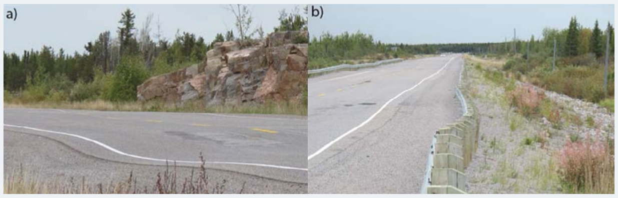


**FIGURE 4:** Photographs of Highway 3 indicating **a)** differential subsidence of the road surface and **b)** guardrail displacement caused by rotational down slope movement of the highway embankment side slope *(Source: Stevens et al., 2012)*.

Winter roads (also called ice roads) make up seasonal transportation networks located primarily on the surfaces of lakes, rivers and bays. Found in the Northwest Territories, Manitoba, Ontario, and to a lesser extent in the Yukon, Nunavut, Alberta, Saskatchewan, Quebec, and Newfoundland and Labrador, these roads provide access to communities and mining operations. While there remains little published scientific research related to ice road seasons and use (cf. Lemmen et al., 2008), media reports and grey literature provide evidence of shortened seasons (e.g. CBC News, 2012a); identify approaches for extending the season, such as ice-road spraying, plowing off roads to enhance the freezing effect, and restricting hauling to certain hours; and demonstrate the potential of ice-road alternatives, such as cargo airships (e.g. Winnipeg Free Press, 2013a; 2013b). The Tibbitt to Contwoyto Ice Road in the Northwest Territories, the world's longest heavy-haul winter road, illustrates challenges and potential adaptations associated with climate change. In 2006, approximately 1200 loads had to be transported by air during the summer and autumn following a shortened ice-road season (JVTC, 2013). The Tibbitt to Contwoyto Joint Venture is conducting research using ground-penetrating radar (Mesher et al., 2008) with a long-term goal of optimizing load capacity and vehicle speeds based on ice properties and water depth information. In addition, a new geographic-information-system-based asset management framework is being developed, and the research has been extended to other ice roads, ice bridges and ice platforms in Canada (Proskin et al., 2011).

Marine transport in northern regions is also important. While most of the Arctic is likely to continue to have only seasonally restricted marine operations, changes are occurring (e.g. Stroeve et al., 2012; *see also* Chapter 2 and 5), and their implications for shipping continue to be studied.

## 3.3 ISSUES SPECIFIC TO COASTAL COMMUNITIES

Projected changes in sea level, sea ice cover, and the intensity and frequency of storm events (*see* Chapter 2) will result in higher risk of coastal erosion, storm surge flooding and submergence. Previous assessments highlight the sensitivities of transport infrastructure in Atlantic Canada and parts of the British Columbia coast to such risks (Warren et al., 2004; Lemmen et al., 2008).

On the Atlantic coast, studies have examined the effects of storm winds and surge activity for various activities and sites. In terms of maritime transport, analysis suggests that hazards in Channel-Port aux Basques, Newfoundland, are likely to have negative economic impacts on transportation systems in the region (Catto et al., 2006). A risk assessment of three coastal roads in Nova Scotia led to recommendations that include engineered shoreline protection and relocation of selected roads further away from the coast (McGillis et al., 2010). Several climate change adaptation plans developed over the past five years make direct reference to coastal transportation infrastructure, including Halifax Harbour (Forbes et al., 2009; Halifax Regional Municipality et al., 2010; Richardson, 2010); Stratford, Prince Edward Island (Greene and Robichaud, 2010); and Yarmouth, NS (Manuel et al., 2012).

On the Pacific coast, the effects of climate change and sea-level rise on transportation are concentrated in areas where the terrain is relatively flat, such as the Roberts Bank – Fraser Delta region in Greater Vancouver and the northeastern coast of Graham Island, Haida Gwaii (Walker and Sydneysmith, 2008). From a transportation asset perspective, Vancouver has the greatest exposure to sea-level rise of all Canadian cities. A recent study identified Vancouver as being among the 20 cities in the world that are most vulnerable to climate change-related flooding (Hallegatte et al., 2013). In July 2012, Vancouver became the first municipality in Canada to adopt a comprehensive climate change adaptation strategy (City of Vancouver, 2012), which included a coastal flood risk assessment as one of the primary actions.

## 3.4 GREAT LAKES SHIPPING

The Great Lakes–St. Lawrence Seaway, stretching 3700 km from the head of Lake Superior to the Gulf of St. Lawrence, is an important international shipping route in one of the most industrialized parts of North America. Vessels carrying dry and liquid bulk commodities must conform to the size limitations of the Seaway, and therein lies the main concern related to climate change (Millerd, 2008, 2011). Projections of warmer temperatures translate into expectations of lower water levels in the Great Lakes system, despite past trends and future projections of increased precipitation (McBean and Motiee, 2008). Lower water levels translate into changes in available vessel drafts. Estimates of changing water levels vary considerably by climate change scenario and model (e.g. Angel and Kunkel, 2010, IJC; 2013), creating uncertainty as to the magnitude of the associated economic impacts and the need for adaptation. Recent media coverage underscores the extent and serious impacts of low water levels, especially when coupled with currently existing maintenance dredging shortfalls (Barrett and Porter, 2012; Associated Press, 2013). For example, one study concluded that for each centimetre decrease in water level, ship capacity decreases by six containers, or 60 tons (Transports Québec, 2012).

## 3.5 ADAPTATION APPROACHES

Increasingly, transportation agencies are using asset management systems for monitoring and decision-making in order to arrive at the most cost-effective approach for designing and maintaining the system. As noted by Meyer et al. (2010), "incorporating climate change-oriented risk appraisal into asset management is the key challenge to using the asset management framework for climate change". To date, there is little evidence that this challenge has been taken up in a comprehensive way, although the implications of climate change for transport infrastructure are increasingly being considered in professional meetings and research projects.

In the context of road networks, the most ambitious Canadian project of its kind was undertaken by Mills et al. (2007, 2009) with the objective of understanding how projected climate futures would affect pavement deterioration processes in Canadian highways. After quantifying changes in pavement deterioration processes and outcomes, the report identifies potential adaptation strategies related to construction and maintenance. Asset management approaches can also be used by other transportation modes, such as airports and port facilities.

Also of relevance to climate change and road transportation is the issue of variable load restrictions. This is of particular importance in the spring, on roads that carry resource commodities. These low-volume roads typically do not warrant alternate, more expensive designs. However, during spring thaw, physical changes can weaken the pavement structure, resulting in premature deterioration. Recent and ongoing research is facilitating the development of models for site-specific calibration of thaw weakening, so that the timing of spring-load restrictions can be optimized (e.g. Baiz et al., 2008). Because of climate variability, this type of adaptation has benefits both for today and for the future as conditions change even more, and would have relevance nation-wide.

In the Great Lakes, where lower water levels are an ongoing concern, there are a range of potential adaptation responses for operators and regulators. These include both structural measures (e.g. relocating facilities, updating docks and slips) and non-structural measures (dredging, using navigational aids and pilotage technologies). Adaptive management approaches (*see* Case Study 4), which involve monitoring, adjusting, experimenting and re-evaluating, are well suited under the uncertainty inherent in projections for the Great Lakes. Similarly, recent studies on adaptation to climate-related hazards in the North (e.g. with respect to ice roads and ice conditions) highlight the need for continual review of plans in light of climate change (Pearce et al., 2010).

**CASE STUDY 4**

### ADAPTING TO CHANGING GREAT LAKE WATER LEVELS: USING AN ADAPTIVE MANAGEMENT APPROACH

Changes in Great Lakes water levels as a result of changing climate and other factors were identified in the 2008 assessment as a major regional (Chiotti and Lavender, 2008) and international (Bruce and Haites, 2008) concern. Since then, the International Upper Great Lakes Study (IUGLS) has evaluated the management of water levels and flows in the upper Great Lakes to meet present-day and future requirements. Analysis has demonstrated that regulation of Lake Superior has limited influence downstream. While building of new infrastructure for additional multi-lake water level and flow management was assessed, it was ultimately discounted at this time because of construction costs and significant environmental and institutional constraints. Instead, the study suggested an adaptive approach to coastal zone management, supported by monitoring and research to detect and manage emerging climate change risks (Leger and Read, 2012).

Adaptive management (*see* Chapter 9, Case Study 4) uses a structured, iterative process to address the uncertainties associated with climate change and the potential for extreme events. The International Great Lakes–St. Lawrence River Adaptive Management Task Team (2013) laid out a detailed plan and institutional arrangements to implement two key elements: i) ongoing review and evaluation of the performance of existing regulation plans; and ii) development of new solutions, beyond lake level regulation, related to extreme water level conditions. This effort seeks the coordinated participation of multiple partners across the basin to gather and share data, assess information, identify impacts, develop adaptation strategies and assess performance.

# 4. CONCLUSION

Well-functioning infrastructure and systems are critical to Canada's economic and social well-being. All sectors depend upon reliable access to clean water, effective stormwater maintenance, effective treatment of wastewater and a safe and efficient transportation network. A changing climate presents risks to these services in several ways, as discussed throughout the chapter. Extreme events emerge as the key concern, evidenced by numerous examples of heavy precipitation overloading stormwater-handling capacity and disrupting transportation corridors. However, slower-onset changes such as higher temperatures, sea level rise, permafrost thaw and declining lake levels are also important factors to consider in infrastructure design, operation and maintenance. The focus for both water and transportation has been on risks, with limited attention given to potential opportunities.

The past five years has seen progress on climate change adaptation and infrastructure. The scope and depth of research have both expanded, and there has been increased engagement of professional communities, attributable, at least in part, to the impact of the PIEVC program. As such, climate change is beginning to be considered by engineers and planners, as well as hydrologists, water and wastewater treatment operators, in the design and maintenance of infrastructure in Canada. Adaptation to date has generally been approached in the context of ongoing maintenance and upgrades, which in many cases will be sufficient to deal with a changing climate, especially gradual change. There are also some examples of specific adaptation measures that take a changing climate into account. Future adaptation will involve further technological advancements and incorporation of climate change into design standards and maintenance practices, and fundamental research is underway to inform these developments. A stand-alone assessment of transportation in Canada, also in development, will increase the baseline of knowledge on climate change impacts and adaptation actions for the sector.

# REFERENCES

ACASA [Atlantic Climate Adaptation Solutions Association] (n.d.): Climate change and saltwater intrusion in a small municipality; Atlantic Climate Adaptation Solutions Association, 2 p.

AMEC Environment and Infrastructure (2012): City of Welland Stormwater and Wastewater Infrastucture Assessment Report; AMEC Environment & Infrastructure, no. TP111002-011.

Angel, J.R. and Kunkel, K. (2010): The response of Great Lakes water levels to future climate scenarios with an emphasis on Lake Michigan-Huron; Journal of Great Lakes Research, v. 36, p. 51-58.

Associated Engineering (2011): City of Calgary Water Supply Infrastructure - Climate Change Vulnerability Risk Assessment; Associated Engineering.

Associated Press (2013): Lake Huron, Lake Michigan hit lowest water levels on record; CBC News, <www.cbc.ca/news/canada/windsor/lake-huron-lake-michigan-hit-lowest-water-levels-on-record-1.1380357>.

Auld, H.E. (2008): Adaptation by design: the impact of changing climate on infrastructure; Journal of Public Works and Infrastructure, v. 1, no. 3, p. 276-288.

Baiz, S., Tighe, S.L., Haas, C.T., Mills, B., and Perchanok, M. (2008): Development of frost and thaw depth predictors for decision making about variable load restrictions; Transportation Research Record, v. 2053, p. 1-8.

Barrett, J. and Porter, C. (2012): Drought hits shippers on Great Lakes; Wall Street Journal, <http://online.wsj.com/article/SB10000872396390444752504578024920103784566.html>.

BC Ministry of Forest, Lands and Natural Resource Operations (2012): Cost of Adaptation: Sea Dikes and Alternative Strategies; BC Ministry of Forest, Lands and Natural Resource Operations, <www.env.gov.bc.ca/wsd/public_safety/flood/pdfs_word/cost_of_adaptation-final_report_oct2012.pdf>.

Bornhold, B.D. (2008): Projected Sea Level Changes for British Columbia in the 21st Century; Government of Canada, <www.env.gov.bc.ca/cas/pdfs/sea-level-changes-08.pdf>, 9 p.

Bourque, A. and Simonet, G. (2008): Quebec; *in* From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON, p. 171-226.

Bruce, J.P. and Haites, E. (2008): Canada in an international context; *in* From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON, p. 387-424.

Camp, J., Abkowitz, M., Hornberger, G., Benneyworth, L., and Banks, J.C. (2013): Climate change and freight transportation infrastructure: current challenges for adaptation; Journal of Infrastructure Systems.

Capano, N. (2013): City of Toronto climate change risk assessment; Transportation Association of Canada Conference and Exhibition, Panel Presentation, Winnipeg, September 24, 2013.

Carrière, A., Prévost, M., Zamyadi, A., and Chevalier, P. (2010): Vulnerability of Quebec drinking-water treatment plants to cyanotoxins in a climate change context; Journal of Water and Health, v. 98, p. 455-465.

Catto, N., Foote, D., Kearney, D., Locke, W., DeYoung, B., Edinger, E., Ingram, D., Karn, J., and Straatman, J. (2006): Impacts of Storms and Winds on Transportation in Southwestern Newfoundland; CCIAP Project A-804, <www.mun.ca/geog/research/CCIAP_Project_A_804.pdf>.

CBC News (2012a): Shorter ice-road season in northern Manitoba in 2011-2012, <www.cbc.ca/news/canada/manitoba/story/2012/03/13/mb-winter-ice-road-closures.html>.

CBC News (2012b): Trains delayed as heat warps railroad tracks, <www.cbc.ca/news/canada/ottawa/story/2012/05/28/ottawa-train-tracks-warped-by-heat-delay-trains.html>.

CBC News (2012c): 200-metre crater sinks Manitoba highway, <www.cbc.ca/news/canada/manitoba/story/2012/07/03/mb-collapsed-road-assessippi-park-manitoba.html?cmp=rss>.

CBC News (2012d): Ice damages hull of sealift ship near Iqaluit, <www.cbc.ca/news/canada/north/story/2012/07/26/north-sealift-ship-damage.html>.

CBC News (2012e): TCH blocked by landslide could be closed for nearly a week, <www.cbc.ca/news/canada/newfoundland-labrador/story/2012/11/19/nl-landslide-blasting-tch-clarenville-1119.html>.

CBC News (2013a): Poor driving conditions span northeastern Ontario, <www.cbc.ca/news/canada/sudbury/story/2013/01/30/sby-road-conditions-school-bus-cancellations-sudbury.html>.

CBC News (2013b): Warm weather threatens ice road to Fort Chipewyan, <www.cbc.ca/news/canada/edmonton/story/2013/02/25/edmonton-fort-chipewyan-ice-roads.html>.

CBC News (2013c): Ice delays supply barge for Western Arctic communities, < http://www.cbc.ca/news/canada/north/ice-delays-supply-barge-for-western-arctic-communities-1.1397771>.

CCPE [Canadian Council of Professional Engineers] (2008): Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure; Canadian Council of Professional Engineers, <www.pievc.ca/e/Adapting_to_climate_Change_Report_Final.pdf>.

Champalle, C., Tudge, P., Sparling, E., Riedlsperger, R., Ford, J. and Bell, T. (2013): Adapting the Built Environment in a Changing Northern Climate: A systematic review of climate hazard-related mapping and vulnerability assessments of the built environment in Canada's North to inform climate change adaptation; report submitted to Natural Resources Canada, Climate Change Impacts and Adaption, Ottawa, Canada, <www.jamesford.ca/wp-content/uploads/2013/05/NRCAN_FinalReport_VAHMBuiltEnvironmentMay16.pdf>.

Cheng, C.S., Auld, H., Klassen, J., and Li, Q. (2007): Possible impacts of climatic change on freezing rain in south-central Canada using downscaled future climate scenarios; Natural Hazards and Earth System Sciences, v. 7, p. 71-87.

Cheng, C.S., Li, G., Li, Q., and Auld, H. (2009): A synoptic weather typing approach to simulate daily rainfall and extremes in Ontario, Canada: potential for climate change projections; Journal of Applied Meteorology and Climatology, v. 49, p. 845-866.

Cheng, C.S., Li, G., and Auld, H. (2011): Possible impacts of climate change on freezing rain using downscaled future climate scenarios: updated for eastern Canada; Atmosphere-Ocean, v. 49, no. 1, p. 8-21.

Cheng, C., Li, Q., Li, G., and Auld, H. (2012): Climate change and heavy rainfall-related water damage insurance claims and losses in Ontario, Canada; Journal of Water Resource and Protection, v. 4, p. 49-62.

Chiotti, Q. and Lavender, B. (2008): Ontario; *in* From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, ON, p. 227-274.

City of Calgary (2007): Water Efficiency Plan, 30-in-30, by 2033; The City of Calgary, Water Resources Calgary, <www.calgary.ca/UEP/Water/Documents/Water-Documents/water_efficiency_plan.pdf>.

City of Calgary (2013): Flood Recovery Operations, the City of Calgary Flood Recovery Framework, <www.calgary.ca/General/flood-recovery/Documents/flood-recovery-operations-framework.pdf>.

City of Vancouver (2012): Climate change adaptation strategy; City of Vancouver, <http://vancouver.ca/green-vancouver/climate-change-adaptation-strategy.aspx>.

CSIRO [The Commonwealth Scientific and Industrial Research Organisation] (n.d.): Adaptation science, opportunities and responses to climate change; The Commonwealth Scientific and Industrial Research Organisation, <www.csiro.au>.

CTV News (2012): Warm winter, no ice roads shows new roads needed: chief, <www.ctvnews.ca/warm-winter-no-ice-roads-shows-new-roads-needed-chief-1.748146>.

Doré, G. and Zubeck, H. (2008): Cold Regions Pavement Engineering; McGraw-Hill/ASCE Press, ISBN:0071600884/9780071600880.

Dzikowski, P. (2013): Changing climate, changing risks, Alberta transportation; Transportation Association of Canada Conference and Exhibition, Panel Presentation, Winnipeg, September 24, 2013.

EBNFLO Environmental AquaResource Inc. (2010): Guide for Assessment of Hydrologic effects of Climate Change in Ontario; report submitted to The Ontario Ministry of Natural Resources and Ministry of the Environment in partnership with Credit Valley Conservation, <http://waterbudget.ca/climatechangeguide>, 234 p.

Economist Intelligence Unit (2012): Water for all? A study of water utilities' preparedness to meet supply challenges to 2030. The Economist Intelligence Unit Limited. <www.oracle.com/us/industries/utilities/utilities-water-for-all-ar-1865053.pdf>.

Emelko, M.B., Silins, U., Bladon, K.D. and Stone, M. (2011): Implications of land disturbance on drinking water treatability in a changing climate: demonstrating the need for "source water supply and protection" strategies; Water Research, v. 45, p. 461-472.

Environment Canada (2013): Engineering Climate Datasets; <http://climate.weather.gc.ca/prods_servs/engineering_e.html>.

Félio, G. (2012): Canadian infrastructure report card: 2012, municipal roads and water systems; Canadian Construction Association, Canadian Public Works Association, Canadian Society for Civil Engineering and Federation of Canadian Municipalities.

Ferguson, G. and Beebe, C. (2012): Vulnerability of Nova Scotia's groundwater supplies to climate change; Atlantic Climate Solutions Association, <http://atlanticadaptation.ca/sites/discoveryspace.upei.ca.acasa/files/Nova%20Scotia%20ACAS%20groundwater%20report%20_0.pdf>, 10 p.

Forbes, D.L., Manson, G.K., Charles, J., Thompson, K.R., and Taylor, R.B. (2009): Halifax Harbour Extreme Water Levels in The Context of Climate Change: Scenarios for a 100-Year Planning Horizon; Geological Survey of Canada, <www.halifax.ca/regionalplanning/documents/HRM-OF_v5.pdf>.

Forbes, K. A., Kienzle, S. W., Coburn, C. A., Byrne, J. M., and Rasmussen, J. (2011): Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada; Climatic Change, v. 105, no. 3-4, p. 555-576.

Fortier, R., LeBlanc, A.M., and Yu, W. (2011): Impacts of permafrost degradation on a road embankment at Umiujaq in Nunavik Quebec, Canada; Canadian Geotechnical Journal, v. 48, no. 5, p. 720-740.

Genivar (2007): City of Portage La Prairie water resources infrastructure assessment phase II- pilot study; report submitted to The City of Portage la Prairie, <www.pievc.ca/e/doc_project_single.cfm?dsid=3&projid=1>.

Genivar (2011): National Engineering Vulnerability Assessment of Public Infrastructure to Climate Change: Climate Change Vulnerability Assessment of the Town Of Prescott's Sanitary Sewage System - Final Case Study Report; Genivar.

GNWT-DOT [Government of Northwest Territories, Department of Transportation] (2011): Climate Change Vulnerability Assessment for NWT Highway 3 - Final Report; Government of Northwest Territories, Department of Transportation, <www.pievc.ca/e/casedocs/nwt-yellowknife/2GNWT%20Hwy%203%20West_Yellowknife_Report.pdf>.

GNWT-DOT [Government of Northwest Territories, Department of Transportation] (2012): Business Plan 2012-2013; Government of Northwest Territories, Department of Transportation, <www.dot.gov.nt.ca/_live/documents/content/DOT%202012-13%20Business%20Plan.pdf>.

Government of Ontario (2012): Building Together: Guide for Municipal Asset Management Plans, <www.moi.gov.on.ca/en/infrastructure/building_together_mis/plan.asp>.

Graveland, B. and Krugel, L. (2013): Train Derails in Calgary on Bridge, Carries Petroleum Product; The Canadian Press, Posted: 06/27/2013, <www.huffingtonpost.ca/2013/06/27/train-derails-calgary-bridge_n_3509067.html>.

Greene, K. and Robichaud, A.G. (2010): Mainstreaming Climate Change Tools for the Professional Planning Community: Climate Change Adaptation Action Plan for Stratford, PEI; Canadian Institute of Planners, Natural Resources Canada, and Atlantic Planners Institute, <www.fcm.ca/documents/reports/PCP/climate_change_adaptation_action_plan_for_stratford_pei_EN.pdf>.

Hallegatte, S., Green, C., Nicholls, R.J., and Corfee-Morlot, J. (2013): Future flood losses in major coastal cities; Nature Climate Change, v. 3, p. 802-806.

Halifax Regional Municipality, Geological Survey of Canada and Natural Resources Canada (2010): Sea level Risk Adaptation Planning for Halifax Harbour; Geological Survey of Canada Natural Resources Canada, <www.halifax.ca/regionalplanning/documents/SLRCowFeb92010revisedforwebsite.pdf>.

IJC [International Joint Commission] (2013): Climate Change Adds to Future Uncertainty Regarding Water Levels; International Joint Commission, <http://ijc.org/files/tinymce/uploaded/documents/IJC-Great-Lakes-Day-Water-Levels-Fact-Sheet.pdf>.

International Great Lakes–St. Lawrence River Adaptive Management Task Team (2013): Building collaboration across the Great Lakes–St. Lawrence River System, an adaptive management plan for addressing extreme water levels; Breakdown of roles, responsibilities and proposed tasks, 72 p.

Jacobs, J.M., Kirchen, P.H., and Daniel, J.S. (2013): Considering climate change in road and building design; EOS Transactions of the American Geophysical Union, v. 94, no. 30, 264 p.

JVTC [Joint Venture Tibbitt to Contwoyto] (2013): The Tibbitt to Contwoyto Winter Road; Joint Venture Tibbitt to Contwoyto, <www.jvtcwinterroad.ca/jvwr/>.

Kerr Wood Leidal Associates Limited (2009): Infrastructure Vulnerability to Climate Change - Fraser Sewerage Area; Kerr Wood Leidal Associates Limited, <www.pievc.ca/e/casedocs/fraser/Metro%20Vancouver%20-%20Fraser%20Sewarage_Final%20Report.pdf>.

Kleindorfer, M., Möderi, M., Sitzenfrei, R., Urich, C., and Rauch, W. (2009): A case independent approach on the impact of climate change effects on combined sewer system performance; Water and Science Technology, v. 60, no. 6, p. 1555-1564.

L'Hérault, E., Allard, M., Dare, G., Barrette, C., Verreault, J., Sarrazin, D., Doyon, J., and Guimond, A. (2011): Assessment of permafrost conditions under northern Quebec's airports: an integrative approach for the development of adaptation strategies to climate warming; AGU Fall Meeting, San Francisco, California, USA, December 5-9, 2011.

Larrivée, C. and Simonet, G. (2007): Testing the assumptions: assessing infrastructures vulnerability to climate change; Municipal World, v. 117, no. 6, p. 27-28.

Lavoie, J. (2013): Storm stops 75 ferry sailings; Times Colonist, <www.timescolonist.com/news/local/storm-stops-75-ferry-sailings-1.31854>.

Leger, W. and Read, J. (2012): Adaptive management: strategy and legacy, Lake Superior regulation: Addressing Uncertainty in Upper Great Lakes Water Levels; report submitted to the International Upper Great Lakes Study Board by the Adaptive Management Technical Work Group, 167 p.

Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E. (ed.) (2008): From Impacts to Adaptation: Canada in a Changing Climate 2007; Government of Canada, Ottawa, ON.

Lepage, J., Doré, G., and Fortier, F. (2010): Experimentation of mitigation techniques to reduce the effects of permafrost degradation on transportation infrastructures at Beaver Creek experimental road site (Alaska Highway, Yukon); 63rd Canadian Geotechnical Conference and the 6th Canadian Permafrost Conference, Calgary, Canada, p.526-533.

MacQuarrie, K., Butler, K., Mott, E., and Green, N. (2012): A case study of coastal aquifers near Richibucto, New Brunswisk: saline groundwater occurrence and potential impacts of climate change on seawater intrusion; Atlantic Climate Adaptation Solutions Association.

Manuel, P., Rapaport, E., Cochran, M., Critchley, J., Johnston, J.A., Muise, J., and Wollenberg, Z. (2012): Yarmouth: A Case Study in Climate Change Adaptation; Atlantic Climate Change Adaptation Solutions Association, <http://atlanticadaptation.ca/sites/discoveryspace.upei.ca.acasa/files/Yarmouth%20Part%202%20-%20Section%206%20-%20Municipal%20Capacity-%20August%2030_0.pdf>.

Maraun, D., Wetterhall, F., Ireson, A.M., Chandler, R.E., Kendon, E.J., Widmann, M., Brienene, S., Rust, H.W., Sauter, T., Themeβl, M., Cenema, V.K.C., Chun, K.P., Goodess, C.M., Jones, R.G., Onof, C., Vrac, M., and Thiele-Eich, I. (2010): Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user; Reviews of geophysics, American Geophysical Union, v. 48, no. 3.

Marsalek, J. and Schreier, H. (2009): Innovation in stormwater management in Canada: the way forward; Water Quality Research Journal of Canada, v. 44, no. 1, v-x.

McBean, E. and Motiee, H. (2008): Assessment of impact of climate change on water resources: A long term analysis of the great lakes of North America; Hydrology and Earth System Sciences, v.12, no. 1, p. 239-255.

McGillis, A., Baird, W.F., Associates Coastal Engineers Ltd. and MacCallum, I. (2010): Infrastructure risk assessment of coastal roads in Nova Scotia; Proceedings of the Transportation Association of Canada Annual Conference, Halifax.

McGregor, R., Hayley, D., Wilkins, G., Hoeve, E., Grozic, E., Roujanski, V., Jansen, A., and Dore, G. (2010): Guidelines for development and management of transportation infrastructure in permafrost regions; Transportation Association of Canada, Ottawa, 177 p.

Mesher, D.E., Proskin, S.A., and Madsen, E. (2008): Ice road assessment, modeling and management; Proceedings of the Transportation Association of Canada Annual Meeting, Toronto.

Metro News (2012): Northern Ontario road repairs progressing after Wawa washout, <http://metronews.ca/news/toronto/418819/wawa-road-repairs-progressing-after-washout/>.

Meyer, M.D., Amekudzi, A., and O'Har, J.P. (2010): Transportation asset management systems and climate change: adaptive systems management approach; Transportation Research Record, v. 2160, p. 12-20.

Millerd, F. (2008): The estimated economic impact of climate change on Canadian commercial navigation on the Great Lakes; in SERA North Economics of Weather, Climate and Climate Change: A Meeting Synthesis, (ed.) B. Mills; Adaptation and Impacts Research Division, Environment Canada. Waterloo, Canada, 31-33 p.

Millerd, F. (2011): The potential impact of climate change on Great lakes international shipping; Climatic Change, v. 104, p. 629-652.

Mills, B., Tighe, S.L., Andrey, J., Smith, J.T., Parm, S., and Huen, K. (2007): the Road Well-traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada; Government of Canada, Environment Canada, Adaptation and Impacts Research Division.

Mills, B., Tighe, S.L., Andrey, J., Smith, J.T., and Huen, K. (2009): Climate change implications for flexible pavement design and performance in southern Canada; Journal of Transportation Engineering, v. 135, no. 10, p. 773-782.

National Post (2013a): Strong winds, snow pounds Atlantic Canada as thousands lose power, <news.nationalpost.com/2013/02/18/strong-winds-snow-snarls-transport-and-causes-power-outages-in-atlantic-canada/>.

National Post (2013b): Massive Alberta snowstorm cripples traffic, causes flight cancellation, <news.nationalpost.com/2013/03/04/massive-alberta-snowstorm-cripples-traffic-causes-flight-cancellations/>.

National Research Council (2008): Potential Impacts of Climate Change on U.S. Transportation; National Research Council of the National Academies, Transportation Research Board, Washington D.C.

NRTEE [National Round Table on the Environment and Economy] (2009): True North: Adapting infrastructure to climate change in northern Canada; National Round Table on the Environment and Economy, <http://emrlibrary.gov.yk.ca/NRTEE%20documents/NRTEE%20Reports%20and%20Publications%20by%20Year/2009/2009-NRTEE%20Reports%20and%20Publications/NRTEE-True%20North_Adapting%20Infrastructure%20to%20Climate%20Change%20in%20Northern%20Canada.pdf>.

Nyland, D., Nodelman, J.R., and Nodelman, J.Y.H. (2011): Climate change engineering vulnerability assessment of transportation infrastructure in British Columbia; Transportation Association of Canada Annual Conference, Edmonton, June 28.

Ouranos (2010): Savoir s'adapter; Ouranos, <www.ouranos.ca/fr/pdf/53_sscc_21_06_lr.pdf>, 128 p.

Pearce, T., Smit, B., Duerden, F., Ford, J.D., Goose, A., and Kataoyak, F. (2010): Inuit vulnerability and adaptive capacity to climate change in Ulukhaktok, Northwest Territories, Canada; Polar Record; v. 46, p.157–177.

Peck, A., Prodanovic, P., and Simonovic, S.P. (2012): Rainfall intensity duration frequency curves under climate change: city of London, Ontario, Canada; Canadian Water Resources Journal, v. 37, no. 3, p. 177-189.

PIEVC [Public Infrastructure Engineering Vulnerability Committee] (2007): PIEVC Engineering Protocol - Version 10 October 2011 - Part 1; Canadian Council of Professional Engineers, <www.pievc.ca/e/doc_list.cfm?dsid=43>.

PIEVC [Public Infrastructure Engineering Vulnerability Committee] (2012): PIEVC Case Studies: Codes, Standards and Related Instruments (CSRI) Review for Water Infrastructure and Climate Change; Report to Engineers Canada, <www.pievc.ca/e/2012_PIEVC_CSRI_Water_report_Final.pdf>.

Pinsonneault, D. (2013): A Few Feet of Snow Won't Stop This Train!; VIA Rail Canada, <www.viaevolution.ca/2013/01/24/a-few-feet-of-snow-wont-stop-this-train/>.

Plosz, B.G., Liltved, H., and Ratnaweera, H. (2009): Climate change impacts on activated sludge wastewater treatment: A case study from Norway; Water Science and Technology, v. 60, no 2, p. 533-541.

Prolog Canada in association with EBA Engineering Consultants Ltd. (2011): The Northern Transportation Systems Assessment, Executive Summary; Report prepared for Transport Canada.

Proskin, S.A., Parry, N.S., and Finlay, P. (2011): Applying GPR in Assessing the Ice Bridges, Ice Roads and Ice Platforms; CGU HS Committee on River Ice Processes and the Environment, 16th workshop on River Ice, Winnipeg Manitoba, September 18-22.

Ptashnick, V. and Hayes, M. (2012): Dozens of Toronto flights cancelled due to fog; The Star, <www.thestar.com/news/gta/2012/01/17/dozens_of_toronto_flights_cancelled_due_to_fog.html>.

Pyke, C., Warren, M.P, Johnson, T., LaGro Jr., J., Scharfenberg, J., Groth, P., Freed, R., Schroeer, W. and Main, E. (2011): Assessment of low impact development for managing stormwater with changing precipitation due to climate change; Landscape and Urban Planning, v. 103, p. 166-173.

Radio Canada (2012): Des chutes de neige records, <www.radio-canada.ca/nouvelles/environnement/2012/12/27/001-neige-tempete-27decembre2012.shtml>.

Radio Canada (2013): Violents orages au Québec: inondations et pannes de courant, <www.radiocanada.ca/regions/Montreal/2013/06/01/003-orage-pluie-pannes.shtml>.

Richardson, G.R.A. (2010): Adapting to Climate Change: An Introduction for Canadian Municipalities; Natural Resources Canada, Ottawa, Ontario, 40 p.

Scheckenberger, R.B., Farrell, A.C., and Senior, M. (2009): Economic Assessment of Climate Change Scenarios on Drainage Infrastructure Design; Transportation Association of Canada Annual Meeting, Vancouver.

Smith, B.R. (2009): Re-thinking wastewater landscapes: combining innovative strategies to address tomorrow's urban wastewater treatment challenges; Water Science and Technology, v.60, p. 1465-1473.

Statistics Canada (2013): Survey of Drinking Water Plants 2011; Catalogue no.16-403-X, p. 7 <www.statcan.gc.ca/pub/16-403-x/16-403-x2013001-eng.pdf>.

Stevens, C.W., Short, N., and Wolfe, S.A. (2012): Seasonal surface displacement and highway embankment grade derived from InSAR and LiDAR, Highway 3 west of Yellowknife, Northwest Territories; Geological Survey of Canada, Open File 7087, 1 DVD.

Stroeve, J., Serreze, M.C., Holland, M. M., Kay, J.E., Malanik, J., and Barrett, A.P. (2012): The Arctic's rapidly shrinking sea ice cover: a research synthesis; Climatic Change, v. 110, p. 1005-1027.

Tanzeeba, S. and Gan, T.Y. (2012): Potential impact of climate change on the water availability of South Saskatchewan River Basin; Climatic Change; v. 112, no. 2, p. 355-386.

The Telegram (2012): Fog, wind, hurricane conditions play havoc with flight schedules, <www.thetelegram.com/News/Local/2012-10-29/article-3109374/Fog-wind-hurricane-conditions-play-havoc-with-flight-schedules/1>.

Thomson, R.E., Bornhold, B.D., and Mazzotti, S. (2008): An examination of the factors affecting relative and absolute sea level in British Columbia; Canadian Technical Report of Hydrography and Ocean Sciences 260, Sidney, BC: Fisheries and Oceans Canada - Institute of Ocean Sciences.

Transport Canada (2011): Transportation in Canada 2011: Comprehensive Report; Minister of Public Works and Government Services, Canada, <www.tc.gc.ca/eng/policy/report-aca-anre2011-index-3010.htm>.

Transportation Safety Board of Canada (2013a): Railway Investigation Report R05H0013, <www.bst-tsb.gc.ca/eng/rapports-reports/rail/2005/r05h0013/r05h0013.asp>.

Transportation Safety Board of Canada (2013b): Railway Investigation Report R02M0050, <www.tsb.gc.ca/eng/rapports-reports/rail/2002/r02m0050/r02m0050.asp>.

Transports Québec (2012): Water Levels in the St. Lawrence River; <www.mtq.gouv.qc.ca/portal/page/portal/ministere_en/ministere/environnement/changemecha_climatiques/adapter_transports_impacts_changements_climatiques/niveaux_eau_saint-laurent>.

Urban Systems (2010): Stormwater infrastructure Climate Change Vulnerability Assessment; Report prepared for the City of Castlegar.

Vajda, A., Tuomenvirta, H., and Jokinen, P. (2012): Observed and future changes of extreme winter events in Europe with implications for road transportation; Proceedings of SIRWEC, May 22-25, Helsinki, Finland, <www.sirwec.org/Papers/helsinki/40.pdf>.

Vasseur, L. and Catto, N. (2008): Atlantic Canada; *in* From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, ON, p. 119-170.

Walker, I. and Sydneysmith, R. (2008): British Columbia; *in* From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, ON, p. 328-386.

Warren, F., Barrow, E., Schwartz, R., Andrey, J., Mills, B., and Riedel, D. (2004): Climate change impacts and adaptation: a Canadian perspective; Government of Canada, Natural Resources Canada Climate Change Impacts and Adaptation Directorate.

Winnipeg Free Press (2013a): Airships to fly our friendly skies?, <www.winnipegfreepress.com/business/airships-to-fly-our-friendly-skies-197265951.html>.

Winnipeg Free Press (2013b) Ice roads, airships could work together, <www.winnipegfreepress.com/opinion/analysis/ice-roads-airships-could-work-together-204044251.html>.

Wolfe, S.A. (2012): Geoscience information for northern highways: from planning to remediation; Quebec Climate Forum 2012, <www.mrifce.gouv.qc.ca/northernforum/acts/ppt/Wolfe_Presentation_EN.ppt>.

Zickefoose, S. (2013): Heavy snow delays flights and transit, weather warning continues; Calgary Herald, <www.calgaryherald.com/technology/Heavy+snow+delays+flights+transit+weather+warning+continues/7431774/story.html#ixzz2UelLrJzn>.

Zimmerman, R. and Faris, C. (2010): Chapter 4: infrastructure impacts and adaptation challenges; Annals of the New York Academy of Sciences, v. 1196, p. 63-85.

# CHAPTER 9:

# ADAPTATION: LINKING RESEARCH AND PRACTICE

Lead Authors:

**Jimena Eyzaguirre** *(ESSA Technologies Ltd.)* and **Fiona Warren** *(Natural Resources Canada)*

Contributing Authors:

**Alain Bourque** *(Ouranos)*, **Al Douglas** *(Ontario Centre for Climate Impacts and Adaptation Resources)*, **Jenny Fraser** *(British Columbia Ministry of Environment)*, **James MacLellan** *(University of New Brunswick)*, **Annette Morand** *(Ontario Centre for Climate Impacts and Adaptation Resources)*, **Linda Mortsch** *(Environment Canada)*, **Laurisse Noel** *(Natural Resources Canada)*, **Marie Raphoz** *(Ouranos)*, **Gregory Richardson** *(Health Canada)*, **James Wellstead** *(British Columbia Ministry of Forests, Lands and Natural Resource Operations)*

Recommended Citation:

Eyzaguirre, J. and Warren, F.J. (2014): Adaptation: Linking Research and Practice; *in* Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, edited by F.J. Warren and D.S. Lemmen; Government of Canada, Ottawa, ON, p. 253-286.

# TABLE OF CONTENTS

# KEY FINDINGS

Since 2008, climate change adaptation research and practice in Canada has been characterized by increasing engagement, diversity and complexity. Understanding of the adaptation process has improved, more groups are involved in adaptation discussions and a growing number of adaptation activities are documented. This progress leads to the following conclusions:

- Adaptation is being undertaken in Canada to achieve a range of goals, such as increasing capacity to adapt, improving resilience to specific climate events (especially extremes), and enhancing ability to thrive under different climate conditions. Among sectors, those with a demonstrated high sensitivity and exposure to climate and weather are generally most active in taking steps to understand, assess and manage vulnerability and risk related to climate change.

- Adaptation is not solely a local issue, although examples from the municipal level still predominate. There are examples of action by all levels of government, as well as community groups and industry, many of which represent collaborative initiatives.

- Understanding of the barriers and challenges to adaptation has improved, with recognition that factors beyond the basic determinants of adaptive capacity need to be addressed in order to increase the will to adapt and the success of adaptation measures. These include consideration of values and risk perception in framing problems and identifying solutions. As a result, understanding of how to overcome key barriers and enable adaptation has improved.

- At present, undertaking planning and policy exercises, building capacity and raising awareness comprise much of the adaptation action documented, with relatively few examples of implementation of specific changes to reduce vulnerability to future climate change, or take advantage of potential opportunities. As such, adaptation implementation in Canada is still in its early stages.

- Several factors can help accelerate the transition between awareness and action, including strong leadership and effective champions, targeted awareness-raising and supportive strategies or policies. Experiencing extreme events, as well as observing impacts of gradual changes (e.g. sea level rise) also stimulate adaptation.

# 1. INTRODUCTION

The concept of adaptation has evolved since it was first recognized as a potential response to climate change in the 1990s, and attitudes have shifted such that adaptation is now viewed as an essential complement to the reduction of greenhouse gas emissions (Klein et al., 2007; Lemmen et al., 2008). Within the research community, focus has expanded beyond biophysical impacts, accompanied by lists of possible adaptation options, to studies that investigate the process of adaptation from a variety of perspectives (e.g. social, environmental, economic and psychological; e.g. Burch and Robinson, 2007; Jantarasami et al., 2010; Berang-Ford et al., 2011; Gifford, 2011; Brisley et al., 2012; O'Brien, 2012). In Canada, several organizations have specific mandates to generate and deliver adaptation knowledge, and all levels of government are beginning to develop and implement adaptation strategies, plans and policy frameworks (e.g. City of Toronto, 2007; Government of Canada, 2011; Government of Quebec, 2012). Engagement has broadened to encompass government, industry, non-governmental organizations and individuals, with mounting recognition that all have responsibility for adaptation action.

Despite these advances, there are few documented examples of adaptation being implemented specifically to reduce vulnerability to future climate conditions. Over recent years, a growing body of research has examined the barriers and challenges to adaptation that are preventing or constraining action. These barriers stem from issues such as information, resources, governance and values. At the same time, knowledge has increased on how to facilitate effective adaptation by enhancing awareness and the will to adapt, building capacity and creating an enabling environment.

This chapter examines the current status of adaptation in Canada with respect to both research and practice, based on scientific and grey literature. Section 2 examines where we were in 2007, at the time of the last assessment (Lemmen et al., 2008), while Section 3 presents a review of international approaches to adaptation. Section 4 examines how we have progressed in Canada since 2007, through discussion of changes in research, engagement, action on adaptation and understanding of barriers. Overcoming barriers and facilitating action are discussed in Section 5. Case studies are incorporated throughout the chapter to expand on a range of issues.

# 2. PREVIOUS ASSESSMENTS

*'From Impacts to Adaptation: Canada in a Changing Climate 2007'* (Lemmen et al., 2008) concluded that although still in early stages, adaptation was occurring, to differing degrees, in every region of the country. Although the definition of adaptation was broad – encompassing any activity, initiative or intention to enhance resilience to current or future climate variability or change – the assessment did demonstrate the growing importance of adaptation for different groups, including communities, higher levels of government (provincial/territorial and federal), industry (associations and companies) and professional organizations. A high potential to adapt was evident for Canada as a whole, although regional disparities relating to differing levels of exposure, sensitivity and capacity were highlighted, as was the observation that high adaptive capacity does not always translate to effective adaptation. Similar conclusions were drawn in the IPCC Fourth Assessment Report (Field et al., 2007).

For the most part, Lemmen et al. (2008) discussed adaptation in the context of potential options, strategies or needs, but it also included examples of adaptation initiatives deployed in response to a climate-related event or a current or perceived risk. For example, the City of Regina introduced drought contingency plans after experiencing the impacts of the 1988 drought (Sauchyn and Kulshreshtha, 2008), while the city of Toronto developed a Hot Weather Response Plan in response to more frequently occurring heat waves (Chiotti and Lavender, 2008). In Quebec, design criteria for electrical transmission facilities were revised after the 1998 ice storm in order to reduce vulnerability to severe weather events (Bourque and Simonet, 2008). Observations of changing risks also led to adaptation; for instance, elevating buildings on pylons in coastal regions to reduce damages from storm surge flooding (Vasseur and Catto, 2008), and winter tourism operators on the Prairies diversifying their activities to add summer recreational opportunities (Sauchyn and Kulshreshtha, 2008). These examples demonstrated that adaptation to climate change does not necessarily involve detailed consideration of changes in climate parameters or precise predictions. Instead, it can be based on simple assumptions that climate-related events (e.g. storms, floods and droughts), temperature increases, and sea-level rise impacts (erosion and flooding) will recur, continue and/or increase in frequency and severity in the future.

The 2008 Assessment also highlighted the role of detailed climate projections as requirements for some types of adaptation implementation. Useable and accessible data on future climate (e.g. temperature, precipitation) and sea level are often required by engineers and resource managers, for example, to determine timely, appropriate and cost-effective adaptation. For instance, data of past trends and future climate projections may be needed to inform decisions on upgrading and replacing infrastructure (such as pipelines, culverts and structures for shoreline protection), planning for hydroelectric facility placement and renovation, and selecting tree species for forestry operations. Lack of availability of such information was identified by practitioners as a barrier to adaptation.

There were many examples of initiatives that served to enhance overall resilience, or build capacity to adapt, while not addressing impacts from specific changes in climate. Often referred to as 'no-regrets' or 'win-win' options designed to bring benefits regardless of climate outcomes, examples include improving water- and energy-use efficiency, diversifying economic activities in resource-dependent communities, and addressing underlying issues that make populations vulnerable (e.g. poverty, poor health status, and limited access to information and education).

Adaptation was being considered and undertaken by many different actors, including individuals and households, business and industry, community organizations, and governments at all levels (municipal, provincial, territorial, federal) (*see* Table 2 in Burton, 2008 ). Municipal governments appeared to be the most active on adaptation (Field et al., 2007; Lemmen et al., 2008), with action primarily triggered by observed damages from past climate-related events (e.g. floods, droughts, heat waves) and also by policy initiatives from higher levels of government that encouraged or required the development of adaptation plans or strategies. Examples of adaptation by industry and business were limited, with climate change adaptation just starting to appear on the agendas of industry and professional organizations (Burton, 2008) and some evidence of investments in adaptation being made (Field et al., 2007). For industry, motivation for adaptation included protecting investments, reducing risks and enhancing corporate reputation (Burton, 2008).

Although many of the chapters in the 2008 Assessment recommended that adaptation be mainstreamed, evidence of this occurring was limited. Mainstreaming refers to integrating climate change into existing decision-making processes, with the goal that climate change be considered in all decisions that are sensitive to climate. Mainstreaming is also sometimes referred to as 'policy integration'. Risk management approaches were also often recommended in the 2008 report. These approaches include a series of steps, ranging from preliminary analysis, to risk estimation and evaluation, to risk controls, then action and monitoring (Bruce et al., 2006), and were presented as an effective approach to decision making under the uncertainty inherent in climate change.

# 3. INTERNATIONAL CONTEXT

An exploration of the research on the status of adaptation at the international level provides important context for assessing the situation in Canada. Several papers have examined international adaptation policies and approaches by analyzing, for example, the types of adaptation being considered (Ford et al., 2011), the existence and role of adaptation plans and strategies (Biesbroek et al., 2010; Preston et al., 2010; Bauer et al., 2012) and trends in adaptation planning and implementation (Gagnon-Lebrun and Agrawala, 2007).

From this research, a common conclusion can be drawn: adaptation implementation is in the early stages in most, if not all, developed countries. Research and understanding of adaptation policies, plans and strategies have advanced considerably over the last 5 to 10 years, yet relatively few examples of adaptation implementation have been documented (Biesbroek et al., 2010; Lesnikowski et al., 2011; Bauer et al., 2012; Webb and Beh, 2013). Common challenges associated with moving adaptation from the planning to the implementation stage include dealing with uncertainties, coordinating adaptation effectively across sectors and different levels of government, and making adaptation a priority for decision makers (OECD, 2012). Inadequate funding and budgets for adaptation were also cited as key implementation challenges (Bauer et al., 2011). The paucity of examples of adaptation implementation may, in part, reflect lag times between action, research and publication, and the lack of established, standard mechanisms for monitoring and measuring adaptation progress (OECD, 2012).

Many countries, including Australia, Germany, the UK and Norway have developed national adaptation strategies, which are generally non-binding frameworks that guide public adaptation policies. National adaptation strategies tend to focus on advancing adaptation by promoting the production and dissemination of data and information, and by identifying priorities for adaptation. Mechanisms to support framework priorities include guidelines for coordination among government departments, a centralized coordination body for developing and implementing the framework, a commitment to improve scientific knowledge integration (e.g. through assessments), and a standing scientific advisory committee that can provide ongoing information and advice to policy decision making (Bauer et al., 2012). Although lacking national adaptation strategies, the OECD (2012) identifies Canada, New Zealand, Slovenia, Sweden and United States as developed countries active on adaptation.

In a review of 7 European adaptation strategies, Biesbroek et al. (2010) concluded that the strategies are useful in that they signal a political commitment on the issue of climate change, but have not yet necessarily translated to adaptation implementation. This is supported by the European Commission itself, which states that although 15 Member States have developed national adaptation strategies, and others are in development, there are "relatively few concrete [adaptation] measures on the ground" (European Commission, 2013). The European Union has now developed a European adaptation strategy, which encompasses all Member States, and complements the national-level strategies.

Although legislated mandates for climate change adaptation are rare, some examples exist. The United Kingdom's Climate Change Act provides for an Adaptation Sub-Committee within the larger climate change scientific advisory committee, and requires that climate change risk assessments and the National Adaptation Programme be renewed every 5 years (Committee on Climate Change, n.d.). As a result, all departments in the UK have a departmental adaptation plan and the UK Treasury provides guidance on climate change adaptation. The government is also able to require reporting on adaptation initiatives by suppliers of public services (e.g. potable water, electricity), with almost 90 organizations providing reports during the first round (Committee on Climate Change, n.d.). Even with legislated requirements for adaptation, the transition from planning to implementation is constrained by challenges, such as evaluation and funding (Boyd et al., 2011). Other examples include the Delta Act of the Netherlands, which requires adaptation initiatives related to water management (e.g. flood safety and freshwater supply) (Delta Programme Commissioner, n.d.) and Norway's requirement that municipalities include climate change risk and vulnerability analysis in their spatial planning. The European Commission has indicated that if progress on adaptation action is not sufficient by 2017, they will consider a legally binding instrument (European Commission, 2013).

# 4. STATUS OF ADAPTATION IN CANADA

In Canada, engagement on adaptation by different groups has increased significantly since the 2008 Assessment. For the most part, however, the many initiatives being undertaken to build Canadians' capacity to adapt have yet to be evaluated or their lessons synthesized in scientific literature. Agreed-upon methods to track and measure actions taken to reduce climate change risk and vulnerability do not yet exist, which prevents meaningful comparisons across sectors. Nevertheless, by linking research and practice, an improved understanding of adaptation as a process is emerging.

## 4.1 RESEARCH AND PRACTICE

Adaptation is increasingly becoming a subject of scientific research and applied analysis. Canadian research on adaptation is being undertaken by a growing number of academic disciplines, exploring a range of sectors and problems (*see* Box 1). Knowledge for adaptation also comes from government-sponsored regional and sectoral assessments of impacts, vulnerability and climate-related risk (e.g. Séguin, 2008; Williamson et al., 2009; Desjarlais and Blondlot, 2010; Crawford and MacNair, 2012), from organizations with the specific mandate to produce this knowledge (e.g. Ouranos, Pacific Climate Impacts Consortium, Ontario Centre for Climate Impacts and Adaptation Resources and the Prairie Adaptation Research Collaborative) and from government programs (e.g. Natural Resources Canada, 2012, Environment Canada, 2013). University research groups and private consulting firms are filling an emerging demand for applied analysis, including undertaking targeted climate change risk assessments (OCCIAR, 2013) and developing compendia of case studies and tools (Nelitz et al., 2013).

Although efforts to understand climate impacts and vulnerabilities remain important, discussions on adaptation

BOX 1

## TRENDS IN CANADIAN ADAPTATION RESEARCH

Many research disciplines contribute to generating information and knowledge that support adaptation planning. To identify broad trends in adaptation research between 2000 and 2012, a structured review of academic articles published by researchers from Canadian research bodies was undertaken, using methods in MacLellan (2008). An initial database search resulted in 743 articles of potential relevance, subsequently narrowed to 428 articles of direct relevance to climate change adaptation planning. Articles were categorized according to five factors: (1) sectors; (2) climate hazards addressed; (3) academic disciplines; (4) theory and methods employed (e.g. climate and impact modeling, vulnerability assessment, participatory methods, cost benefit analysis); and (5) geographic or ecosystem focus. Analysis led to the following conclusions:

- The rate of publication on climate change adaptation has grown exponentially. Between 2000 and 2012, the number of climate change adaptation articles published by researchers associated with Canadian institutions increased almost tenfold, exceeding trends in overall publication rates in all fields of study.
- Research publications on climate change adaptation are increasingly diverse, as suggested by the number of journals publishing articles about adaptation for the first time. In 2007, 13 journals published articles on climate change adaptation by researchers associated with Canadian institutions for the first time; the number of journals doing so in 2012 was 32.
- Sectoral coverage of adaptation research is also increasing. Figure 1 shows the distribution of research articles by sector for two time periods. Between 2000 and 2007, the top three sectors studied were water management, agriculture and the forest sector. After 2007, publications addressing health adaptation increased significantly; this sector is now among the top three studied. Coverage of all sectors, except for water management and transport, increased from one period to another.
- The Arctic has been a major focus of adaptation research. Further, research associated with the Arctic picked up significantly after 2005, likely a combined effect of the generation and dissemination of research for the Arctic Climate Impact Assessment (ACIA, 2005) and subsequent research investments through the International Polar Year (e.g. Kulkarni et al., 2012) and ArcticNet[1].

Trends in research methods are difficult to discern, as they are discipline and sector-specific. Three general points are worth noting from the analysis:

1. Adaptation research in the Arctic stands out as being highly inter-disciplinary, integrative and participatory. Subsistence and natural resource harvesting predominates as a research focus (40% of Arctic articles with a sectoral focus), followed by health (23%) and ecosystem conservation (10%). Arctic research also makes heavy use of surveys and participatory methodologies, and integrates social and cultural aspects of climate change adaptation with impacts modeling.
2. Although many articles refer to funding and financial resources as important in adaptation planning, fewer than 10 articles specifically analyzed the costs and benefits of adaptation (e.g. Crowe and Parker, 2008; Samarawickrema and Kulshreshtha, 2008; Lantz et al., 2012; Ochuodho et al., 2012). A direct focus on the assessment and selection of adaptation options using economic tools was absent.
3. An increase is apparent in the number of studies using quantitative methods, such as citation analysis and content analysis, to integrate and analyze research. Seven percent of all articles we assessed could be considered systematic reviews, some of which have direct relevance to specific policy questions (e.g. Hewitt et al., 2011).

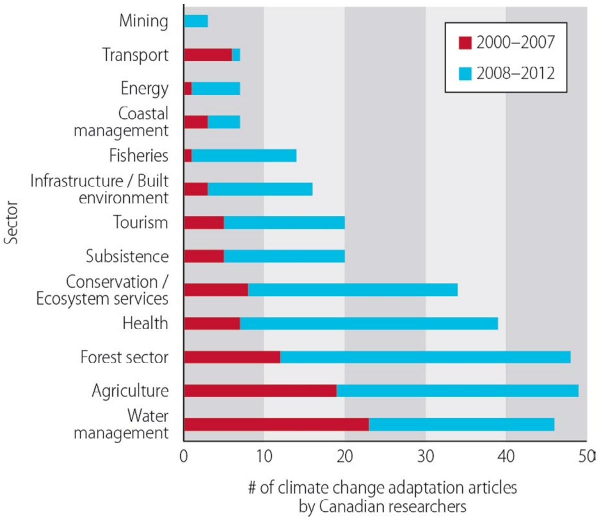


**FIGURE 1:** Number of climate change adaptation articles by Canadian researchers by sector (2000-2012).

This analysis is limited by its focus on the volume of academic literature. Despite this limitation, it does provide a snapshot of the evolving research capacity in support of adaptation in Canada. Expanding trend analysis to include grey literature and consideration of research uptake by decision makers would be useful.

have evolved from whether to adapt, to how to adapt. Building on pioneering work on adaptation policy and decision-making frameworks (e.g. Willows and Connell, 2003; Lim and Spanger-Siegfried, 2005), numerous Canadian guides and templates describing the adaptation process are now available (e.g. Quebec Ministry of Public Security, 2008; Natural Resources Canada, 2009; Jackson et al., 2011; CREXE, 2012), some of which are highly context-specific (Gleeson et al., 2011). Based on broad patterns across existing frameworks, along with observed adaptation activities undertaken by Canadian organizations, a generic adaptation process of awareness, preparation, implementation and iterative learning is proposed (*see* Box 2). Governments, often on a partnered basis, have implemented a range of initiatives to understand how adaptation occurs among different groups and to encourage further action. These include pilot activities (e.g. surveillance systems for heat-related illnesses; Chapter 7 – Human Health, Rodgers and Behan, 2012, Regional Adaptation Collaboratives Program, Natural Resources Canada, 2013a), case studies and best practices

**BOX 2**

## THE ADAPTATION PROCESS

Like any process involving changes in thinking and practice, adapting to a changing climate involves deepening levels of engagement (phases) and actions that can be taken in support of decision making (steps). Figure 2 summarizes these phases and steps, which integrate observations on how adaptation is occurring in Canada with common elements of several adaptation planning frameworks. Although presented as a linear process, organizations may take different pathways as they transition and iterate through these phases and steps.

Phases in the adaptation process include awareness, preparation, implementation and iterative learning.

The seven steps are:

1. **Awareness of climate change:** the adaptation process begins once an individual or organization becomes aware of a changing climate as a threat or opportunity.
2. **Awareness of the need to adapt:** an awareness of the magnitude of the problem helps to identify adaptation as a solution.
3. **Mobilizing resources:** awareness can lead individuals and organizations to dedicate human and/or financial resources to help clarify the nature of threats or opportunities.
4. **Building capacity to adapt:** involves applying scientific information, financial resources, and skills to focused activities such as issue screening, risk assessment and in-depth analysis to generate the understanding needed for informed decision making.
5. **Implementing targeted adaptation actions:** concrete actions are put in place to reduce vulnerability (risk or exposure) to climate change and/or to take advantage of opportunities.
6. **Measuring and evaluating progress:** measuring and evaluating the effectiveness of adaptation actions and related assumptions and uncertainties provides the feedback necessary for improved management.
7. **Learning, sharing knowledge with others and adjusting:** the last step leads to refinements in the adaptation actions implemented and transfer of lessons to future adaptation.

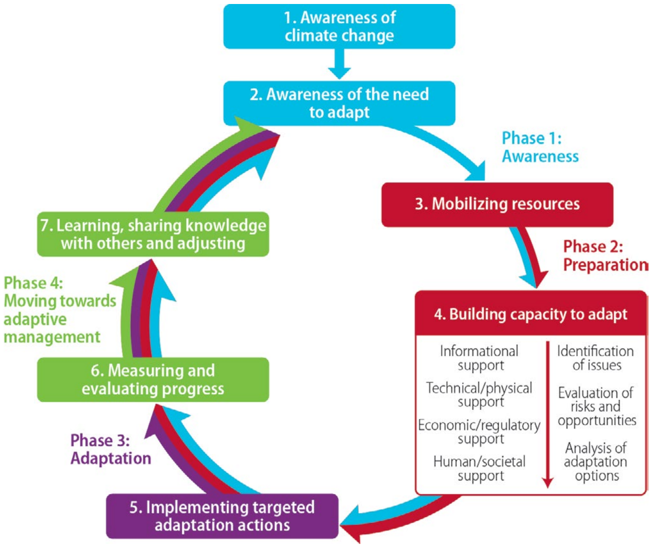


**FIGURE 2:** Stages and steps in the adaptation process.

This Assessment highlights numerous examples of Canadian adaptation activities suggesting that, for the groups involved, steps 1 and 2 have been surpassed. Evidence of having reached steps 3 and 4 is also available, in the form of strategies or adaptation plans at provincial/territorial levels and within some local governments, as well as adaptation programs and initiatives supported by governments but implemented on a partnered basis. The creation of organizations with the specific mandate to generate knowledge for adaptation (e.g. Natural Resources Canada's Adaptation Platform, Ouranos, Pacific Climate Impacts Consortium, Ontario Centre for Climate Impacts and Adaptation Resources and Prairie Adaptation Research Collaborative) indicates high levels of activity intended to build capacity to adapt. Less progress is evident along the remaining three steps, although some examples of implementation of targeted actions are documented (*see* Table 1).

(e.g. PIEVC, 2012, NRTEE, 2012a; Rodgers and Behan, 2012, Fraser and Strand, 2011) and several initiatives promoting knowledge-sharing.

Policy and research communities also demonstrate an emerging interest in tracking and evaluating progress on adaptation (e.g. Leclerc, 2012; Ford et al. 2013). Survey research has explored patterns of awareness of climate change impacts and engagement on adaptation among groups, including businesses (e.g. Environics Research Group, 2010; NRTEE, 2012b), municipalities (Robinson and Gore, 2011; Carmin et al., 2012), and individuals, including public servants (e.g. BC Stats, 2012), members of professional associations (Davidson and Bowron, 2012) and households (e.g. Berry et al., 2009). Among other uses, evidence from these surveys serves to set baselines and informs future policy and program design. A lack of consistent characterizations of adaptation – and specifically of 'successful' adaptation – are among the current challenges to monitoring and evaluating adaptation progress (e.g. Ford et al., 2013) and to comparing results across studies (Dupuis and Biesbrock, *in press*).

In practice, Canada's approach to adaptation over the past few years reflects a focus on enabling local and regional (e.g. watershed-level) action (Mullan et al., 2013), although an overall rise in engagement by groups across sectors and levels of decision making has occurred (UNFCCC, 2011). Chapters 3 through 8 of this Assessment provide a number of examples of adaptation activities by governments, industry and non-governmental organizations (*see* Table 1). These include activities that build capacity for future adaptation, as well as the implementation of targeted activities to reduce vulnerability to climate risks or to exploit opportunities (Smit and Wandel, 2006; UKCIP, 2010).

| | | Type of adaptation activity | |
|---|---|---|---|
| Examples | Chapter | Build capacity to adapt | Implement actions |
| **Government** | | | |
| The communities of Cambridge and Milton, ON, are assessing the economic impacts of climate change on the design of drainage infrastructure in flood-prone areas | 8 | X | |
| The region of Durham, ON, is integrating climate change considerations into local planning documents | 8 | X | |
| The cities of Toronto and Windsor, ON, and Winnipeg, MB, have used outputs of heat-health vulnerability assessments to develop or update their heat alert and response systems (HARS) | 7 | X | X |
| Quebec city is over-designing culverts to account for the increasing frequency and intensity of rain events | 8 | | X |
| The city of Calgary, AB, has increased water conservation efforts to maintain 2003 removal levels | 8 | | X |
| British Columbia, Quebec, Yukon and Northwest Territories undertook sector-specific assessments of vulnerability, risks and opportunities (agriculture, northern transportation systems) | 4, 8 | X | |
| British Columbia is establishing an assisted migration adaptation trial for 15 commercial tree species in sites ranging from central Yukon to southern Oregon | 3 | X | |
| British Columbia, Alberta and Quebec are modifying seed transfer guidelines for reforestation to take shifting climate conditions ideal for tree growth into account | 3 | X | |
| As part of the Lake Simcoe Protection Plan, Ontario is requiring the development of a climate change adaptation strategy for the watershed | 6 | X | |
| Drawing on scientific, traditional and local knowledge, Yukon's land use plan for the Peel Watershed will integrate climate change considerations | 6 | X | |
| British Columbia is developing a range of policy guidance to mainstream adaptation into coastal zone management and land-use planning | 8 | X | |
| Manitoba is protecting winter habitat for the Qamanirjuaq barren-ground caribou herd in the transition zone between boreal and tundra ecosystems | 6 | | X |
| The federal government has undertaken several activities to raise awareness of health-related risks from climate change among public health and medical practitioners and the public itself | 7 | X | |
| The federal government is considering adjusting biosecurity policies to adapt to the effects of changing climate on invasive alien species | 4 | X | |

*Table 1 continued on next page*

| Examples | Chapter | Type of adaptation activity | |
|---|---|---|---|
| | | Build capacity to adapt | Implement actions |
| The federal government is developing tools to guide public health managers on vector-borne disease surveillance and control methods | 7 | X | |
| The federal government is taking into account the continued melt of glaciers in Banff and Jasper National Parks in the siting of new viewing locations and interpretive centres | 5 | | X |
| The federal government is establishing ecologically-based regions for bluetongue control, a viral disease mainly affecting ruminants, in anticipation of shifts in prevalence of the disease | 4 | | X |
| A range of intergovernmental initiatives to raise adaptation on the policy agenda and facilitate knowledge-sharing | 3, 4 | X | |
| Industry | | | |
| Industry associations in British Columbia are developing a tourism action plan to respond to Mountain Pine Beetle damage | 3, 5 | X | |
| An oil and gas company is developing and implementing a water strategy that includes engagement at policy levels and working with local stakeholders on site-specific water issues | 3 | X | |
| Quebec's hydro-electric corporation is integrating climate change considerations in demand forecasts, to inform rate adjustments and procurement plans | 3 | X | |
| Actors in the agro-industry sector are adopting real-time monitoring and other technologies to help increase efficiencies in irrigated agriculture | 4 | X | X |
| Maple syrup producers are adjusting start times for tapping sugar maple trees and installing more efficient collection systems | 4 | | X |
| Some property insurers are adjusting insurance coverage (e.g. no longer offering sewer back up insurance in communities with recurring losses) to better align with exposure to climate risk | 5 | | X |
| Mining companies operating in the North are applying techniques to protect northern infrastructure from permafrost warming (e.g. deeper pile foundations, adjustable foundations) | 3 | | X |
| Tourism operators are improving management of impacts from current climate variability (e.g. snowmaking, irrigation, fire smart landscaping, seasonal diversification and insurance and financial products such as snow or sunshine guarantees) | 5 | | X |
| Non-governmental organizations | | | |
| The Canadian Medical Association issued a policy statement as a call to action on climate change adaptation by health authorities | 7 | X | |
| The Canadian Standards Association has issued a technical guide for building infrastructure on permafrost including potential effects of future climate on permafrost | 3 | X | |
| Engineers Canada has undertaken a range of initiatives to equip engineering professionals with tools and information to adapt (e.g. a vulnerability assessment protocol, case studies, training workshops) | 8 | X | |

**TABLE 1:** Selected examples of adaptation from the sectoral chapters.

A few observations can be drawn from the examples of adaptation documented in this assessment. First, direct experience with climate-related events and recognition of weather and climate sensitivity remain important triggers for adaptation in public and private sectors alike. For example, the 2011 Manitoba flood led to an expanded consideration of health impacts in disaster planning and recovery efforts (Chapter 7 – Human Health; Case Study 3); whereas an increasing trend of damage to homes and businesses caused by severe weather such as heavy rains, wind and wildfire in Canada and abroad has led Canadian insurers to consider adaptation (Chapter 5 – Industry). Other drivers of adaptation include regulatory compliance, reputational concerns and the desire to retain access to international markets (Chapters 3 – Natural Resources, 4 – Food Production and 8 – Water and Transportation Infrastructure). Government roles in protecting societies' most vulnerable individuals and preserving public health and safety provide the impetus for undertaking activities to understand risks and vulnerabilities, and to implement targeted measures (Chapters 7 – Human Health and 8 – Water and Transportation Infrastructure).

Second, examples of adaptation actions to proactively manage risks from future climate are limited. Of the 63 examples of adaptation actions compiled overall, 60 percent involve the following: research; monitoring climate impacts; assessing vulnerabilities, risks and opportunities; developing stand-alone adaptation strategies; and mainstreaming adaptation within existing policies and planning. The balance comprises activities implemented to prevent or offset harm from current climate-related risks, including operational changes to address impacts of current climate variability and of observed gradual changes such as permafrost degradation. Beyond trials for assisted migration of tree species (*see* Case study 2 in Chapter 3 – Natural Resources), evidence of novel actions taken to manage risks associated with potentially unfamiliar, large-scale or step changes in climate conditions is lacking.

Third, collaboration is occurring across sectors, with objectives including acquiring knowledge for adaptation and expanding the range of options to adapt. For instance, the Ontario government established a research partnership with the University of Guelph to help augment understanding of animal diseases related to climate change (Chapter 4 – Food Production). Partnerships to help build a case for adaptation have also been observed. The Co-operators Insurance Group, together with the Institute for Catastrophic Loss Reduction, undertook an initiative to demonstrate the technical and economic feasibility of building climate-resilient homes (Chapter 5 – Industry). Implementation of adaptation can also require collaboration. For example, a partnership between the Chaplin mine in Saskatchewan and the conservation group Ducks Unlimited Canada helped the mine to gain access to secondary water sources to offset effects of dry years (Chapter 3 – Natural Resources).

Engagement and action on adaptation differ among stakeholder groups, and so the following sections discuss advances in adaptation by governments (federal, provincial/territorial and local) and industry, including their roles, objectives and approaches.

### 4.1.1 FEDERAL GOVERNMENT

The federal government plays an important role in delivering scientific information on climate change impacts and adaptation, and in adaptation mainstreaming (OAG, 2010). This is consistent with emerging understanding of the roles of government as adaptors and facilitators of adaptation (e.g. NRTEE, 2009; Cimato and Mullan, 2010; Hallegatte et al., 2011). As facilitators, government agencies are responsible for removing barriers and creating incentives so that people and organizations across society are more inclined to proactively adapt. As adaptors, government agencies are responsible for adjusting policy, programming and operational decisions to account for changing climate.

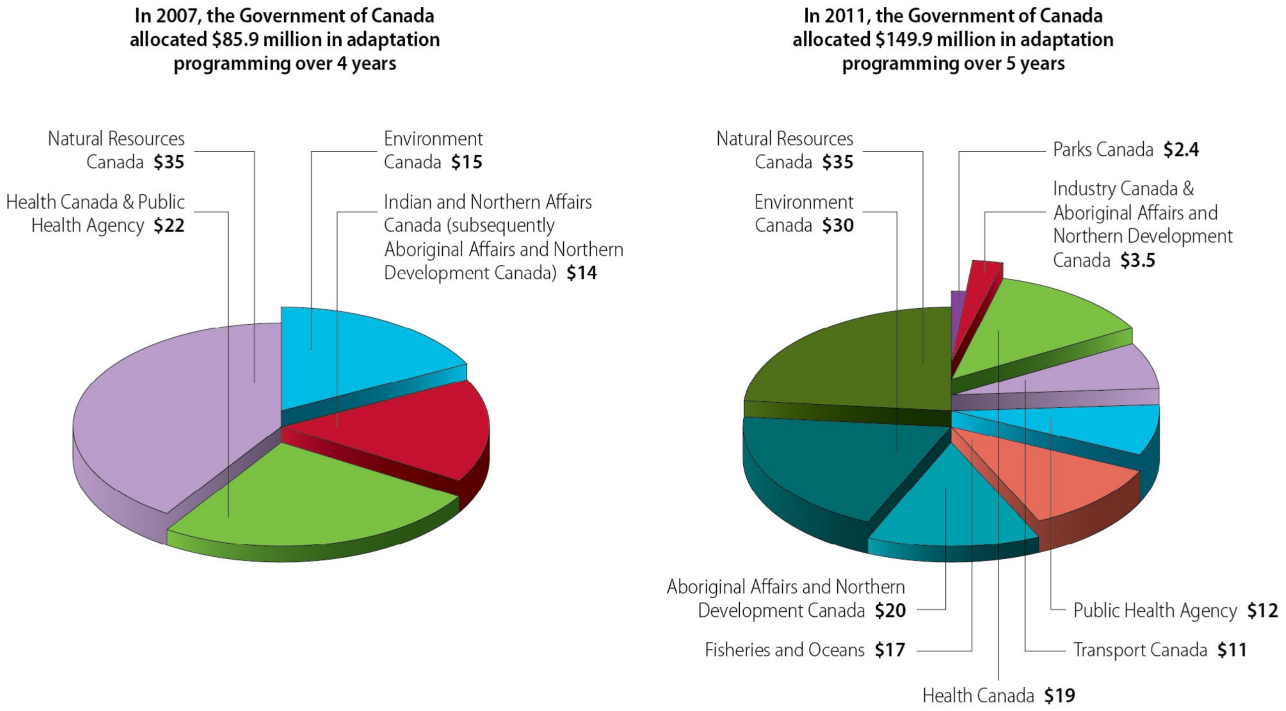


**FIGURE 3:** Evolution of federal spending on adaptation programs *(Data from: Environment Canada, 2013; CNW, 2007).*

Although criticized for the perceived lack of sustained leadership on adaptation and the absence of a national adaptation strategy (NRTEE, 2009; OAG, 2010; Dickinson and Burton, 2011; Hanna et al., 2013), federal efforts to build Canadians' capacity to adapt to climate change have deepened over the past five years. A rise in federal engagement on adaptation is evident: between 2007 and 2011 the number of departments and agencies delivering adaptation programs grew from five to nine (*see* Figure 3) while the Federal Adaptation Policy Framework was adopted in 2011 to guide future adaptation priorities (Government of Canada, 2011). Funding has supported, for example, development of climate change scenarios, community adaptation planning, provision of information and decision support tools targeting health and infrastructure adaptation (Environment Canada, 2010; 2013), and collaboration among different orders of government, industry and adaptation practitioners (*see* Case Study 1).

Available literature suggests several ways of enhancing federal action on adaptation, including: enhanced activity

### CASE STUDY 1

## COLLABORATION TO ENHANCE ADAPTATION DECISION MAKING

Recognizing that climate change impacts and adaptation decisions cross-cut jurisdictional and sectoral boundaries and involve a wide range of actors, Canada's federal, provincial and territorial governments have adopted collaboration as a key principle for advancing knowledge and action on adaptation. Although collaboration takes time and can present many challenges, it also offers significant benefits with respect to efficient use of resources, sharing of data, experience and expertise, inspiring action amongst peers, and helping to avoid divergent goals and conflicts (Spencer et al., 2012).

Building on foundational work on climate change impacts and adaptation (e.g. Smit, 1993), the Canadian Climate Impacts and Adaptation Research Network (C-CIARN) was developed to raise awareness and build relationships on the issue. Operating from 2001 to 2007, the network consisted of 14 sectoral and regional offices, with the primary goal of building linkages between the research and the decision-making communities, including federal, provincial and territorial government departments.

Based upon the results achieved and relationships built by C-CIARN, six Regional Adaptation Collaboratives (RACs) were established across Canada in 2008 (North, BC, Prairies, Ontario, Quebec and Atlantic), which focused on activities to facilitate practical adaptation. Each RAC focused on priorities defined on the basis of scientific understanding (e.g. Lemmen et al., 2008) and regional policy priorities. Common themes included water resource management, infrastructure and municipal planning (Natural Resources Canada, 2013a). Each RAC developed its own network of decision makers and practitioners, including governments, industry and non-government organizations, and also drew upon the researchcommunity. In total, more than 150 organizations have been involved in the RACs, producing more than 230 products – including guidelines, standards, tools, adaptation plans, case studies and technical reports (Natural Resources Canada, 2013b; Figure 4). Regional networking was complemented by collaborative activities with targeted practitioner organizations, such as professional engineers and planners.

The most recent mechanism aimed at enhancing collaboration on adaptation across Canada is the Adaptation Platform, launched in 2012 (Natural Resources Canada, 2013a). The Adaptation Platform brings together many of the players previously engaged in collaborative activities (federal, provincial and territorial governments, and professional organizations) along with industry associations and financial sector representatives, to address shared adaptation priorities by pooling knowledge, capacity and financial resources to produce information and tools that regions and sectors need in order to understand and adapt to the effects of a changing climate.

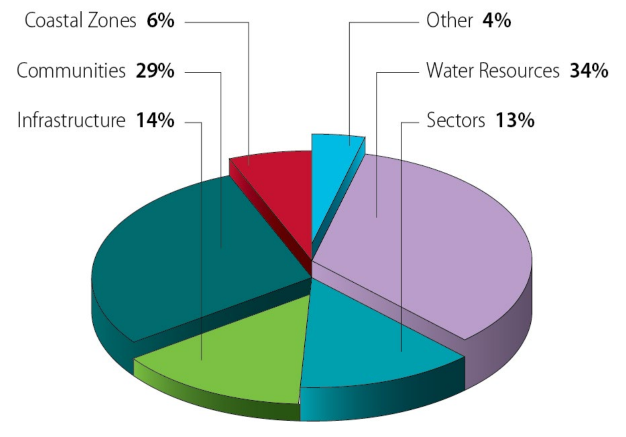


**FIGURE 4:** Thematic distribution of Regional Adaptation Collaborative products *(Source: Natural Resources Canada, 2013b).*

The Platform provides a structure to initiate and undertake activities to advance shared regional and sectoral adaptation priorities in Canada. It consists of a plenary and a series of working groups. Plenary members are senior-level representatives who help define priority areas for working-group efforts, align interests and resources, and identify opportunities for adaptation. Working groups focus on key economic sectors (e.g. forestry, mining), common information needs (climate scenarios), and broader themes deemed important in continuing to advance adaptation (e.g. measuring progress, science assessment).

related to generating and disseminating information for adaptation; improving adaptation mainstreaming efforts in policy areas such as disaster risk reduction, major project approvals, infrastructure funding and fisheries management; and improved coordination to avoid duplication and adverse side-effects, and to ensure that lessons are transferred across sectors and geopolitical boundaries (Jessen and Patton, 2008; Dickinson and Burton, 2011; NRTEE, 2012b).

## 4.1.2 PROVINCIAL AND TERRITORIAL GOVERNMENTS

Adaptation has grown in importance among provincial and territorial governments (*see* Table 2). British Columbia, Ontario and Quebec have stand-alone adaptation strategies and action plans and have established scientific advisory bodies to guide adaptation efforts. The remaining provinces and territories have either integrated their adaptation efforts into broader climate change action plans, or are in the process of developing adaptation strategies or plans (e.g. Saskatchewan, New Brunswick, Prince Edward Island and Northwest Territories) (David Suzuki Foundation, 2012). In recent years, several governments have completed some form of risk or vulnerability assessment (e.g. BC Agriculture and Food Climate Action Initiative, 2012) and some provide for specific sectoral actions and commitments (e.g. measures to enhance the health of individuals and communities in a changing climate; Government of Quebec, 2012). Evaluations of jurisdictional efforts relative to adaptation needs do not yet exist; however, differences are apparent across the country in terms of capacity to assess vulnerability, and to plan and implement adaptation actions (*see* Chapter 7 – Human Health).

| Province / Territory | Strategy, plan, framework | Examples of adaptation activities or resources |
|---|---|---|
| British Columbia | Preparing for Climate Change – British Columbia's Adaptation Strategy (2010)[2] | $94.5 million to establish the Pacific Institute for Climate Solutions (PICS) to assess, develop and promote viable emission reduction and adaptation options as inputs to policy[3]<br>Forest policy guidance, decision support tools and knowledge to help BC forest managers adapt to climate change[4] |
| Alberta | Climate Change Strategy: Responsibility. Leadership. Action (2007) – includes adaptation efforts[5] | A Climate Change Adaptation Framework and accompanying manual to help organizations integrate climate change risk into existing Enterprise Risk Management systems and strategic planning approaches[6]<br>Involvement in research on climate change and water supplies[7], including through the Prairie Adaptation Research Collaborative (PARC) |
| Saskatchewan | | Launched in 2010, Saskadapt.ca is the province's climate change impacts and adaptation information portal to help residents and organizations adapt[8]<br>The Management and Reduction of Greenhouse Gases and Adaptation to Climate Change Act, including provisions for coordination of adaptation planning[9] |
| Manitoba | Climate Change Action Plan "Beyond Kyoto" (2008) includes adaptation efforts[10] | Improvements in flood protection, including upgrading the Red River Floodway to withstand a 1-in-700- year spring flood from a previous 1-in-90-year spring flood[11]<br>The new Provincial Planning regulation includes provisions for local planning to prepare for climate change impacts[12] |
| Ontario | Climate Ready: Ontario's Adaptation Strategy and Action Plan 2011-2014[13] | A guide to help integrate climate change projections into hydrologic modeling to inform water budgets required under the Clean Water Act<br>A web-based adaptation toolbox to help plan for the impacts of climate change on ecosystems and natural resources[14] |
| Quebec | Quebec in Action: Greener by 2020 – 2013-2020 Government Strategy for Climate Change Adaptation[15] | $200 million has been allocated to implement adaptation actions in the province<br>Adaptation has been mainstreamed into several laws and policies: the Water Act, the Dam Safety Act; and the Québec Strategy for Drinking Water Conservation |
| Yukon | Climate Change Action Plan (2009) – includes adaptation efforts[16]; Pan-Territorial Adaptation Strategy (2011)[17] | Sector-specific risk and vulnerability assessments (infrastructure, forest health, forest tree species, water resources)[18]<br>An inventory of permafrost information[19] |
| Northwest Territories | Pan-Territorial Adaptation Strategy (2011) | An Adaptation Framework for the Northwest Territories is in development[20]<br>Vulnerability assessment of highway corridor completed in 2011[21] |

*Table 2 continued on next page*

| Province / Territory | Strategy, plan, framework | Examples of adaptation activities or resources |
|---|---|---|
| Nunavut | Upagiaqtavut – Setting the Course: Climate Change Impacts and Adaptation in Nunavut – framework for adaptation activities (2011); Pan-Territorial Adaptation Strategy (2011) | The Atuliqtuq project aims to build community capacity to adapt through awareness-raising, research, tool development and planning<br>A permafrost monitoring network that operates in cooperation with hamlets and the federal government[22] |
| New Brunswick | Climate Change Action Plan 2007-2012 includes adaptation efforts[23]; Climate Change Adaptation Strategy for Atlantic Canada[24] | Launch of a Climate Change Indicators website that uses local information to help the public understand how the climate is changing[25]<br>Assessment, tool development and planning support to enhance climate resilience of infrastructure and communities[26] |
| Nova Scotia | Toward a Green Future: Nova Scotia's Climate Change Action Plan (2009) – includes adaptation efforts[27] | A Climate Change Action Fund launched in 2009 issues yearly calls for projects to support community efforts to understand impacts and actions to prepare for climate change[28]<br>Requirement for municipalities to develop and submit climate change action plans (including emissions mitigation and adaptation) for receipt of federal gas tax revenue[29] |
| Prince Edward Island | Prince Edward Island and Climate Change: A Strategy for Reducing the Impacts of Global Warming (2008) – includes adaptation efforts[30] | Development of climate change scenarios for use by nine target communities[31]<br>Assessment and tool development to increase understanding of communities' vulnerability to climate change[32] |
| Newfoundland and Labrador | Charting Our Course: Climate Change Action Plan (2011) – includes adaptation efforts[33] | Development of a 7-step guide to help the province's communities assess climate change vulnerabilities, complete with case studies and a resource guide[34]<br>Development of a workbook to help municipal officials and staff manage the impacts of climate change on infrastructure[35] |

**TABLE 2:** Examples of provincial and territorial adaptation activities.

Governments commonly frame adaptation by drawing attention to current vulnerabilities, local experiences and observations. Mountain pine beetle infestations in British Columbia, permafrost degradation and changing glacier cover in Yukon, and Nova Scotia's hurricane experiences are a few examples. Sectors receiving the most attention are those that factor heavily into the regional economy or make-up (e.g. forests in British Columbia, agriculture in Alberta and Saskatchewan, infrastructure and human health in Ontario, coastal areas in Atlantic regions). Territorial and many provincial documents highlight the cultural and heritage impacts of a changing climate on northern communities.

Building community and local government capacity to adapt is a priority shared across provinces and territories. Common lines of action include: funding climate change adaptation research; enhancing existing emergency preparedness initiatives; strengthening urban and rural land-use planning and infrastructure investment through adaptation mainstreaming; and providing guidance, coordination and sharing of data information and lessons learned. Provinces and territories have jurisdiction over a number of local matters germane to climate change adaptation, including land-use planning (Richardson and Otero, 2012), so attention on enabling local preparedness and action is expected.

### 4.1.3 COMMUNITIES AND LOCAL GOVERNMENTS

Adaptation planning is gaining momentum in many communities and local governments across Canada. Surveys of Canadian municipalities and case studies indicate an upward trend in adaptation activity (Robinson and Gore, 2011), a roughly equal distribution of activity between preparation, assessment, planning and implementation (Carmin et al., 2012), efforts to develop adaptation plans, policies or programs in consultation with internal and external stakeholders (Richardson and Lemmen, 2010), and some indications of staff time being allocated to adaptation planning (Merrill and Zwicker, 2010). Among global counterparts sampled by ICLEI–Local Governments for Sustainability, Canadian cities stand out for their concern about housing safety, health impacts of shifting disease vectors, degree of integration of adaptation within community planning, partnerships with other cities and non-governmental organizations and creation of adaptation-focused commissions or task forces (Carmin et al., 2012). Support from local politicians and government agencies is variable, with some studies noting strong support (e.g. Carmin et al., 2012) and others highlighting lack of political will as a barrier to adaptation (e.g. Davidson and Bowron, 2012). Small communities are less likely to engage in adaptation than larger ones (Hanna et al., 2013).

Several factors incite communities and local governments to address adaptation (*see* Case Study 2). Adaptation planning and projects emerge in response to extreme climate and weather events (e.g. Wellstead, 2011; Rodgers and Behan, 2012) as well as to gradual changes such as sea level rise and permafrost thaw (Richardson and Lemmen, 2010). Other factors include learning from peers and coupling actions to adapt to climate change with immediate priorities, such as water conservation (Richardson and Lemmen, 2010; Picketts et al., 2013).

### CASE STUDY 2

## HOW DO COMMUNITIES ADAPT TO CLIMATE CHANGE? A COMPARATIVE CASE STUDY OF HALIFAX, NOVA SCOTIA AND BEAUBASSIN EAST, NEW BRUNSWICK

This case study compares the approach to adaptation taken by two Atlantic communities: Halifax Regional Municipality (HRM), Nova Scotia and Beaubassin East, New Brunswick. Although exposed to similar climate threats, the differences between the two communities in terms of size, location, culture and resources dictate different management responses (*see* Table 3). With a population of 390 000, Halifax is a major seaport with significant industrial, military and municipal infrastructure, whereas Beaubassin East is a coastal community of 6000 inhabitants.

*Adaptation planning in Halifax*

Halifax has experienced frequent extreme weather in recent years. Of particular note is Hurricane Juan, which flooded part of downtown in September 2003 and caused an estimated $200 million in damages to property and infrastructure. This event and others since have heightened public awareness of climate change threats and helped spur the community to take adaptive action (Richardson, 2010).

In August 2006, the HRM Council adopted a Regional Municipal Planning Strategy, which included policies to address climate change (Halifax Regional Municipality, 2006). The strategy recognized the need to gather scientific information on sea-level rise, storm surges and vulnerability, to inform the development of an area-specific land use plan for Halifax Harbour. In 2009, HRM planners collaborated with scientists from federal and provincial governments and universities to deliver the information needed (HRM et al., 2010). Three scenarios of future sea levels and extreme water levels in Halifax Harbour were developed: a minimum scenario based on continuation of the historic rate of sea level change; a medium scenario using the upper limit of projections for mean sea-level rise from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007); and a higher projection based on more recent scientific literature (Forbes et al., 2009).

In early 2010, Halifax Council agreed to use the medium scenarios on an interim basis and as a baseline upon which a plan could be developed. Planners have been working on preparing an adaptation plan since 2010 (Richardson, 2010), with several interim adaptation measures being implemented in the meantime. For example, planners have created a risk assessment database containing information on the vulnerability of harbour-front properties and council passed an updated Municipal Planning Strategy and Land Use By-law for the downtown Halifax waterfront in 2010, prescribing a 2.5 m threshold above the ordinary high water mark for ground floor elevations of any new development downtown. More recently, the city used development agreements to establish a minimum ground floor elevation for new buildings in at-risk zones (Richardson and Otero, 2012). In one example, local officials and the developer agreed to establish minimum elevations for a new marina and other seaside structures in downtown Dartmouth that were several metres higher than prescribed in area plans.

*Adaptation planning in Beaubassin East*

Beaubassin East has been affected by various strong storm surges in the last 15 years. A storm in January 2000 was the most severe in the last hundred years, flooding parts of the community and damaging homes, cottages and quays (Doiron, 2012).

In 2007, a new planner for the Beaubassin East Planning Commission noticed that new buildings in the community were not constructed to withstand anticipated future changes in sea level. He undertook to modify local regulations to enhance resilience to rising sea level. The planner delivered a series of presentations to inform councillors about local climate change impacts and the need to develop adaptation measures to address them.

*Case Study 2 continued on next page*

Two steps enabled the development of a new zoning by-law. First, a literature review identified tools and practices that other communities had used to adapt, as well as best estimates of sea-level rise. Second, the Planning Commission obtained Lidar data and a grant to develop a high resolution digital map of the projected depth of a flooding event in 2100, using the January 2000 storm as a baseline. This map was an important tool to engage councillors and the public.

Council passed an updated zoning by-law in March 2011 to enhance protection of new construction in the coastal zone of Beaubassin East (Doiron, 2012). The by-law identifies a sea level rise "protection zone" in which the minimum ground floor elevation of any new building must be at least 1.43 m above the current 1-in-100-year flood mark. The regulation is an "overlay" zone – where all previous zoning conditions apply. Rather than prohibit development outright, the zoning by-law imposes stricter building requirements and includes a two-phase permitting system. The developer is first required to get a land surveyor to establish the minimum ground floor elevation for the proposed building. After construction, a surveyor must measure the ground floor elevation and certify compliance with the new standard.

The enactment and implementation of the by-law has provided opportunities for outreach to developers and the community on the impacts of climate change and sea level rise (Richardson and Otero, 2012). For example, a local planner has compiled a binder of information that includes reports and articles documenting adaptation measures and design techniques implemented in other jurisdictions that prospective developers can access. Since the by-law was passed, several new homes and cottages have been constructed to the new standards. The by-law has also subsequently been adopted by the Town of Shediac (population 6000), a nearby coastal community.

| Summary Table | | |
|---|---|---|
| | Halifax | Beaubassin East |
| **Population** | 390 000 | 6000 |
| **Climate change issues** | Sea level rise and storm surge flooding | Sea level rise and storm surge flooding |
| **Land use planning tool** | Development Agreements (i.e. minimum ground floor elevation established through negotiation) | An updated zoning by-law imposes a minimum ground-floor elevation in at-risk zones of the community |
| **Adaptation plan** | Halifax in process of developing an adaptation plan (since 2009) | No stand-alone plan. New "sea level rise protection zones" identified within the zoning by-law, which includes a preamble outlining the issue and approach |

**TABLE 3:** Land-use planning tools and adaptation plans in the two communities.

*Conclusions*

Halifax and Beaubassin East are among the first coastal communities in Canada to take concrete action to build resilience to climate change. Although their approaches are distinct, certain enabling factors are present in both cases, including exposure to significant damage from recent storms, one or more champions advocating for action on adaptation, a solid scientific basis to determine the extent of the threat in the local area, public and councillor engagement to obtain buy-in, and the use of visualizations to engage the public, council and stakeholders. Beaubassin East's experience demonstrates that even a small community with limited resources can implement regulations to build resilience to climate change. Halifax is an example of the iterative nature of adaptation planning, where interim measures can be implemented in the lead up to a comprehensive plan.

The evolution of adaptation activities by communities and local governments varies, and largely depends on context. Some community adaptation initiatives have stemmed from internal planning processes (e.g. Toronto's Climate Change Action Plan [City of Toronto, 2007] and Halifax's Harbour Plan [City of Halifax, 2005]), while others received significant external support and prompting for their adaptation activities (e.g. District of Elkford, 2009). Collaboration is important in many cases (Carlson, 2012). An example of local authorities working with higher levels of government is the collaboration between Health Canada, the Manitoba government and the Winnipeg and Assiniboine local health authorities to develop and test the effectiveness of heat alert and response systems (Health Canada, 2012). In some cases, mainstreaming is a guiding principle. For example, Toronto's Climate Change Action Plan calls for consideration of climate change mitigation and adaptation across the city's policies, activities and programs, and in their Heat Alert and Response System (City of Toronto and the Clean Air Partnership, 2008).

Berrang-Ford et al. (2011) found that most adaptation action in developed countries is occurring within municipalities. Although definitive evidence is not available to support this conclusion for Canada at present, relative to other levels of government, Canadian communities and local governments have been objects of much case-study research (e.g. Parkins and MacKendrick, 2007; Ford et al., 2008; Burch, 2010; Richardson and Lemmen, 2010; Boyle and Dowlatabadi, 2011; Richardson and Otero, 2012; Rodgers and Behan, 2012; Picketts et al., 2012; 2013). The relatively high level of community and local government activity could be a combination of the local nature of climate impacts (Richardson, 2010), the belief among community planners and infrastructure engineers that a changing climate affects their practice (Davidson and Bowron, 2012; CSA Group, 2012), and support from higher-level governments in the form of policies, decision support tools and other resources to inform adaptation planning (e.g. Hanna et al., 2013).

### 4.1.4 INDUSTRY

Canadian businesses and industry sectors are becoming aware of the risks and opportunities that a changing climate presents. Concerns about more frequent and severe weather events predominate; both negative and positive climate change impacts are recognized, with the balance between risk and opportunity differing by sector (NRTEE, 2012b). Of the industry sectors analyzed in NRTEE (2012a), companies in financial services and insurance sectors were the most likely to report opportunities from the impacts of climate change, such as the creation of new financial products. However, research on business opportunities in a changing climate is scant (Chapter 5 – Industry). Globally and within Canada, industry councils and associations are increasingly engaged in raising awareness of the business relevance of climate adaptation. For example, some have facilitated knowledge sharing (the Canadian Electricity Association), funded applied research and tool development to inform industry strategy (the Insurance Bureau of Canada), issued policy statements to guide industry practice (the International Federation of Consulting Engineers) and released adaptation frameworks of general applicability to members (NRTEE, 2012b; ICMM, 2013).

Although Canadian businesses are adjusting practices in response to individual weather and climate-related events, actions in anticipation of future climate change remain limited (Johnston et al., 2011; NRTEE, 2012b). Companies that are taking action to adapt are primarily focused on understanding the implications of climate change on their operations, developing frameworks to guide strategic and operational decisions and assessing the merits of alternative adaptation options (Chapter 3 – Natural Resources; Chapter 5 – Industry; Horton and Richardson, 2011; NRTEE, 2012a). Outside of proactive planning in some mining sites in Canada's North (Chapter 3 – Natural Resources), revisions to corporate design standards and codes of practice are among the most concrete documented examples of business adjustments in light of changing climate (Horton and Richardson, 2011; NRTEE, 2012a). The integration of climate adaptation into planning and management approaches already used by business is also taking place, but to unknown degrees and effect. These approaches include contingency and disaster planning as well as adaptive management.

This Assessment highlights forestry, hydroelectricity, insurance and tourism as sectors most engaged in adaptation. Other research also emphasizes the adaptation activity of sectors reliant on nature and natural resources, such as forestry, agriculture and tourism, and of those with major capital assets, such as utilities and transportation (Deloitte, 2011; Ford et al., 2011; Ceres and Climate Change Lawyers Network, 2012). Factors that can contribute to a difference between actual and reported levels of preparedness include a lack of common benchmarks and performance metrics for adaptation, along with confidentiality and reputational concerns (Agrawala et al., 2011; NRTEE, 2012b).

## 4.2 BARRIERS AND CHALLENGES

Understanding of the barriers and challenges to planned adaptation has grown since 2008 (e.g. Richardson, 2010; Johnston et al., 2011; NRTEE, 2012a; Picketts et al., 2012) and has given rise to new scholarship that explores factors that constrain the 'readiness' of organizations to adapt (Moser and Ekstrom, 2010; Clar et al., 2013; Ford et al., 2013) beyond those associated with adaptive capacity (Smit and Pilofosova, 2001; Yohe and Tol, 2002).

This section expands on barriers and challenges to adaptation identified in Chapters 3 to 8 of this Assessment. It considers the role of information and communications, resources, governance and norms, psychology and values, and leadership in hindering progress on adaptation by various stakeholder groups (*see* Table 4).

| Type of barrier / challenge | Example | Chapter |
|---|---|---|
| Information and communications | Difficulties teasing out multiple influences on visitation choices (e.g. fuel price, transportation costs, border restrictions, reputation, demographic and market trends) from climate change impacts | 5 |
| | Mismatch between spatial and temporal resolution of climate projections and management needs. Difficulties obtaining reliable projections at scales relevant to management needs | 3, 5, 6 |
| | Availability of guidance to interpret climate scenarios and factor modeling outputs into infrastructure and mine closure design | 3 |
| | Lack of data and information on weather extremes (e.g. future patterns of rainfall extremes) | 5, 8 |
| | Limited data and information on past and future sector-specific climate change impacts (e.g. climate change impacts on forests, wind, solar and biomass energy production; water-related impacts of climate change and implications for oil sands development, shale gas and enhanced oil recovery; climate change impacts on water resource infrastructure; health impacts) | 3, 7, 8 |
| Resources (economic, skills, technology) | Few incentives for action beyond business as usual (e.g. incremental cost of applying existing engineering or technological solutions to adapt mine operations to climate change, or of preserving ecological goods and services on agricultural lands) | 3, 5, 6 |
| | Lack of expertise and understanding surrounding local impacts of climate change on business operations, and effective adaptation solutions | 5 |
| | Limited adaptation options for snowmobiling (e.g. widespread implementation of snowmaking is impractical) | 5 |
| | Lack of: financial resources for surveillance, prevention and control of vector-borne diseases; expertise and capacity to diagnose emerging vector-borne diseases; licensed and effective products for disease-vector control | 7 |
| Governance and norms | Complexities redefining sustainable forest management related to number of players and trade-offs involved | 3 |
| | Influence of non-climate stressors, such as region-wide demographic changes and rural outmigration | 4 |
| | Reliable access to non-commercial food supplies at risk if infrastructure integrity is vulnerable to climate change | 4 |
| | Designs based on future climate projections shift paradigm from building code and current design approaches | 5 |
| | Coastal adaptation plans typically led by government agencies outside of public health such that health impacts may not considered | 7 |
| Psychology and values | Perceived importance of climate change low relative to economic challenges, job losses and mill closures facing the sector | 3 |
| | Uncertainty in future climate change projections hinders investment decisions on adaptation | 3 |
| | Optimism about capacity to overcome climate change adaptation challenges | 5 |
| | Continued focus on replacement of aging infrastructure, on capacity upgrades to deal with increasing population and on changing regulatory requirements to address risks to water supply infrastructure – with the role of changing codes, standards and related instruments receiving less attention | 8 |
| Leadership | Proactive adaptation planning in mining is rare despite use of climate scenarios for impact assessment and identification of monitoring and adaptation strategies | 3 |
| | Taking a 'wait-and-see approach' due to difficulties finding the correct balance between waiting for more information to inform future action and taking action in the short term based on available information | 3 |

**TABLE 4:** Barriers and challenges to adaptation highlighted in previous chapters.

Although discussed separately below, the different types of barriers and challenges to adaptation are often interrelated and can be mutually reinforcing (e.g. Burch, 2010). For example, the combined effects of high rates of household poverty and low levels of education, limited capacity of public health practitioners to monitor, diagnose and treat climate-sensitive diseases, inter-jurisdictional issues and unequal access to resources constrain adaptation of Aboriginal health systems (Chapter 7 – Human Health).

### 4.2.1 INFORMATION AND COMMUNICATIONS

Barriers and challenges related to information for adaptation continue to be widely-cited as factors constraining action in Canada. Previous chapters in this assessment highlight issues related to the availability and accessibility of data and information on both average and extreme climate conditions, climate projections and their interpretation, climate change impacts research, and methods and tools to help integrate climate change information into decision making.

A key concern raised in the literature on this subject is the mismatch between the climate data and information available and that which is perceived necessary for adaptation purposes. Calls for site-specific, detailed and short-term climate projections to inform provincial and territorial (ACC Community of Practice, 2011), industry (Kovacs, 2011) and community (McLeman et al., 2011) risk assessments and planning processes are documented, as are demands for local projections of climate variables other than temperature and precipitation averages. A related concern is the density and effectiveness of weather and climate monitoring networks (Steenhof and Sparling, 2011; Pennesi et al., 2012), which are the source of data for downscaling climate projections. Challenges in meeting such information demands are not unique to Canada. For example, Reisinger et al. (2011) identify gaps in baseline climate data and in the availability of probabilistic climate projections as impediments to adaptation of local governments in New Zealand.

Gaps in data and information to help characterize vulnerability to climate change also create challenges in assessing risks and planning for adaptation (NRTEE, 2009). Historical records of system responses to climate-related events can be used to inform estimates of potential climate change impacts. For example, reliable records of direct and indirect health impacts from extreme-weather events, climate-related damages to homes and tourist responses to environmental change would support trend analysis (Chapters 5 – Industry, and 7 – Human Health) useful for building a case for action. Targeted climate change risk assessments – of municipal infrastructure for example – also benefit from the documentation of climate-related damages to operations and assets (Peck et al., 2013).

However, not all decisions are equally subject to climate change risk, and initial discussions are underway on the resolution of climate change information needed to adapt. Factors such as the degree of sensitivity to climate and the types of management options being considered influence the detail and precision of climate change information needed to make good decisions (Willows and Connell, 2003). Information needs surrounding climate change impacts and adaptation – and the mechanisms and approaches to consolidate and integrate this information in decision making – will vary by sector, geographic location and by end-use. On a regional basis, climate service centres (e.g. Pacific Climate Impacts Consortium, Ouranos) are working with users to define what they require and what is feasible to supply (Murdock and Burger, 2010).

Despite advances in building the knowledge base to support climate change adaptation, challenges remain in conveying complex scientific and technical information to a range of groups (ACC Community of Practice, 2011). Factors limiting interest and understanding include: framing of climate change as an environmental issue, rather than as an economic and social issue; failing to relate climate change impacts to existing concerns and local action; difficulties communicating complex science and underlying uncertainties to non-specialist audiences; and science outreach activities that are limited to a one-way flow of information (Shaw et al., 2009; Sheppard et al., 2011; NRTEE, 2012b; Picketts et al., 2013). Researchers and adaptation practitioners are becoming aware of approaches to enhance the uptake of climate change information in local planning processes (e.g. Shaw et al., 2009; Sheppard et al., 2011) and deploying communications strategies tailored to public health officials and other professionals (Clarke and Berry, 2012).

### 4.2.2 RESOURCES

Limitations – whether real or perceived – with respect to economic resources, skills and expertise, and technologies for adaptation, are commonly identified as barriers to taking adaptation action.

#### ECONOMIC RESOURCES

Despite a noted lack of quantitative information on the costs of adaptation (e.g. NRTEE, 2010; Ochuodho et al., 2012), these costs stand out as a key perceived barrier for stakeholders in both private and public sectors. Survey research cited the costs of adaptation as "the most significant barrier to taking climate change into account in decision making" for over half of business, provincial and municipal government respondents (Environics Research Group, 2010). Although some adaptation actions – such as infrastructure upgrades – can be costly, the costs of not adapting are typically underemphasized (e.g. NRTEE, 2012a, b). Over the past 5 years there has been a significant rise in interest in examining the economic merits of implementing adaptive measures (Mills, 2008; Desjarlais and Larrivée, 2011; NRTEE, 2011; Olar and Lessard, 2013), although few Canadian guides and tools to appraise the costs and benefits of adaptation are currently available (e.g. Webster et al., 2008).

The ability to allocate scarce resources to adaptation is another concern raised by several groups. Within an organization, competing priorities (ACC Community of Practice, 2011), the lack of visibility of the unit championing adaptation and budgetary processes that consider capital and operational spending separately (Burch, 2010) can diminish the chances of securing funding for adaptation activities. In extreme situations, crisis management and urgent needs hinder consideration of investments in planned adaptation (e.g. Boyle and Dowlatabadi, 2011; Ford and Berrang-Ford, 2011; Pearce et al., 2011). Market signals can also discourage investment in adaptation actions. For example, companies currently have limited incentives to pay the added cost of applying existing engineering or technological solutions to adapt operations to climate change (Chapter 3 – Natural Resources; NRTEE, 2012b). The size of a company also appears to play a role (Environics Research Group, 2010; NRTEE, 2012b), due in part to limited financial resources and dedicated staff, as well as short-term planning horizons (NRTEE, 2012b; C2ES, 2013).

Beyond funding, context and timing also influence vulnerability to climate change and options to adapt cost-effectively. For example, economic reliance on a single industry and the ability to adopt economic diversification strategies were key considerations in assessing adaptation options for communities affected by the mountain pine beetle outbreak in British Columbia (Parkins and MacKendrick, 2007). Other research emphasizes strategic consideration of replenishment and renewal cycles as windows of opportunity for adaptation (Williamson et al., 2012).

### SKILLS AND EXPERTISE

There are limitations related to accessing the required knowledge, skills and dedicated staff to assess climate risks, devise adaptation strategies and integrate adaptation in routine planning and operations in the public sector. Provinces and territories identify a lack of dedicated staff and staff with the right skills as concerns for advancing adaptation (ACC Community of Practice, 2011). Survey analysis of public servants in British Columbia concludes that they would benefit from information on climate change impacts and current adaptation efforts specific to their mandate areas (BC Stats, 2012).

These limitations in human capacity have affected the rate at which adaptation is being addressed. For example, in Ontario, the first round of Source Water Protection plans do not include climate change modeling outputs in water budgets, because of the variable capacity of the province's 34 Conservation Authorities to manipulate climate change scenario outputs, apply downscaling methods and meet reporting requirements (de Loë et al., 2011). Climate data, and guidance on integrating climate model outputs into hydrological modelling and training were made available as a result (http://waterbudget.ca/climatechangetraining). In the public health sector, officials admit to lacking the necessary knowledge to inform adaptation decisions despite the availability of information resources such as weather warnings and air quality reports (Clarke and Berry, 2012). Low scientific capacity and understanding of climate change impacts and adaptation have also been found among forest managers working in companies and regulatory agencies (Johnston et al., 2011).

Capacity constraints related to human resources appear to be the most pronounced within small planning departments and agencies (OECD, 2012; Hanna et al., 2013). The capacity of municipalities in Canada's North to plan for emergencies is uneven, with particular challenges for small, remote communities (NRTEE, 2009). Hiring outside expertise to provide analysis and tailored information on climate change impacts and adaptation is an option for some organizations with low scientific and technical capacity (e.g. Johnston and Hesseln, 2012).

### TECHNOLOGIES FOR ADAPTATION

Challenges related to technological options are sector-specific, but, in all cases, the right incentives need to be in place to develop and deploy novel technologies. Current technological options available to forest managers can address current climate risks. However, cost and public acceptability could limit the widespread deployment of novel technologies, such as high flotation tires on skidders that allow operations to proceed on unfrozen ground, or genetic modifications to tree species to thrive in future climate conditions (Johnston and Hesseln, 2012). Limits in technological options for sectors such as public health (Chapter 7 – Human Health), electricity (Chapter 3 – Natural Resources) and tourism (Chapter 5 – Industry) indicate potential opportunities for innovation.

## 4.2.3 GOVERNANCE AND NORMS

Research on the governance of adaptation has gained ground in the past few years (Adger et al., 2009; 2010), exploring issues such as how to promote coherent and collaborative action within and across public and private sectors. Policy development on adaptation is challenged by the need for integration across policy domains and levels of government, engagement of non-government organizations, and mobilization of scientific knowledge (Bauer et al., 2012). For complex policy domains such as fisheries and oceans management, climate change adds to governance uncertainty. Some large-scale changes such as ocean acidification are unprecedented, and effective management responses are unclear. Communications and negotiations with fisheries stakeholders now need to account for diverse understanding and perceptions of climate change (McIlgorn et al., 2010). This complexity can cause agencies to focus on short-term implications and their own policy silos (Lemieux et al., 2013). Moreover, coordination within and across levels of government, and any partnered work, takes time, resources (McLeman et al., 2011; ACC Community of Practice, 2011) and the deployment of specific skills (e.g. communication, negotiation, development of shared visions).

Networks, both formal and informal, can enhance capacity to adapt (*see* Case Study 1). However, opportunities to take up climate change information and establish relationships across policy domains are not always seized. For example, analytical capacity in the Canadian financial sector is high, yet employees in this sector seem resistant to engage in climate change adaptation issues (Williams and McNutt, 2013). As adaptation grows in maturity as a policy issue, a transition from governance reliant on voluntary networks, to a mix of networks and hierarchical approaches is likely (Bauer et al., 2012).

As an approach to addressing adaptation, mainstreaming is both promising and challenging. Several studies conclude that creating new processes or frameworks to tackle adaptation are unnecessary. Reasons include the already-high workload of, for example, public health officials (Clarke and Berry, 2012) and a preference to work within existing rules and with familiar planning approaches (Jantarasami et al., 2010; Davidson and Bowron, 2012). Integrating adaptation considerations across existing policies and management approaches is not necessarily straightforward. Consistent and agreed-upon guidance on how to mainstream adaptation is a recognized gap in the areas of built infrastructure and codes, standards and related instruments (Steenhof and Sparling, 2011) and forest management planning (Johnston et al., 2011; Johnston and Hesseln, 2012). Adjusting existing processes and frameworks to account for changing climate can involve challenging core assumptions (Steenhof and Sparling, 2011).

Policies designed to address issues unrelated to climate change can also pose barriers to adaptation. For example, for natural resource and conservation managers, policies that target single species management (e.g. biodiversity, alien invasive species), as opposed to focusing on broader management goals, can become problematic with climate change-related shifts in ranges and abundances of species (Jantarasami et al., 2010; Johnston et al., 2011). By stipulating conditions, such as harvest levels and species to be replanted, aspects of provincial forest policies, such as tenure agreements, limit the potential to adopt innovative adaptation approaches by forest companies (Johnston et al., 2011; Johnston and Hesseln, 2012). Finally, outdated community development plans and provincial planning frameworks, as well as a lack of long-term sustainability plans, discourage municipal adaptation – as shown for three municipalities in the lower mainland of British Columbia (Burch, 2010).

### 4.2.4 PSYCHOLOGY AND VALUES

People and groups perceive, interpret and act on new situations differently and the implications of this for adaptation are increasingly being recognized. Psychology research has helped to understand why capacity to adapt does not necessarily translate into action. Understanding of the roles played by values, culture and social interactions in framing problems and in identifying acceptable solutions is growing (Burch and Robinson, 2007; Lynam, 2011). The interplay between individual and collective attitudes and behaviour has also been explored (Wellstead and Stedman, 2011; Cunsolo Willox et al., 2012; Wolfe et al., 2013).

Limitations in how we think, view the world and perceive risk figure prominently in the literature on psychological barriers to adaptation (Gifford, 2011). Short-term thinking, using uncertainty as a reason to postpone action, being selective about what is paid attention to and optimism bias are apparent in research into governments (ACC Community of Practice, 2011), business and industry (Johnston et al., 2011; Kovacs, 2011; Johnston and Hesseln, 2012; Linnenluecke et al., 2012; NRTEE, 2012 a, b), public health and emergency preparedness (Hutton, 2011; Clarke and Berry, 2012) and vulnerable populations (Berry, 2011; Wolfe, 2011). World views shape people's definition of acceptable adaptation options. For example, in one study, experts rejected novel approaches to biodiversity and conservation policy that considered species-for-species tradeoffs (Hagerman et al., 2010). In some cases, people perceive behavioural change as risky, either financially, socially, and functionally (Gifford, 2011). At present, financial risk appears to be the dominant source of risk that constrains adaptation (e.g. Johnston and Hesseln, 2012).

Values underlie beliefs, attitudes and behaviour, both by individuals and as groups. Until recently, the literature mainly addressed values by way of highlighting impacts on culturally-significant activities and places and the importance of indigenous knowledge and perspectives (Burch and Robinson, 2007; Pearce et al., 2011; Wolfe et al., 2013). Understanding the influence of values on responses to a changing climate is an emerging research topic (Hutton, 2011; Cunsolo Willox et al., 2012; Wolfe et al., 2013). Research has shown, for example, that residents in communities of comparable location and socio-economic characteristics can perceive climate-related events – and therefore the relevance of adaptation – differently. In Labrador, one community associated an unseasonably-warm winter with a sense of loss and isolation, whereas another rated the warm winter as neutral to positive (Wolfe et al., 2013). Other studies test the influence of individual attitudes and organizational culture on engagement in adaptation. For example, public servants in British Columbia are more likely to integrate adaptation thinking in their work if they work in natural resource ministries (BC Stats, 2012). Accounting for cultural differences among professions – municipal planners, engineers and employees in direct service delivery – is also important in adaptation planning (Burch, 2010).

### 4.2.5 LEADERSHIP

Leaders – whether individuals or organizations – who are willing to champion new ideas and create change can be influential drivers of adaptation (*see* Case Study 2). Conditions internal and external to the organization affect leadership abilities. Limited demand from citizens and other external stakeholders is considered to be a factor slowing government action on adaptation (ACC Community of Practice, 2011).

Internal organizational structures can also hinder action. Rigid hierarchies, the absence of clear mandates and delegation of responsibilities can deter managers from allocating resources and staff time to adaptation planning and resources (Jantarasami et al., 2010). Even individuals who are motivated to integrate climate change adaptation in their work and are knowledgeable about how to do so may fail to act because of competing priorities (Davidson and Bowron, 2012).

# 5. OVERCOMING BARRIERS AND FACILITATING ACTION

Research on overcoming barriers and challenges to adaptation tends to focus on enhancing awareness and building adaptive capacity; however, there is increasing recognition that for adaptation to be successfully implemented, the will or desire to adapt is also necessary. This requirement has received little attention so far in the literature on climate change and adaptation. This section discusses approaches and mechanisms being used to overcome existing barriers and facilitate sustained adaptation.

## 5.1 INCREASING AWARENESS

The first step towards adaptation implementation is awareness of climate change, potential impacts, and the need to adapt (*see* Box 2). Increased awareness of climate change can occur spontaneously (e.g. through the experience of extreme events) or through planned activities (e.g. workshops, awareness-raising campaigns, learning modules or publications).

Extreme events can act as a wake-up call, raising awareness of current vulnerabilities to weather, which can trigger adaptive responses (Berrang-Ford et al., 2011; Ford et al., 2011). Media coverage of extreme weather events often makes the association with climate change (e.g. CBC, 2013; Kolbert, 2012; Thompson, 2013), which can provide an opportunity for initiating discussions on adaptation. There are several examples throughout this report and elsewhere of adaptation actions being catalyzed by extreme events, such as floods, wildfire and windstorms (e.g. Lemmen et al., 2008; Richardson, 2010). For businesses, extreme weather events can also increase awareness of climate change (NRTEE 2012a; IEMA, 2013). Extreme weather and climate events can present a shock that stimulates organizations to rethink their operations and assumptions and adjust appropriately (Burch, 2010). However, others caution that adaptation in response to a crisis or disaster brings risks of redundancies if time is not taken to adequately incorporate and consider adaptation in the context of existing policies, procedures and practices (Plummer et al., 2010).

Several organizations in Canada have developed tools to raise awareness of adaptation among practitioner groups and decision makers. For example, the Canadian Institute of Planners (CIP) introduced a Climate Change Impacts and Adaptation Program that includes the development of Continuous Professional Learning (CPL) modules for its members (Canadian Institute of Planners, 2013). Similarly, the Federation of Canadian Municipalities (FCM) partnered with the Canadian Standards Association (CSA) to develop an e-learning course for municipalities, which is focused on adapting critical infrastructure to climate change and severe weather events (FCM, 2013). The National Round Table on the Environment and Economy (NRTEE) developed a 'dashboard for business success in a changing climate,' to raise awareness of adaptation within organizations, and help businesses assess and manage climate change risks and opportunities (NRTEE, 2012b). University-level courses are also an important mechanism for raising awareness of climate change adaptation through education. Targeted activities such as these take into account the culture and values of the groups they are seeking to influence, which is important for addressing psychological and communication barriers to adaptation (*see* Section 4.2).

Workshops are frequently used as a mechanism to raise awareness and stimulate local adaptation. These typically bring together people with expertise in climate change science and adaptation with community leaders, municipal staff and sometimes the general public. Although the explicit goals of these workshops vary, and may include, for example, identifying priorities (e.g. Picketts et al., 2012; Stocker et al., 2012), setting the stage for ongoing collaboration and dialogue (e.g. Stocker et al., 2012) and enhancing adaptive capacity (*see* Case Study 3), they all have the underlying benefit of increasing awareness of the value of adaptation

CASE STUDY 3

## BUILDING ADAPTIVE CAPACITY IN THE COLUMBIA BASIN

The Columbia Basin in southeastern British Columbia covers 671 000 square kilometres and encompasses a variety of ecosystems including grassland, interior rainforest, wetlands and alpine (Figure 5). Hydroelectric power generation, forestry, mining, tourism and agriculture constitute major economic activities in the Basin, all reliant on natural resources. Adaptation to climate change is one initiative of the Columbia Basin Trust (CBT), which supports efforts to create and maintain social, economic and environmental well-being in the Canadian portion of the Columbia River Basin. Identified risks associated with a changing climate include changes in glacial runoff, water temperature, freeze/thaw cycles, diseases and pathogens, flooding, frequency of droughts, severity of wildfires, landslides, avalanche risk and biodiversity (Columbia Basin Trust, 2008).

Building on their past work, the CBT established a model for one-day workshops to help mainstream adaptation efforts throughout the basin using climate projections and guidance material (e.g. Columbia Basin Trust, 2012). An adaptation planning process that could take a year or more is condensed into a single day filled with local government dialogue that defines three priorities for the community in terms of climate change resilience. The condensed workshop models have been well received by communities and by practitioners, such as watershed and emergency managers. Collaborative follow-up work has included refinement of communications strategies and existing plans, such as flood hazard plans, to incorporate climate-related data.

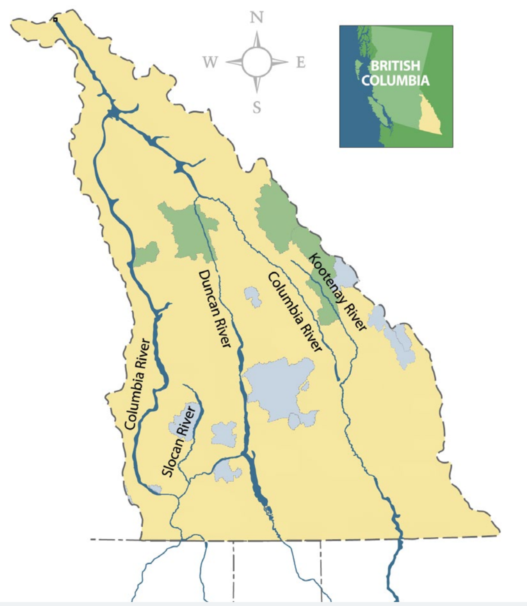


**FIGURE 5:** Map of the Columbia Basin Region *(Source: Columbia Basin Trust, 2008).*

among those who are positioned to implement and/or demand change.

Data visualization has emerged as an important tool to enhance communication at workshops, portraying scientific data on projected climate impacts in a way that is relevant to local users (e.g. Sheppard et al., 2011; Cohen et al., 2012; Colombo and Byer, 2012). Examples include illustrations of how flooding would increase in a specific region with projected sea level rise (Figure 6) or how mountain snow conditions would change in response to changing climate (Cohen et al., 2012). Variables can be adjusted to demonstrate the influence of adaptation measures, thereby increasing awareness and encouraging continued dialogue (Cohen et al., 2012). Other approaches to interactive visuals include the use of Google Earth in workshops, where researchers present a base map of the region, then overlay economic, social, ecological and cultural layers to allow participants to work together to identify 'sustainability hotspots' and to stimulate discussion on climate change adaptation (Stocker et al., 2012).

**FIGURE 6:** Example of a graphic output of data visualization – visualizing a dyke infrastructure scenario *(Source: www.fraserbasin.bc.ca/_Library/CCAQ_BCRAC/bcrac_delta_visioning-policy_4d.pdf ).*

## 5.2 BUILDING CAPACITY

This section highlights ongoing efforts and evolving approaches to continue building capacity to adapt effectively to future climate change.

### 5.2.1 ADDRESSING INFORMATION NEEDS

One of the most commonly cited barriers to adaptation is deficiencies in information for decision making (*see* Section 4.2). Decision makers are looking for the right type of information, at an appropriate scale and level of detail that is accessible and understandable.

Over the past 5 years there has been an increase in the availability and quality of climate scenarios. Several groups in Canada have focused on providing scenario data, and making it publicly accessible (e.g. the Canadian Climate Change Scenarios Network, the Pacific Climate Impacts Consortium, and Ouranos). These groups assist decision makers in adapting to climate change by providing access to relevant and useable data, maps and graphs of future climate conditions.

In recognition of the need to package climate data in understandable and useable formats, many projects have focused on communicating and interpreting information relevant to decision makers through workshops, community meetings and other participatory initiatives (e.g. Ogden and Innes., 2009; Shaw et al., 2009; Hennessey, 2010; Picketts et al., 2012; Stocker et al., 2012). Engaging stakeholders in defining research questions and outputs is recommended as a way to make science more useable for decision makers (Halliday, 2008; Ford et al., 2013). Lessons learned from these projects can help to inform other communities, particularly with respect to methods and approaches, and there is an opportunity for jurisdictions that are more advanced on adaptation planning to share their knowledge with others. The National Climate Change Adaptation Community of Practice (CCACoP) is an example of a mechanism to transfer information, knowledge and understanding on adaptation (Case Study 4).

**CASE STUDY 4**

### PROMOTING ADAPTATION BY SHARING INFORMATION AND KNOWLEDGE THROUGH A VIRTUAL COMMUNITY OF PRACTICE

The Climate Change Adaptation Community of Practice (CCACoP) supports the efforts of Canadian provinces and territories to incorporate climate change adaptation into planning and policies through the transfer of knowledge across jurisdictions. It is an interactive online portal that provides a space for researchers, experts, policymakers and practitioners from across Canada to come together to ask questions, generate ideas, share knowledge and communicate with others working on climate change adaptation. Launched in 2010, the CCACoP stemmed from an idea of the Council of the Federation, a provincial and territorial forum, which endorsed the creation of such a virtual community in 2008. It currently has more than 500 members.

The knowledge-exchange and communication that takes place during webinars and through the 'Call for Knowledge' forum helps to form new relationships and connect practitioners from across Canada. The growing and increasingly diverse membership (*see* Figure 7) and the intensifying site activity help to increase awareness and promote adaptation. The community has evolved to include issue-specific sub-communities such as the *Forestry Adaptation Community of Practice* (FACoP), established in 2012 on behalf of the Canadian Council of Forest Ministers. The main elements contributing to the success of the portal are (1) a stable web platform; (2) advisor input and member feedback; (3) a dedicated community facilitator; (4) cross-disciplinary membership; and (5) ongoing and consistent communication to members.

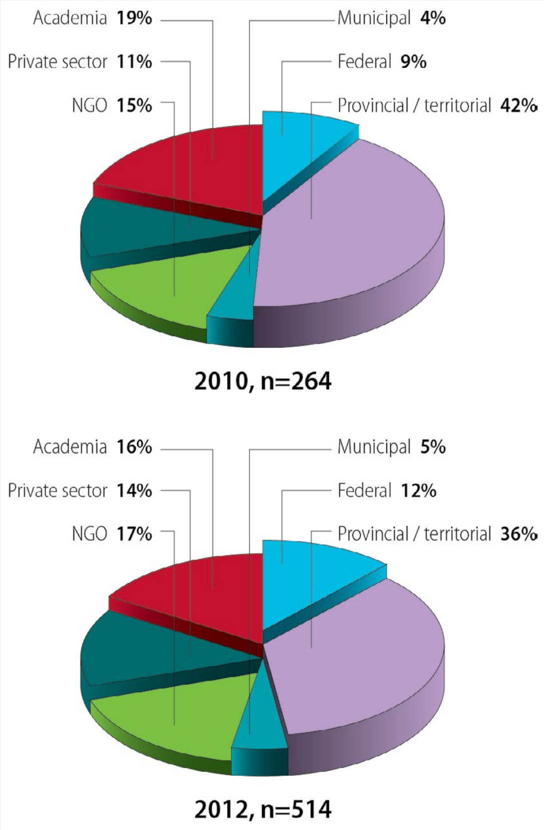


**FIGURE 7:** Membership of the national Climate Change Adaptation Community of Practice.

### 5.2.2 DEVELOPING AND DISSEMINATING ADAPTATION TOOLS

Over the past 5 years, there has been a substantial increase in the number of decision support tools available for municipalities. These include maps and visualizations, guidance for scenario interpretation and use, and adaptation guidebooks and toolkits (*see* Carlson, 2012; Richardson and Otero, 2012; Health Canada, 2013).

Professional organizations have also been developing tools to assist their members in adapting to a changing climate. For example, in 2008, the Canadian Institute of Planners developed a policy that required members to consider climate change in their actions and recommendations, developed a model standard of practice and assessed current planning tools for their use in adaptation. This work was supported by training modules for university planning courses and in-service training of planners (Canadian Institute of Planners, 2013).

Engineers Canada (along with partners) developed the PIEVC Protocol to assess the vulnerability of public infrastructure from an engineering perspective and consider adaptation options using a triple bottom line perspective. The tool has been applied in 26 case studies to both test the tool, and develop a reference library of case studies (PIEVC, 2012). The information in the case studies provided the basis for a review of codes, standards and related instruments in three categories of infrastructure (water resources, transportation and buildings; *see* Chapter 8 – Water and Transportation Infrastructure). Training workshops were held across the country to raise awareness of the need to adapt and to encourage awareness and use of the tool. Such follow up is important, as developing tools is only the first step – dissemination and facilitating uptake must follow, to ensure the tool is used effectively.

### 5.2.3 ADDRESSING ECONOMIC RESOURCE CONSTRAINTS

Approaches to addressing financial and economic constraints for adaptation will vary, depending on the actor and context. For industry and business, adaptation implementation will often depend on having a business model where the benefits of adapting are clearly laid out. This can involve cost-benefit analyses, but such analyses are relatively few (IEMA, 2013), perhaps because of the intrinsic difficulties in estimating potential future benefits. However, companies may be able to identify opportunities where acting today (in present value terms), would cost less than acting later (e.g. where it is more cost-efficient to incorporate adaptive measures into building design, rather than retrofitting later; Fankhauser and Soare, 2013).

Assessing costs of adaptation should give consideration to co-benefits (NRTEE, 2011; IEMA, 2013). Other ways to moderate the potential costs of adaptation include developing policies and strategies that can be reassessed and updated over time, which reduces the up-front costs and the risks associated with over-adapting (Colombo and Byer, 2012). A focus on win-win measures that would provide immediate benefits and increase longer-term resilience to climate change, is another recommended strategy. Examples include improving water efficiency, enhancing flood protection, implementing measures to deal with heat stress and improving environmental management to protect ecosystems (Fankhauser and Soare, 2013).

In many cases, issues of economic constraints in Canada are more about facilitating the use of existing resources, rather than creating more financial resources (Burch, 2010). In cases where large investments in infrastructure are required, the costs are sometimes shared by multiple levels of government (e.g. Andrachuk and Smit, 2012).

### 5.2.4 CREATING THE WILL TO ADAPT

Underlying attitudes also need to be considered to advance adaptation, especially within work environments, in both the public and private sector. For example, cultural norms within organizations that value maintaining the status quo can be challenging to address (Jantarasami et al., 2010). Suggested ways to foster an adaptation-supportive environment and empower employees to change their way of thinking about climate change adaptation include: i) developing dynamic and flexible management processes; ii) establishing clear mandates that prioritize adaptation; iii) providing education on the issue of climate change; iv) clearly designating responsibilities; and v) ensuring adequate funding (Jantarasami et al., 2010; Davidson and Bowron, 2012).

Although there are many commonalities between the public sector and the private sector with respect to the will to adapt, there are also key differences. Businesses may have more flexibility to respond in innovative ways, being less constrained by policies and procedures than in the public sector; but at the same time, they are driven by their bottom-line and, if publicly owned, are accountable to their shareholders. Businesses may also be less likely to share or report on their information on adaptation for proprietary reasons (*see* Chapter 5 – Industry). To increase the will to adapt within the business environment, highlighting adaptation initiatives that would increase comparative advantages over competitors (for example by building resilience to supply chain disruptions) is a motivating influence, as is demonstrating the potential for co-benefits (IEMA, 2013) and enhancing corporate reputation. Differences in the nature of the business are also important to consider, as some industries place great value on innovation and leadership, while others tend towards a more conservative business culture. Approaches and attitudes will also differ between large, international conglomerates, and small and medium enterprises (NRTEE, 2012b).

Mechanisms that promote corporate social responsibility and environmental sustainability (e.g. forest certification schemes, environmental management systems) could increase awareness and interest in adaptation in the private sector (Johnston and Hesseln, 2012), as could growing demands for reporting on climate change and material risk (*see* Chapter 5 – Industry; NRTEE, 2012a, b). However, relying on market-based mechanisms to drive adaptation is likely insufficient. For example, research suggests only a minor role for insurance in inducing planned adaptation of built infrastructure to climate change (NRTEE, 2009; Cook and Dowlatabadi, 2011; OECD, 2012).

CASE STUDY 5

## DEVELOPING ADAPTIVE MANAGEMENT PLANS: GREAT LAKES EXAMPLE

The International Upper Great Lakes Study (IUGLS) of water level changes in the Great Lakes basin concluded that costs and environmental and institutional constraints precluded investment in structural adaptation measures at this time. Adaptive management provided the best mechanism for addressing future uncertainties and the risks associated with extreme water levels due to natural variability and climate change (Leger and Read, 2012; *see also* Case Study 4 in Chapter 8).

The study used an adaptive management scoping process to explore a number of key questions (Figure 8). The process used "decision scaling" to link *bottom-up* stakeholder-defined water level thresholds with *top-down* development of climate change scenarios (Brown et al., 2011; 2012; Moody and Brown, 2012). The first step engaged stakeholders and resource experts using a range of methods (onsite surveys, interviews, data collection, analysis and modeling, expert judgment, and public information sessions) to assess system vulnerability and define coping zones for key issues.

Three coping zones were defined, with corresponding management alternatives. Zone A levels are acceptable (within the historical range, but not the extreme highs and lows) and within the tolerance and expectations of stakeholder groups. In Zone B, levels are outside the expectations of an interest but current management regimes can be used to cope with them. While there may be significant changes in activities, benefits, and costs in this zone, most interests do not face serious financial consequences or irreversible impacts. Zone C levels create persistent negative consequences. For example, hazard zone policies and major infrastructure would be compromised. In this state, interests are forced to make significant changes in activities, forego long-standing benefits, or experience significant permanent or long-lasting adverse impacts (Leger and Read, 2012). Then a range of methods – historical data, General Circulation Model (GCM) and Regional Climate Model (RCM) scenarios, stochastic and paleo-analysis – were employed to generate climate information on the range and frequency of water level conditions, including extremes (International Upper Great Lakes Study, 2012; *see also* Chapter 2). These were then used to develop risk matrices that examine the probability and consequence of specific events.

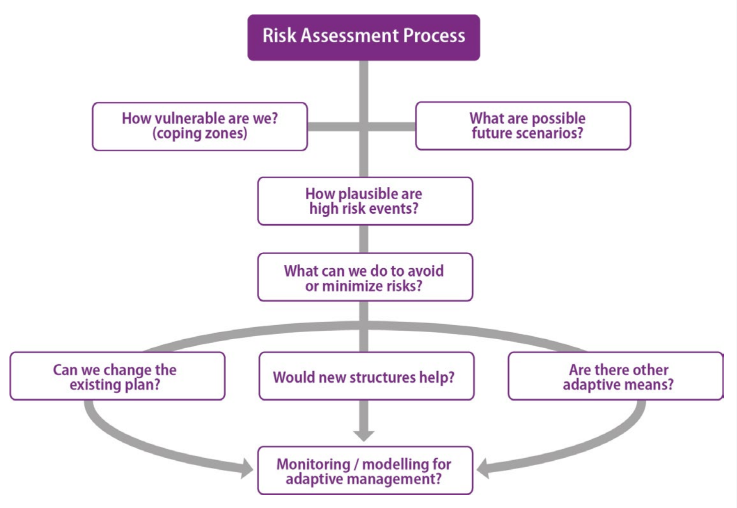


**FIGURE 8:** Adaptive management assessment process *(modified from Leger and Read, 2012, Figure 2-1, p. 8).*

Armed with this understanding of key risks and thresholds, long-term monitoring, system modeling and performance assessment inform the ongoing evaluation of management activities. Existing policies, practices and plans need to be reviewed, and where found wanting, be revised as new information emerges, knowledge evolves and/or the water level regime changes. To that end, according to Leger and Read (2012), "[…] the adaptive management strategy […] is focused on what is necessary […] in order to develop a greater understanding of appropriate adaptive actions, and of when and how they should be implemented or adjusted to minimize future risks." Adaptive Management Pilots addressing pressing regional or local water level issues have been proposed as a means of initiating the process and testing and refining methods of collaboration.

To date, adaptation in Canada has been primarily focused on no-regrets options, incremental changes to existing systems and flexible, adaptive approaches (*see* Case Study 5). These approaches tend to minimize the actual and perceived risks of adaptation, such as over-adapting, mal-adapting and wasting resources. Some researchers suggest, however, that these will not always be sufficient as climate continues to change and that larger, transformational changes will be needed (Kates et al., 2012; O'Brien, 2012; Rickards and Howden, 2012, *see* Box 3). In such cases, increasing the will to adapt and to embrace this type of change will likely be even more challenging than for incremental approaches.

### 5.2.5 CREATING AN ENABLING ENVIRONMENT

Creating an environment that is supportive of adaptation includes removing and reducing barriers (such as policies and regulations that constrain adaptation), enabling adaptation and empowering people to accept and embrace change.

Government policies and programs influence adaptive capacity (Ford and Pearce, 2012), with the role of government varying, depending on level (e.g. municipal, provincial/territories, federal) and respective mandates (*see* Section 4.1). Roles for all levels in creating an enabling environment include building strong communication channels, providing access to data and information (e.g. research, project results, tools and climate change information), increasing engagement of citizens and stakeholders, and implementing flexible and adaptive policies (Corkal et al., 2011). Adaptive policies are designed to respond in an ongoing manner to changing, uncertain and complex conditions (Swanson et al., 2010). Assisting vulnerable groups and addressing existing barriers are also seen as roles for governments (Fankhauser and Soare, 2013). Clearly articulating climate change adaptation as a priority and providing opportunities to integrate climate change throughout the organizational structure can also contribute to building an enabling environment (Burch, 2010; Lemieux et al., 2013). Providing opportunities for, and encouraging – enhanced and effective collaboration (between various levels of government, different departments and external stakeholders, including industry) is also an important role for government. Indeed, in the Canadian context, collaboration is seen as fundamental to advancing adaptation (Government of Canada, 2011; *see also* Case Study 1).

**BOX 3**

#### TRANSFORMATIONAL CHANGE

Transformational change as a response to climate change is an emerging field of research (O'Brien, 2012). As such, definitions and interpretations are still evolving (Rickards and Howden, 2012). Some see 'transformation' as a separate and distinct response to climate change (in addition to mitigation and adaptation; O'Brien, 2012). Others interpret transformation as a type of adaptation that encompasses larger scale, more extensive adaptations, and adaptations that are new to a region or resource system (Kates et al., 2012), differentiating instead between *incremental* and *transformational* adaptation (Park et al., 2012; Figure 9). Either way, transformational changes would result in significant and widespread shifts which, while bringing significant benefits, could also challenge environmental, social and economic norms, the status quo and/or current value systems.

Examples of transformational change include significant changes in land use (e.g. from agriculture to forestry), relocating entire communities to reduce risks from coastal erosion (Kates et al., 2012) and paradigm shifts in thinking (ACT, 2013). Compared to incremental approaches, transformational adaptation brings potential for greater gains, but with greater risks (Rickards and Howden, 2012). However, it is noted that while the changes would be fundamental, they are not necessarily irreversible (Park et al., 2012; Rickards and Howden, 2012). As applied to climate change, the concept of transformational change has primarily been discussed to date in the context of natural ecosystems and agriculture, and through a theoretical lens.

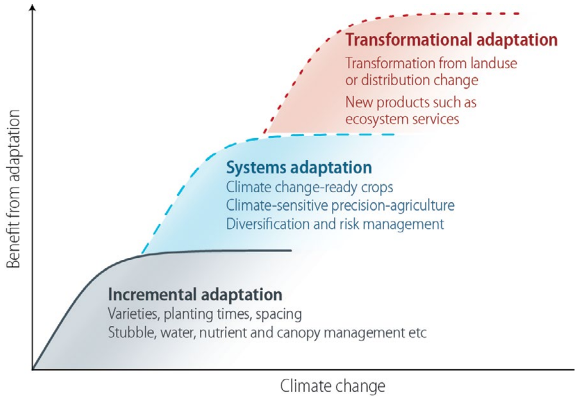


**FIGURE 9:** Differentiating levels of adaptation with examples from agriculture *(from Howden et al., 2010; Rickards and Howden, 2012).*

The importance of "champions" in driving adaptation within organizations – people who have the initiative, enthusiasm and authority to implement change – has also been noted in the literature (Tompkins et al., 2010; Richardson and Lemmen, 2010; *see also* Case Study 2). While the role of individuals can be important, Van Damme (2008) and Johnston and Hesseln (2012) emphasize the importance of embedding progressive attitudes and adaptation thinking in corporate culture, rather than relying on the presence of key individuals.

# 6. SUMMARY

Trends in adaptation research and action in Canada over the past 5 to 10 years reflect a complex issue informed by diverse research, expanded levels of engagement, and increasing examples of implementation. Discussions have moved beyond justifying and clarifying the legitimacy of adaptation as a response to climate change, to understanding the process of adaptation – who is adapting, how and why they are adapting, and what is constraining or enabling the process.

In Canada, there are examples of adaptation occurring at all levels of government, by industry groups, non-governmental organizations and individual companies. Similar to the situation in 2008, activity at the municipal level still appears to dominate. Municipalities have been developing adaptation plans, participating in awareness-raising workshops, and some have made changes to their policies and procedures to take a changing climate into account. Higher levels of government have also developed adaptation strategies and policy frameworks, and have been facilitating climate change adaptation through the establishment of collaborative mechanisms to facilitate applied research, development of decision support tools and sharing of adaptation experiences. Industry has become more engaged in the issue, particularly within sectors with high sensitivity and exposure to climate and weather (e.g. forest, hydroelectricity and tourism) and adaptation activities have grown within public service sectors, with, for example, numerous examples of proactive adaptation planning within the health sector.

Overall, significant progress has been made on adaptation activities in Canada; over the past five years there has been an increase in adaptation engagement, research, awareness, planning (including strategies and policies) and collaboration. Progress is less evident in the implementation of measures to adapt to future climate conditions (i.e. specific changes made to structures or approaches to reduce vulnerability or take advantage of potential opportunities). Although some examples are available, such as the revised sea dyke guidelines in BC (*see* Chapter 8 – Water and Transportation Infrastructure) and the diversification of winter resorts to include warm-season activities (*see* Chapter 5 – Industry), the number does not appear proportionate to our high capacity to adapt and our ever-growing knowledge base. This is similar to the situation in other developed countries, where implementation is also still in its early stages (e.g. *see* Bierbaum et al., 2013; Bauer et al., 2012; Biesbroek et al., 2010).

At each step of the adaptation process (Figure 2), barriers and challenges can constrain or limit adaptation. Some of these – such as limited resources, information gaps, or lack of technology – are increasingly understood. Others, such as values and psychological biases, are less tangible, though likely just as important as they influence the will to adapt, a critical factor in ensuring that awareness and adaptive capacity actually translate to action. New understanding of barriers has emerged, both as a result of increased adaptation activities, and of increased integration of perspectives from other disciplines.

Moving forward will require further attention on overcoming barriers and facilitating adaptation. Learning from others and the practical application of research will help in this regard, as will continued contributions from organizations developing learning modules and guidance material on adaptation. As the public and private sectors continue to become more engaged on the issue, understanding the benefits and trade-offs of implementing adaptation measures will become more pressing. All levels of government have a continuing role in creating an enabling environment for adaptation.

In conclusion, our understanding of the adaptation process in Canada is continually improving, and examples of adaptation implementation have grown over the past 5 years. We have the awareness and the capacity needed to adapt in most cases. Continuing efforts on addressing barriers and enhancing our will to adapt (for all groups involved) will help ensure that adaptation continues to advance to the degree necessary for maintaining social, economic and environmental sustainability in the long term.

# REFERENCES

ACC [Adaptation to Climate Change] Community of Practice (2011): Provincial and Territorial Adaptation Projects and Initiatives – Survey Results. March 2011.

ACIA (2005): Arctic Climate Impact Assessment; Cambridge University Press, 1042p. <http://www.acia.uaf.edu>.

ACT [Adaptation to Climate Change Team] (2013): Summary for Decision Makers - Climate Change Adaptation and Canada's Crops And Food Supply; Adaptation to Climate Change Team, <http://act-adapt.org/wp-content/uploads/2013/07/07-13-CFS-Summary-WEB.pdf>.

Adger, W.N., Lorenzoni, I., and O'Brien, K. (ed.) (2009): Adapting to Climate Change: Thresholds, Values, Governance; Cambridge University Press.

Adger, W. N., Brown, K., and Conway, D. (2010): Progress in global environmental change; Global Environmental Change, v. 20, no. 4, p. 547-549.

Agrawala, S., Carraro, M., Kingsmill, N., Lanzi, E., Mullan, M., and Prudent-Richard, G. (2011): Private sector engagement in adaptation to climate change: approaches to managing climate risks; in OECD Environment Working Papers; OECD Publishing.

Andrachuk, M. and Smit, B. (2012): Community-based vulnerability assessment of Tuktoyaktuk, NWT, Canada to environmental and socio-economic changes; Regional Environmental Change, v. 12, no. 4, p. 867-885.

Bauer, A., Feichtinger, J. and Steurer, R. (2011): The governance of climate change adaptation in 10 OECD countries: challenges and approaches - discussion paper; Institute of Forest, Environmental, and Natural Resource Policy, University of Natural Resources and Applied Life Sciences, Vienna, <www.wiso.boku.ac.at/fileadmin/_/H73/H732/_TEMP_/InFER_DP_11_1__The_Governance_01.pdf>.

Bauer, A., Feichtinger, J. and Steurer, R. (2012): The governance of climate change adaptation in 10 OECD countries: challenges and approaches; Journal of Environmental Policy and Planning, v. 14, no. 3, p. 279-304.

BC Agriculture & Food Climate Action Initiative (2012): BC Agriculture Climate Change Adaptation Risk and Opportunity Assessment: Provincial Report; British Columbia Agriculture & Food Climate Action Initiative, March 2012.

BC Stats (2012): Preparing for a Changing Climate: Perceptions of BC Public Service Employees; British Columbia, < www.bcstats.gov.bc.ca/Files/1f1b77b7-0866-4841-8b75-9c22af000864/Preparing for a Changing Climate Survey Report - June 2012.pdf>.

Berrang-Ford, L., Ford, J.D., and Paterson, J. (2011): Are we adapting to climate change?; Global Environmental Change, v. 21, no. 1, p. 25-33.

Berry, P. (2011): Risk perception, health communication and adaptation to the health impacts of climate change in Canada; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

Berry, P., Pajot, M., Hutton, D., Clarke, K-L., and Verret, M (2009): The Role of Risk Perception and Health Communication in Adapting to the Health Impacts of Climate Change in Canada. Report Prepared for Natural Resources Canada. Ottawa.

Bierbaum, R., Smith, J.B., Lee, A., Blair, M., Carter, L., Chapin III, F.S. and Verduzco, L. (2013): A comprehensive review of climate adaptation in the United States: more than before, but less than needed; Mitigation and Adaptation Strategies for Global Change, v. 18, no. 3, p. 361-406.

Biesbroek, G.R., Swart, R.J., Carter, T.R., Cowan, C., Henrichs, T., Mela, H., and Rey, D. (2010): Europe adapts to climate change: comparing national adaptation strategies; Global Environmental Change, v. 20, no. 3, p. 440-450.

Bourque, A. and Simonet, G. (2008): Quebec; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, Ontario, p. 171-226.

Boyd, E., Street, R., Gawith, M., Lonsdale, K., Newton, L., Johnstone, K. and Metcalf, G. (2011): Leading the UK adaptation agenda: a landscape for stakeholders and networked organizations for adaptation to climate change; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

Boyle, M. and Dowlatabadi, H. (2011): Anticipatory adaptation in marginalized communities within developed countries; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

Brisley, R., Welstead, J., Hindle, R. and Paavola, J. (2012): Socially just adaptation to climate change; Joseph Rowntree Foundation, July 2012.

Brown, C., Werick, W., Leger, W. and Fay, D. (2011): A decision-analytic approach to managing climate risks: application to the Upper Great Lakes; Journal of the American Water Resources Association, v. 47, no. 3, p. 524–534.

Brown, C., Ghile, Y., Laverty, M. and Li, K. (2012): Decision scaling: linking bottom-up vulnerability analysis with climate projections in the water sector; Water Resources Research, v. 48, W09537.

Bruce, J.P., Egener, M. and Noble, D. (2006): Adapting to Climate Change: A Risk-based guide for Ontario Municipalities; Natural Resources Canada, Climate Change Impacts and Adaptation Program, 42 p. <https://adapt.nd.edu/resources/508/download/Adapting-to-Climate-Change-a-Risk-Based-Guide-for-Ontario-Municipalities.pdf>.

Burch, S. (2010): In pursuit of resilient, low carbon communities: an example of barriers to action in three Canadian cities; Energy Policy, v. 38, p. 7575-7585.

Burch, S. and Robinson, J.A. (2007): Framework for explaining the links between capacity and action in response to global climate change; Climate Policy, v. 7, p. 304-316.

Burton, I. (2008): Moving forward on adaptation; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, Ontario, p. 425-440.

C2ES [Center for Climate and Energy Solutions] (2013): Weathering the storm: building business resilience to climate change; Center for Climate and Energy Solutions, July 2013.

Canadian Institute of Planners (2013): Planning for climate change; Canadian Institute of Planners, <www.planningforclimatechange.ca/wwwroot/dsp_HomePage.cfm>.

Canadian Institute of Planners (2013): CIP National Affairs initiatives; Canadian Institute of Planners, <www.cip-icu.ca/web/la/en/pa/0e47adaf838c4becbb11dab1691d696b/template.asp>.

Carlson, D. (2012): Preparing for climate change: an implementation guide for local governments in British Columbia; West Coast Environmental Law, <www.retooling.ca/_Library/docs/WCEL_climate_change_FINAL.pdf>.

Carmin, J., Nadkarmi, N. and Rhie, C. (2012): Progress and challenges in urban climate adaptation planning: results of a global survey; DUSP/MIT, Cambridge, Massachusetts.

CBC (2013): Calgary floods spotlight cities' costly failure to plan for climate change, <www.huffingtonpost.ca/2013/06/28/alberta-floods-climate-change_n_3514976.html>.

Ceres and Climate Change Lawyers Network (2012): Business resilience in a changing climate: Canadian corporate disclosure on risks and opportunities from the physical impacts of climate change; report commissioned by the National Round Table on the Environment and the Economy.

Chiotti, Q. and Lavender, B. (2008): Ontario; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, Ontario, p. 227-274.

Cimato, F. and Mullan, M. (2010): Adapting to climate change: analysing the role of government; Defra Evidence and Analysis Series - Paper 1, January 2010.

City of Halifax (2005): Halifax Harbour Plan, <www.halifax.ca/harboursol/documents/HalifaxHarbourPlan_000.pdf>.

City of Toronto (2007): Change is in the air: climate change, clean air and sustainable energy action plan, <www.toronto.ca/changeisintheair/pdf/clean_air_action_plan.pdf>.

City of Toronto and the Clean Air Partnership (2008): Ahead of the storm - preparing Toronto for climate change, <http://www.toronto.ca/legdocs/mmis/2008/pe/bgrd/backgroundfile-12951.pdf >.

Clar, C., Prutsch, A. and Steurer, R. (2013): Barriers and guidelines for public policies on climate change adaptation: a missed opportunityfor scientific knowledge-brokerage; Natural Resources Forum, v. 37, p. 1-18.

Clarke, K.L. and Berry, P. (2012): From theory to practice: a Canadian study of the utility of climate change adaptation frameworks to address health impacts; International Journal of Public Health, v. 57, p.167-174.

CNW (Canadian NewsWire) (2007): Canada leading by example - Baird announces new funding for adaptation on climate change, <www.newswire.ca/fr/story/36479/canada-leading-by-example-baird-announces-new-funding-for-adaptation-on-climate-change>.

Cohen, S.J., Sheppard, S. Shaw, A., Flanders, D., Burch, S., Taylor, B., Hutchinson, D., Cannon, A., Hamilton, S., Burton, B. and Carmichael, J. (2012): Downscaling and visioning of mountain snow packs and other climate change implications in North Vancouver, British Columbia; Mitigation and Adaptation Strategies for Global Change, v. 17, p. 25-49.

Colombo, A.F. and Byer, P.H. (2012): Adaptation, flexibility and project decision-making with climate change uncertainties; Impact Assessment and Project Appraisal, v. 30, no. 4, p. 229-241.

Columbia Basin Trust (2008): The Basin, <www.cbt.org/The_Basin/>.

Columbia Basin Trust (2012): From Dialogue to Action, <www.cbt.org/uploads/pdf/DialoguetoAction_Final_lo-res.pdf>.

Committee on Climate Change (n.d.): UK adaptation policy; Committee on Climate Change, <www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/uk-adaptation-policy/>.

Communauté rurale Beaubassin-est. (2011): Arrêté 09-1B; Grand-Barachois, N.B., <www.beaubassinest.ca/userfiles/file/09-1E%20Modifiant%20l%27arr%C3%AAt%C3%A9%20adoptant%20le%20plan%20rural.pdf>.

Cook, C. and Dowlatabadi, H. (2011): Learning adaptation: climate-related risk management in the insurance industry in climate change adaptation in developed nations, (ed.) J. Ford and L. Berrang-Ford; Springer, New York, p. 255-265.

Corkal, D.R., Diaz, H. and Sauchyn, D. (2011): Changing roles in Canadian water management: a case study of agriculture and water in Canada's south Saskatchewan river basin; International Journal of Water Resources Development, v. 27, no. 4, p. 647-664.

Crawford, E. and MacNair, E. (2012): BC Agriculture Climate Change Adaptation Risk and Opportunity Assessment - Provincial Report; British Columbia Agriculture & Food Climate Action Initiative, March 2012.

CREXE [Centre de Recherche et D'Expertise en Evaluation], (2012) : Elements of a frame of reference for evaluating adaptation to climate change: The RAC-Québec case. Submitted to Ouranos Consortium, March, 2012. <http://www.ouranos.ca/media/publication/248_RapportCrowleyetal-En-2012.pdf>.

Crowe, K.A. and Parker, W.H. (2008): Using portfolio theory to guide reforestation and restoration under climate change scenarios; Climatic Change, v. 89, no. 3-4, p. 355-370.

CSA Group (2012): National Survey of Canada's Infrastructure Engineers about Climate Change. Prepared for Engineers Canada, May 2012.

CTV.ca News Staff (2010): Extreme heat wave example of climate change: expert, <www.ctvnews.ca/extreme-heat-wave-example-of-climate-change-expert-1.530132>.

Cunsolo Willox, A., Harper, S.L., Ford, J.D., Landman, K., Houle, K., Edge, V.L. and Rigolet Inuit Community Government (2012): From this place and of this place: Climate change, sense of place, and health in Nunatsiavut, Canada; Social Science & Medicine, v. 75, p. 538-547.

David Suzuki Foundation (2012): All over the map 2012: a comparison of provincial climate change plans; David Suzuki Foundation, March 2012.

Davidson, G. and Bowron, B. (2012): Perspectives on climate change: benchmarking CIP members; Canadian Institute of Planners, March 2012.

de Loë, R. (2011): Mainstreaming climate change adaptation in drinking water source protection in Ontario: challenges and opportunities; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

Deloitte (2011): Canadian business perspectives on the role of government in private sector climate adaptation; National Round Table on the Environment and the Economy.

Delta Programme Commissioner (n.d.): Delta Act, <www.deltacommissaris.nl/english/topics/delta_act/>.

Desjarlais, C. and Blondlot, A. (2010): Learning to Adapt to Climate Change; Ouranos, Montreal, <http://www.ouranos.ca/en/publications/about-climate-change.php>.

Desjarlais, C. and Larrivée, C. (2011): Analyse économique de l'adaptation aux changements climatiques en matiere de drainage urbain au Québec: compairason de diverses strategies d'adaptation pour un secteur de Montréal; Ouranos.

Dickinson, T. and Burton, I. (2011): Adaptation to climate change in Canada: a multi-level mosaic; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

District of Elkford. (2009): Official community plan and climate change adaptation strategy, <www.elkford.ca/include/get.php?nodeid=78>.

Doiron, S. (2012): From climate change plans to by-laws, it's time to act. The sea level rise zone adaptation by-law - new coastal development regulation; Plan Canada, v. 52, no. 4.

Dupuis, J. and Biesbroek, R. (in press): Comparing apples and oranges: the dependent variable problem in comparing and evaluating climate change adaptation policies; Global Environmental Change, August 2013.

Environics Research Group (2010): National climate change adaptation benchmark survey; Natural Resources Canada.

Environment Canada (2010): Evaluation review of the clean air agenda adaptation theme: review of program evaluation and performance measurement findings; Environment Canada, Audit and Evaluation Branch, December 2010.

Environment Canada (2013): Canada's ongoing commitment to climate change adaptation, <ec.gc.ca/default.asp?lang=En&n=2D1D6FA7-1&news=B67A7995-A1CA-4DE3-89D2-E4E3C0E24BFB>.

European Commission (2013): Questions and answers: EU strategy on adaptation to climate change, <europa.eu/rapid/press-release_MEMO-13-334_en.htm>.

Fankhauser, S. and Soare, R. (2013): An economic approach to adaptation: illustrations from Europe; Climatic Change, v. 118, no. 2, p. 367-379.

FCM [Federation of Canadian Municipalities] (2013): Adapting to Severe Weather and a Changing Climate, <www.fcm.ca/home/issues/environment/climate-change-adaptation/adaptation-resources/adapting-to-severe-weather-and-a-changing-climate.htm>.

Field, C.B., Mortsch, L.D., Brklacich, M., Forbes, D.L., Kovacs, P., Patz, J.A., Running, S.W. and Scott, M.J. (2007): North America; in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson; Cambridge University Press, Cambridge, UK, p. 617-652.

Forbes, D. L., Manson, G. K., Charles, J., Thompson, K. R. and Taylor, R. B. (2009): Halifax Harbour extreme water levels in the context of climate change: scenarios for a 100-year planning horizon; Geological Survey of Canada, Ottawa, ON, Open File 6346, iv+22 p.

Ford, J., and Pearce, T. (2012): Climate change vulnerability and adaptation research focusing on the Inuit subsistence sector in Canada: directions for future research; The Canadian Geographer, v. 56, no. 2, p. 275-287.

Ford, J., Smit, B., Wandel. J., Allurut, M., Shappa, K., Ittusujurat, H. and Qrunnut, K. (2008): Climate change in the Arctic: current and future vulnerability in two Inuit communities in Canada; The Geographical Journal, v. 174, no. 1, p. 45-62.

Ford, J.D., Berrang-Ford, L. and Paterson, J. (2011): A systematic review of observed climate change adaptation in developed nations; Climatic Change, v. 106, p. 327-336.

Ford, J.D., Berrang-Ford, L., Lesnikowski, A., Barrera, M. and Heymann, S.J. (2013): How to track adaptation to climate change: a typology of approaches for national-level application; Ecology and Society, v. 18, no. 3, 40 p.

Ford, J.D. and Berrang-Ford, L. (2011): Introduction; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

Fraser, J. and Strand, M. (2011): Climate change adaptation for local government: a resource guide; Pacific Institute for Climate Solutions, June 2011.

Gagnon-Lebrun, F. and Agrawala, S. (2007): Implementing adaptation in developed countries: an analysis of progress and trends; Climate Policy, v. 7, no. 5, p. 392-408.

Gifford, R. (2011): The dragons of inaction: psychological barriers that limit climate change mitigation and adaptation; American Psychologist, v. 66, no. 4, p. 290-302.

Gleeson, J., Gray, P., Douglas, A., Lemieux, C.J. and Nielsen, G. (2011): A practitioner's guide to climate change adaptation in Ontario's ecosystems; Ontario Centre for Climate Impacts and Adaptation Resources, Sudbury, Ontario, 74 p.

Government of Canada (2011): Federal Adaptation Policy Framework; Environment Canada, Gatineau, QC.

Government of Quebec (2012): Quebec in Action - Greener by 2020: Government Strategy for Climate Change Adaptation.

Hagerman, S., Dowlatabadi, H., Satterfield, T. and McDaniels, T. (2010): Expert views on biodiversity conservation in an era of climate change; Global Environmental Change, v. 20, p. 192-207.

Halifax Regional Municipality (2006): Regional municipal planning strategy (Policy 2.2.5 and E-16); Halifax, <www.halifax.ca/regionalplanning/documents/Regional_MPS.pdf>.

Halifax Regional Municipality (2007): HRM climate change: developer's risk management guide; Halifax, N.S., <www.halifax.ca/climate/documents/DevelopersGuidetoRiskManagment.pdf>.

Halifax Regional Municipality, Geological Survey of Canada and Natural Resources Canada (2010): Sea level rise adaptation planning for Halifax Harbour; Halifax, N.S.: Presentation to the Committee-of-the-Whole - Halifax Regional Council. <www.halifax.ca/council/agendasc/documents/100209cow4.pdf>.

Hallegatte, S., Lecocq, F. and de Perthuis, C. (2011): Designing climate change adaptation policies: an economic framework; World Bank.

Halliday, R. (2008): Evaluation of multidisciplinary research projects and teams – climate change impacts and adaptation program; Prepared for Natural Resources Canada.

Hanna, K., Dale, A., Filion, P., Khan, Z., Ling, C., Rahaman, K. and Seasons, M. (2013): Planning for adaptation in an uncertainty setting: local government action in Canada; Conference paper submitted to AESOP-ACSP Joint Congress, 15-19 July, 2013, Dublin.

Health Canada (2012): Heat Alert and Response Systems to protect Health: Best Practices Guidebook; Ottawa, Ontario, <www.hc-sc.gc.ca/ewh-semt/alt_formats/pdf/pubs/climat/response-intervention/response-intervention-eng.pdf>.

Health Canada (2013): Climate Change and Health, <www.hc-sc.gc.ca/ewh-semt/pubs/climat/index-eng.php>.

Hennessey, R. (2010): Scenario planning as a tool to ensure robust adaptation; Plan Canada, v. 50, no. 4, p. 32-35.

Hewitt, N., Klenk, N., Smith, A.L., Bazely, D.R., Yan, N., Wood, S., MacLellan, J.I., Lipsig-Mumme, C.and Henriques, I. (2011): Taking stock of the assisted migration debate; Biological Conservation, v. 144, no. 11, p. 2560-2572.

Horton, B. and Richardson, G.R.A. (2011): Climate change adaptation and Canadian municipal and business decision-makers: a snapshot of 2009; CCIAD Discussion Paper Series, Natural Resources Canada.

Howden, S.M., Crimp, S. and Nelson, R.N. (2010): Australian agriculture in a climate of change; in Managing Climate Change: Papers from Greenhouse 2009 Conference, (ed.) I. Jubb, P. Holper and W. Cai; CSIRO Publishing, Melbourne, p. 101-112.

Hutton, D. (2011): Behavioural health and risk perception: factors in strengthening community resiliency and emergency preparedness; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York, v. 42, p. 133-142.

ICMM [International Council of Mining & Metals] (2013): Adapting to a changing climate: implications for the mining and metals industry, March 2013.

IEMA [Independent Environmental Monitoring Agency] (2013): Climate change adaptation: building the business case, <https://www.iema.net/system/files/iema_guidance_report_v5.pdf>.

International Upper Great Lakes Study (2012): Lake Superior regulation: addressing uncertainty in Upper Great Lakes water levels; Final Report to the International Joint Commission, March 2012, 215 p.

Jackson, E., Barry, L. and Marzok, N. (2011): Changing climate, changing communities: municipal climate adaptation guide and workbook; ICLEI Canada, Toronto, Ontario, Canada, <www.icleicanada.org/images/icleicanada/pdfs/GuideWorkbookInfoAnnexes_WebsiteCombo.pdf>.

Jantarasami, L., Lawler, J.J. and Thomas, C.W. (2010): Institutional barriers to climate change adaptation in U.S. national parks and forests; Ecology and Society, v. 15, no. 4, 33 p.

Jessen, S. and Patton, S. (2008): Protecting marine biodiversity in Canada: adaptation options in the face of climate change; Biodiversity, v. 9, no. 3-4, p. 47-58.

Johnston, M. and Hesseln, H. (2012): Climate change adaptive capacity of the Canadian forest sector. Forest Policy and Economics, 24, 29-34.

Johnston, M., Williamson, T., Nelson, T., Van Damme, L., Ogden, A. and Hesseln, H. (2011): Adaptive capacity of forest management systems in publicly owned forest landscapes in Canada; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York, v. 42, p.267-278.

Kates, R.W., Travis, W.R. and Wilbanks, T.J. (2012): Transformational adaptation when incremental adaptations to climate change are insufficient; Proceedings of the National Academy of Sciences of the United States of America, v. 109, no. 19, p. 7156-7161.

Klein, R.J.T., Huq, S., Denton, F., Downing, T.E., Richels, R.G., Robinson, J.B. and Toth, F.L. (2007): Inter-relationships between adaptation and mitigation; in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson; Cambridge University Press, Cambridge, UK, p. 745-777.

Kolbert, E. (2012): Watching Sandy, ignoring climate change, <www.newyorker.com/online/blogs/newsdesk/2012/10/watching-hurricane-sandy-ignoring-climate-change.html>.

Kovacs, P. (2011): Overview: climate change adaptation in industry; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

Kulkarni, T., Watkins, J.M., Nickels, S.and Lemmen, D.S. (2012): Canadian International Polar Year (2007-2008): an introduction; Climatic Change, v. 115, p. 1-11.

Lantz, V., Trenholm, R. Wilson, J. and Richards, W. (2012): Assessing market and non-market costs of freshwater flooding due to climate change in the community of Fredericton, Eastern Canada; Climatic Change, v. 110, no. 1-2, p. 347-372.

Leclerc, L. (2012): Background document and workshop report: measuring progress on adaptation in Canada; Final report to Ouranos Inc. 32 p.

Leger, W. and Read, J. (2012): Adaptive management: strategy and legacy; in Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels; Final report to the International Upper Great Lakes Study Board, Adaptive Management Technical Work Group, 167 p.

Lemieux, C.J., Thompson, J.L., Dawson, J. and Schuster, R.M. (2013): Natural resource manager perceptions of agency performance on climate change; Journal of Environmental Management, v. 114, p. 178-189.

Lemmen, D.S., Warren, F.J., Lacroix, J. and Bush, E. (ed.) (2008): From impacts to adaptation: Canada in a changing climate 2007; Government of Canada, Ottawa, ON.

Lesnikowski, A.C., Ford, J.D., Berrang-Ford, L., Paterson, J.A., Barrera, M. and Heymann, S.J. (2011): Adapting to health impacts of climate change: a study of UNFCCC Annex I parties; Environmental Research Letters, v. 6, 044009.

Lim, B. and Spanger-Siegfried, E. (ed.) (2005): Adaptation policy frameworks for climate change: developing strategies, policies and measures; United Nations Development Programme, New York and Cambridge University Press, Cambridge.

Linnenluecke, M.K., Griffiths, A. and Winn, M. (2012): Extreme weather events and the critical importance of anticipatory and organizational resilience in responding to impacts; Business Strategy and the Environment, v. 21, p. 17-32.

Lynam, T. (2011): Making sense of what enables and what constrains adaptation to climate change; 19th International Congress on Modelling and Simulation, Perth, Australia, p. 12-16.

MacLellan, J.I. (2008): Climate change adaptation for neophytes; in Linking Climate Models to Policy and Decision-making, (ed.) A. Fenech and J.I. MacLellan, p. 37-80; Environment Canada, Toronto, Canada.

McIlgorn, A., Hanna, S., Knapp, G., Le Floc'H, P., Millerd, F., and Minling, P. (2010). How will climate change alter fishery governance? Insights from seven international case studies. Marine Policy, 34, 170-177.

McLeman, R., Brklacich, M., Woodrow, M., Vodden, K., Gallaugher, P. and Sander-Regier, R. (2011): Opportunities and barriers for adaptation in Canadian rural and resource-based communities; in Climate Change Adaptation in Developed Nations: From Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York, New York.

Merrill, S. and Zwicker, G. (2010): Capacity for climate change adaptation in New Brunswick municipalities; Environmental Trust Fund Project No. 090179, March, 2010.

Mills, B. (ed.) (2008): SERA North: economics of weather, climate, and climate change; Synthesis of a meeting held 21-22 February, Waterloo, Ontario, Canada; Environment Canada, Adaptation and Impacts Research Division, Waterloo, Canada, 64 p.

Moody, P. and Brown, C. (2012): Modeling stakeholder-defined climate risk on the Upper Great Lakes; Water Resources Research, v. 48, W10524.

Moser, S. and Ekstrom, J. (2010): A framework to diagnose barriers to climate change adaptation; Proceedings of the National Academy of Sciences, v. 107, no. 51.

Mullan, M., Kingsmill, N., Kramer, A.M. and Agrawala, S. (2013): National Adaptation Planning: Lessons from OECD Countries, OECD Environment Working Papers, no. 54, OECD Publishing.

Murdock, T.Q. and Burger, G. (2010): Research plan for regional climate impacts: Pacific climate impacts consortium, p. 39.

Natural Resources Canada (2009): Coastal vulnerability in the Halifax regional municipality; Climate Change Geoscience Program, Ottawa, Ontario.

Natural Resources Canada (2012): Adaptation platform, <www.nrcan.gc.ca/earth-sciences/climate-change/community-adaptation/platform/11958>.

Natural Resources Canada (2013a): Impacts and adaptation: equipping Canadians to adapt to our changing climate, <www.nrcan.gc.ca/earth-sciences/climate-change/community-adaptation/54>.

Natural Resources Canada (2013b): RAC and tools synthesis state of play summary; Climate Change Impacts and Adaptation Division, Ottawa, 3 p.

Nelitz, M., Boardley, S. and Smith, R. (2013): Tools for climate change vulnerability assessments for watersheds; Prepared by ESSA Technologies Ltd. for the Canadian Council of Ministers of the Environment.

NRTEE [National Round Table on the Environment and the Economy] (2009): True North: adapting infrastructure to climate change in Northern Canada; National Round Table on the Environment and the Economy, Ottawa, Ontario.

NRTEE [National Round Table on the Environment and the Economy] (2010): Degrees of change: climate warming and the stakes for Canada. National Round Table on the Environment and the Economy, Ottawa, Ontario.

NRTEE [National Round Table on the Environment and the Economy] (2011): Paying the price: the economic impacts of climate change for Canada; National Round Table on the Environment and the Economy, Ottawa, Ontario.

NRTEE [National Round Table on the Environment and the Economy] (2012a): Facing the elements: building business resilience in a changing climate (case studies report) National Round Table on the Environment and the Economy, Ottawa, Ontario.

NRTEE [National Round Table on the Environment and the Economy] (2012b): Facing the elements: building business resilience in a changing climate (advisory report), National Round Table on the Environment and the Economy, Ottawa, Ontario.

OAG [Office of the Auditor General] (2010): Report of the Commissioner of the Environment and Sustainable Development to the House of Commons – Chapter 3 – Adapting to Climate Impacts.

O'Brien, K. (2012): Global environmental change II: from adaptation to deliberate transformation; Progress in Human Geography, v. 36, no. 5, p. 667-676.

OCCIAR [Ontario Centre for Climate Impacts and Adaptation Resources] (2013): Welcome to OCCIAR, <www.climateontario.ca/index.php>.

Ochuodho, T.O., Lantz, V.A., Lloyd-Smith, P. and Benitez, P. (2012): Regional economic impacts of climate change and adaptation in Canadian forests: a CGE modeling analysis; Forest Policy and Economics, v. 25, p. 100-112.

OECD [Organisation for Economic Co-operation and Development] (2012): Policy forum on adaptation to climate change in OECD countries summary note, 10-11; Organisation for Economic Co-operation and Development, Paris, May 2012.

Ogden, A.E. and Innes, J.L. (2009): Application of structured decision making to an assessment of climate change vulnerabilities and adaptation options for sustainable forest management; Ecology and Society, v. 14, no. 1, 11 p.

Olar, M. and Lessard, C. (2013): Analyse économique des impacts des changements climatiques sur les étiages et leurs consequences sur divers usages de l'eau dans le basin versant de la rivière Yamaska; Ouranos.

Park, S.E., Marshall, N.A., Jakku, E., Dowd, A.M., Howden, S.M., Mendham, E. and Fleming, A. (2012): Informing adaptation responses to climate change through theories of transformation; Global Environmental Change, v. 22, no. 1, p. 115-126.

Parkins, J.R. and MacKendrick, N.A. (2007): Assessing community vulnerability: a study of the mountain pine beetle outbreak in British Columbia, Canada; Global Environmental Change, v. 17, p. 460-471.

Pearce, T., Ford, J.D., Duerden, F., Smit, B., Andrachuk, M., Berrang-Ford, L. and Smith, T. (2011): Advancing adaptation planning for climate change in the Inuvialuit Settlement Region (ISR): a review and critique; Regional Environmental Change, v. 11, p. 1-17.

Peck, A.M., Bowering, E.A. and Simonovic, S.P. (2013): A flood risk assessment to municipal infrastructure due to changing climate part II: case study; Urban Water Journal.

Pennesi, K., Arokium, J. and McBean, G. (2012): Integrating local and scientific weather knowledge as a strategy for adaptation to climate change in the Arctic; Mitigation and Adaptation Strategies to Global Change, v. 17, p. 897-922.

PIEVC [Public Infrastructure Engineering Vulnerability Committee] (2012): PIEVC case studies: codes, standards and related instruments (CSRI) review for water infrastructure and climate change, <www.pievc.ca/e/2012_PIEVC_CSRI_Water_report_Final.pdf>.

Picketts, I.M., Werner, A.T., Murdock, T.Q., Curry, J., Déry, S.J. and Dyer, D. (2012): Planning for climate change adaptation: lessons learned from a community-based workshop; Environmental Science and Policy, v. 17, p. 82-93.

Picketts, I., Déry, S.J. and Curry, J.A. (2013): Incorporating climate change adaptation into local plans; Journal of Environmental Planning and Management.

Plummer, R., Velaniškis, J., de Grosbois, D., Kreutzwiser, R.D. and de Loë, R. (2010): The development of new environmental policies and processes in response to a crisis: the case of the multiple barrier approach for safe drinking water; Environmental Science and Policy, v. 13, no. 6, p. 535-548.

Preston, B., Westaway R. and Yuen E. (2010): Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations; Mitigation and Adaptation Strategies for Global Change, p. 1-32.

Quebec Ministry of Public Security (2008): Concepts de base in sécurité civile; Gouvernement du Québec.

Reisinger, A., Wratt, D., Allan, S. and Larsen, H. (2011): The role of local government in adapting to climate change: lessons from New Zealand; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J.D Ford, and L. Berrang-Ford; Springer, New York, New York.

Richardson, G. and Lemmen, D.S. (2010): Lessons learned from Canadian municipal adaptation case studies; Plan Canada, p, 26-28.

Richardson, G. and Otero, J. (2012): Planning tools for local adaptation to climate change; Natural Resources Canada, Ottawa, Ontario.

Richardson, G.R.A. (2010): Adapting to climate change: an introduction for Canadian municipalities; Natural Resources Canada, Ottawa, Ontario, 40 p.

Rickards, L. and Howden S.M. (2012): Transformational adaptation: agriculture and climate change; Crop and Pasture Science, v. 63, p. 240-250, <http://www.publish.csiro.au/nid/40/paper/CP11172.htm>.

Robinson, P. and Gore, C. (2011): The spaces in between: a comparative analysis of municipal climate governance and action; Presented at the American Political Science Association, Annual Conference, Seattle, Washington, September 1-4, 2011.

Rodgers, C. and Behan, K. (2012): Accelerating adaptation in Canadian communities: case studies; Clean Air Partnership, July 2012.

Samarawickrema, A. and Kulshreshtha, S. (2008): Value of irrigation water for drought proofing in the South Saskatchewan River Basin (Alberta); Canadian Water Resources Journal, v. 33, no. 3, p. 273-282.

Sauchyn. D. and Kulshrethra, S. (2008): Prairies; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix, and E. Bush; Government of Canada, Ottawa, Ontario, p. 275-328.

Séguin, J. (2008): Human health in a changing climate: a Canadian assessment of vulnerabilities and adaptive capacity; Health Canada, Ottawa, Ontario.

Shaw, A., Sheppard, S., Burch, S., Flanders, D., Weick, A., Carmichael, J., Robinson, J. and Cohen, S. (2009): Making local futures tangible – synthesizing downscaling and visualizing climate change scenarios for participatory capacity building; Global Environmental Change, v. 19, p. 447-463.

Sheppard, S.R.J., Shaw, A., Flanders, D., Burch, S., Wiek, A., Carmichael, J. Robinson, J. and Cohen, S. (2011): Future visioning of local climate: a framework for community engagement and planning with scenarios and visualization; Futures, v. 43, p. 400-412.

Smit, B. (ed.) (1993): Adaptation to climatic variability and change, report of the task force on climate adaptation: the Canadian climate program; Atmospheric Environment Service of Environment Canada, Guelph, Ontario.

Smit, B. and Pilifosova, O. (2001): Adaptation to climate change in the context of sustainable development and equity; in Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, (ed.) J.J. McCarthy, O.F. Canzianni, N.A. Leary, D.J. Dokken and K.S. White; Cambridge University Press, Cambridge, UK, p. 877-912.

Smit, B. and Wandel, J. (2006): Adaptation, adaptive capacity and vulnerability; Global Environmental Change, v. 16, no. 3, p. 282-292.

Spencer, C., Richardson, G., Arsenault, C., Kertland, P., O'Dea, N. and Wilson, M.A. (2012): The role of collaboration in effective decision-making; Second Nordic International Conference on Climate Change Adaptation, Abstracts, p. 22-23.

Steenhof, P. and Sparling, E. (2011): The role of CSRIs in facilitating adaptation to climate change; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

Stocker, L., Burke, G., Kennedy, D. and Wood, D. (2012): Sustainability and climate adaptation: using Google Earth to engage stakeholders; Ecological Economics, v. 80, p. 15-24.

Swanson, D., Barg, S., Tyler, S., Venema, H., Tomar, S., Bhadwal, S., Nair, S., Roy, D. and Drexhage, J. (2010): Seven tools for creating adaptive policies; Technological Forecasting and Social Change, v. 77, no. 6, p. 924-939.

Thomson, G. (2013): Thomson: Alberta must adapt and upgrade in disasters' wake; Edmonton Journal, July 6, 2013.

Tompkins, E.L., Adger, W.N., Boyd, E., Nicholson-Cole, S., Weatherhead, K. and Arnell, N. (2010): Observed adaptation to climate change: UK evidence of transition to a well-adapting society; Global Environmental Change, v. 20, no. 4, p. 627-635.

UKCIP [UK Climate Impacts Program] (2010): The UKCIP adaptation wizard v. 3.0; UK Climate Impacts Program, Oxford, UK.

UNFCCC [United Framework Convention on Climate Change] (2011): Report of the in-depth review of the fifth national communication of Canada; United Framework Convention on Climate Change.

Van Damme, L. (2008): Can the forest sector adapt to climate change?; The Forestry Chronicle, v. 84, p. 301-306.

Vasseur, L. and Catto, N. (2008): Atlantic Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, (ed.) D. Lemmen, F. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, Ontario, p. 119-170.

Webb, R. and Beh, J., (2013): Leading adaptation practices and support strategies for Australia: an international and Australian review of products and tools; National Climate Change Adaptation Research Facility, Gold Coast, p.120.

Webster, A., Gagnon-Lebrun, F., Desjarlais, C., Nolet, J., Sauvé, C. and Uhne, S. (2008): L'évaluation des avantages et des coûts de l'adaptation aux changements climatiques; Ouranos.

Wellstead, J. (2011): Climate adaptation in Canadian communities – scoping report, final draft; Commissioned by the National Round Table on the Environment and the Economy.

Wellstead, A.M. and Stedman, R.C. (2011): Climate change policy capacity at the sub-national government level; Journal of Comparative Policy Analysis: Research and Practice, v. 13, no. 5, p. 461-478.

Williams, R.A. and McNutt, K. (2013): Climate change adaptation and policy capacity in the Canadian finance sector: a meso analysis; Review of Policy Research, v. 30, no. 1, p. 91-113.

Williamson, T.B., Colombo, S.J., Duinker, P.N., Gray, P.A., Hennessey, R.J., Houle, D., Johnston, M., Ogden, A. and Spittlehouse, D.L. (2009): Climate change and Canada's forests: from impacts to adaptation; Sustainable Forest Management Network and Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 104 p.

Williamson, T., Hesseln, H. and Johnston, M. (2012): Adaptive capacity deficits and adaptive capacity of economic systems in climate change vulnerability assessment; Forest Policy and Economics, v. 15, p. 160-166.

Willows, R.I. and Connell, R.K. (ed.) (2003): Climate adaptation: risk uncertainty and decision-making; UKCIP Technical Report, United Kingdom Climate Impacts Programme, Oxford.

Wolfe, J. (2011): Climate Change Adaptation as a Social Process; in Climate Change Adaptation in Developed Nations: Theory to Practice, (ed.) J. Ford and L. Berrang-Ford; Springer, New York.

Wolfe, J., Allice, I. and Bell, T. (2013): Values, climate change and implications for adaptation: Evidence from two communities in Labrador, Canada; Global Environmental Change, v. 23, p. 548-562.

Yohe, G. and Tol, R.S.J. (2002): Indicators for social and economic coping capacity - moving toward a working definition of adaptive capacity; Global Environmental Change, v. 12, p. 25-40.

# END NOTES

[1] www.arcticnet.ulaval.ca/research/theme1.php

[2] www.env.gov.bc.ca/cas/adaptation/pdf/Adaptation_Strategy.pdf

[3] www.pics.uvic.ca/about

[4] www.for.gov.bc.ca/het/climate/actionplan/index.htm

[5] www.environment.alberta.ca/02248.html

[6] www.srd.alberta.ca/MapsPhotosPublications/Publications/ClimateChangeAdaptationFramework.aspx

[7] www.environment.alberta.ca/03136.html

[8] www.parc.ca/saskadapt/

[9] www.energy.ca/users/getdownload.asp?DownloadID=621

[10] www.gov.mb.ca/beyond_kyoto/

[11] www.gov.mb.ca/asset_library/en/beyond_kyoto/adapting_to_climate_change.pdf

[12] www.gov.mb.ca/ia/plups/pdf/cca.pdf

[13] www.ene.gov.on.ca/stdprodconsume/groups/lr/@ene/@resources/documents/resource/stdprod_085423.pdf

[14] www.mnr.gov.on.ca/en/Business/ClimateChange/2ColumnSubPage/STDPROD_092481.html

[15] www.mddefp.gouv.qc.ca/changements/plan_action/stategie-adaptation2013-2020-en.pdf

[16] www.env.gov.yk.ca/publications-maps/documents/YG_Climate_Change_Action_Plan.pdf

[17] www.anorthernvision.ca/strategy/

[18] www.env.gov.yk.ca/publications-maps/documents/ccap_progressreport_eng_2012.pdf

[19] www.env.gov.yk.ca/publications-maps/documents/ccap_progressreport_eng_2012.pdf

[20] www.nwtclimatechange.ca/content/actions

[21] www.ikadapt.ca/wp-content/uploads/2013/01/NWT_CC_newsletter2_PRINT.pdf

[22] env.gov.nu.ca/sites/default/files/3154-315_climate_english_sm.pdf

[23] www2.gnb.ca/content/dam/gnb/Departments/env/pdf/Climate-Climatiques/2007-2012ClimateChangeActionPlan%20.pdf

[24] www2.gnb.ca/content/dam/gnb/Departments/env/pdf/Climate-Climatiques/ClimateChange%20AdaptationStrategyAtlanticCanada.pdf

[25] www.atlanticadaptation.ca/acasa/sites/discoveryspace.upei.ca.acasa/files/New%20Brunswick%20Climate%20Change%20Adaptation%20Project%20Profiles%20-%20February%202013.pdf

[26] www.atlanticadaptation.ca/new-brunswick-communities

[27] www.climatechange.gov.ns.ca/files/03/32/CCAP_final3_FOR_WEB.pdf

[28] www.gov.ns.ca/nse/climate-change/docs/NSCCAF_About.pdf

[29] www.nsinfrastructure.ca/uploads/Gas_Tax_PAER_website_2011.pdf

[30] www.gov.pe.ca/photos/original/env_globalstr.pdf

[31] www.atlanticadaptation.ca/regional-climatescenarios

[32] www.atlanticadaptation.ca/prince-edward-island-communities

[33] www.exec.gov.nl.ca/exec/cceeet/publications/climate_change.pdf

[34] www.env.gov.nl.ca/env/climate_change/vultool/vultool_toc.html

[35] www.municipalnl.ca/userfiles/files/DEC-00306-Infrastructure%20Workbook%20(Web-Email%20Quality).pdf