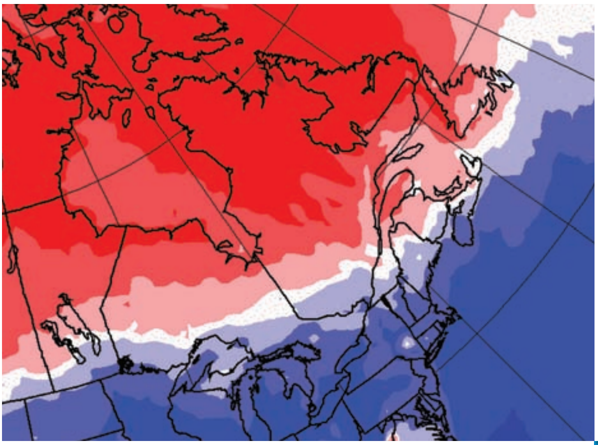
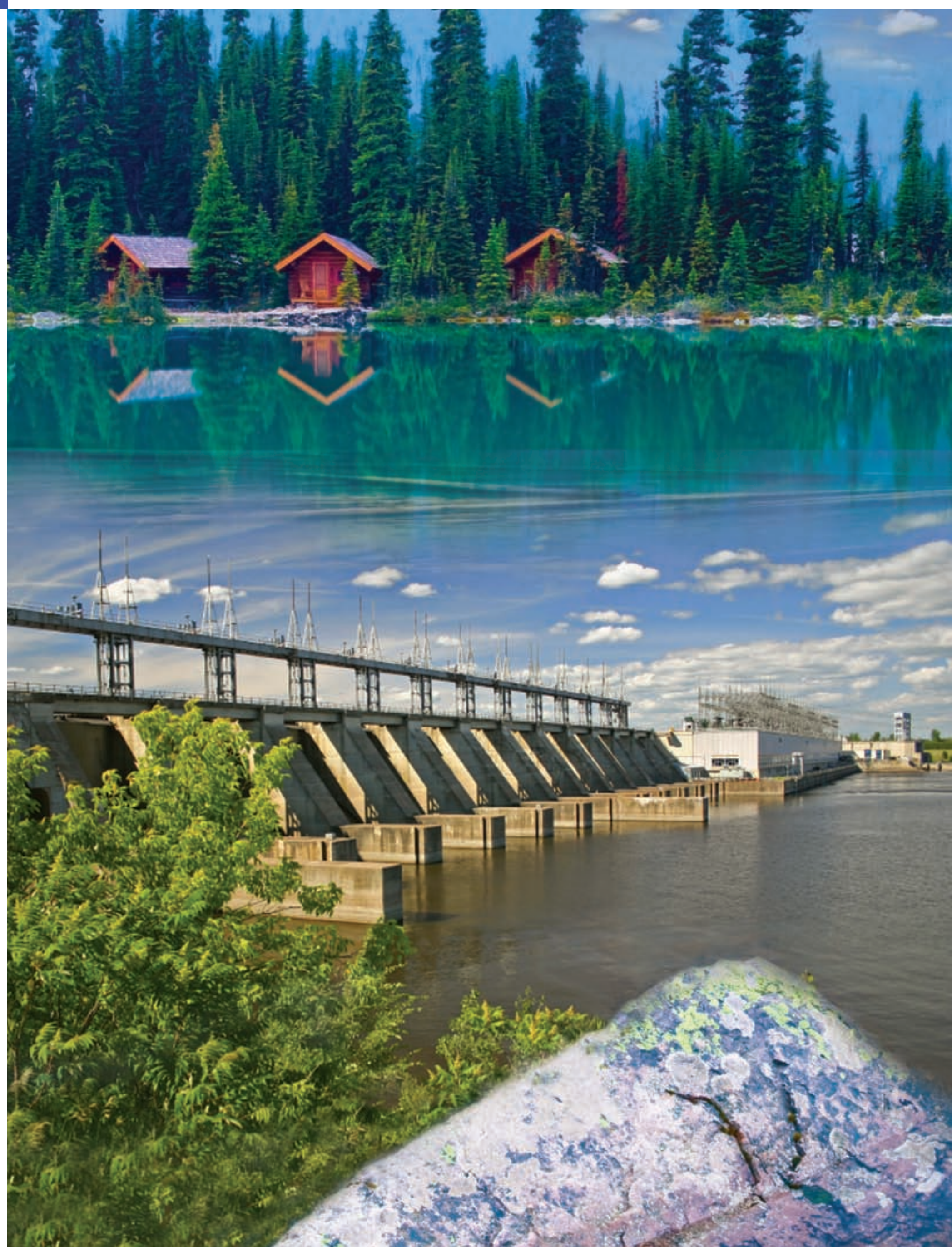
CONSORTIUM ON REGIONAL CLIMATOLOGY
AND ADAPTATION TO CLIMATE CHANGE



LEARNING to Adapt *to Climate Change*



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LEARNING
to Adapt
to Climate Change

OURANOS 2010

OURANOS, a research consortium on regional climatology
and adaptation to climate change, is a joint initiative
of the government of Quebec, Hydro Québec
and the Meteorological Service of Canada
with the participation of UQAM, the INRS,
and the Université de Laval and McGill University.

FOREWORD

There is no longer any question that the warming of our climate system is in large part the result of human actions. It is also very clear that worldwide greenhouse gas emissions will continue to increase over the coming decades and that significantly more warming is inevitable. Even if greenhouse gas emissions are reduced enough to stabilize their concentration, the processes of climate warming and rising sea levels will continue for centuries.

In every part of the world, this warming will be accompanied by numerous negative impacts not only for ecosystems but for the built environment, the health of populations and various socioeconomic activities. Quebec will not be spared in this, and so must learn how to cope with these challenges.

However, many of these impacts can be reduced or avoided with energetic mitigation measures. Moreover, the sooner we put these measures in place, the more they will help to minimize the impacts. In this regard, we must hope that international negotiations and national policies establish realistic and effective objectives and action plans as quickly as possible.

Even with the progress we hope, significant impacts are expected, with certain systems, sectors and regions in Quebec more seriously affected by this climate evolution. For others, though, climate change – at least in the mid-term – may mean business opportunities for the seizing. This is why establishing appropriate measures and adaptation strategies is a critical tool for coming to terms with climate change.

Since Ouranos was created in 2001, Quebec has at its disposal exceptional expertise for shaping its adaptation strategies. The research work generated, coordinated and achieved by Ouranos to date has already served to channel efforts and orient decision-making in a direction that integrates the most recent knowledge on climate change.

This document *Learning to Adapt to Climate Change* is meant to provide a picture of current knowledge on this topic in a way that will be accessible to all Quebeckers who want to learn about the issues of climate change in their region and their field of interest.

Chair of the Board of Directors,

Pierre Baril

ACKNOWLEDGEMENTS

This document is the product of the collaboration of twelve specialists, directly or indirectly connected to Ouranos, who prepared the various sections. These individuals were able to draw upon the ever-growing body of research that is being produced by different groups, focussing on the changes in the Quebec climate, the foreseeable impacts of these changes, the vulnerability of natural and socio-economic systems and the courses of action that should be given priority in order to adapt.

Consequently, Ouranos wants to acknowledge the work of Diane Chaumont, Caroline Larrivée, Nancy Lease, Michel Allard, Alain Bourque, Claude DesJarlais, Pierre Gosselin, Daniel Houle, René Roy, Jean-Pierre Savard, Richard Turcotte and Claude Villeneuve, as well as their colleagues and all the researchers who have contributed in recent years to clarifying the stakes of climate change for Quebec. We also owe thanks to Line Bourdages and Travis Logan for the maps showing climate and growing degree-days that illustrate this document.

Finally, we must acknowledge the patient and pain-staking work of coordination performed by Anne Blondlot and Claude DesJarlais, not to mention their revision efforts, in which they were ably aided by Robert Siron.

The publication of this document and its English-language translation would not have been possible without the financial support of the members of Ouranos, and to them we are also indebted.

Executive Director,

André Musy

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PRINCIPAL CONCLUSIONS

In Quebec, climate change will have major impacts on the built environment, economic activities, the population and the natural environment, and the magnitude and costs of these impacts will probably increase as time goes on.

1. Already, several climatic changes can be observed.

In recent decades, Quebec's climate has evolved in significant ways. Daily mean temperature in the South of Quebec has increased by 0.2°C to 0.4°C per decade, this warming being greater for minimum than for maximum temperatures. The temperature increase was also reflected in a shorter frost season, an increase in the number of growing degree-days, and a reduction in the number of heating degree-days.

There has also been a noticeable increase in the number of days with low-intensity rain and changes in snow precipitation, which has decreased in the South of Quebec and increased in the North.

2. Greater anticipated changes in the North and in winter.

In general, the climate will warm up throughout Quebec, and more markedly in winter than in summer. This means that by the time horizon of 2050, temperatures will have increased by 2.5°C to 3.8°C in the South of Quebec and by 4.5°C to 6.5°C in the North. In summer, the temperature will increase by between 1.9°C and 3.0°C in the South and between 1.6°C and 2.8°C in the North.

Increases in winter precipitation — by 16.8% to 29.4% in the North and 8.6% to 18.1% in the South — are expected by the 2050 time horizon. Greater winter precipitation will lead to an increase in snow accumulation on the ground in the North. In the South of Quebec, however, it is expected that less snow will accumulate, due to warmer temperatures and a shortened frost season. In the summer, precipitations will increase by between 3.0% and 12.1% in the North, while in the South, no significant change in precipitations is expected.

3. Climate change will have a direct impact on infrastructure throughout Quebec.

In Quebec`s Arctic, the rapid and marked increase in temperatures will accelerate the melting of the permafrost, which will expose infrastructure and buildings to the risks of subsidence and buckling. The airport runways in several communities, which are essential for supplies and communication, could suffer severe damage and require more frequent maintenance.

Meanwhile, buildings and public infrastructure in the coastal areas of the Gulf of St. Lawrence and the St. Lawrence River estuary will be exposed to increased shoreline erosion. Rising sea levels, reduced ice-field, the geomorphology of certain coastlines, and changes in the storm regime will combine to intensify the natural processes of erosion.

In the South, an increase in the frequency, intensity and duration of extreme climate events such as precipitations represent increased risks to aging infrastructures. The replacement or refurbishment of these infrastructures is the ideal time to adapt their construction for the climate of the future.

4. Climate change will have a direct impact on several economic activities, with consequences both positive and negative.

Forest harvesting, hydroelectricity generation, agriculture, tourism and several other sectors will be affected directly by changes in temperature and precipitations. In many cases, climatic changes and their indirect effects such as outbreaks of pests and forest fires or low water levels will have negative impacts on the activities that lie at the very heart of the economic well being of many Quebec communities. In addition, recent weather events have taught us that communities both urban and rural are profoundly dependent on infrastructure to supply water, energy and transport, and these are all exposed to the vagaries of climate. Conversely, there are positive aspects to certain climate modifications — for example, increased hydro-energy potential, reduced demand for heating and gains in plant life productivity — that could benefit the Quebec economy.

5. Climate change represent a challenge for human health.

Climate change will have numerous and varied impacts on human health. These range from the direct effects of average warming and urban heat islands, air pollution, forest fires and wildfires, summer and winter storms and UV exposure to the indirect effects resulting from changes in the quality and quantity of water resources or in zoonotic diseases. In particular, higher temperatures associated with higher humidity levels and more frequent and intense heat waves pose significant threats to human health. A second and equally serious set of impacts is related to the effect of higher temperatures on air pollution, especially in the form of pollens, ozone and air-borne particulates.

6. Certain ecosystems are more sensitive.

The Arctic region will possibly be the most affected by the magnitude of climate change, and species that are well adapted to the extreme conditions of the region will find themselves competing with species moving from the South. Terrestrial and aquatic ecosystems have already begun to change in particular in their structure due to the degradation of the permafrost, the formation of thermokarst basins and ponds, and the expansion of shrub populations.

In the South, milder winters and warmer, more humid summers will mean increased evaporation from natural waterways, destabilizing wetlands that are dependent on the flood regime. Moreover several threatened species surviving in fragmented habitats, with poor ability to migrate, and already suffering from various stresses — will be at greater risk.

Climate change alters the dynamics of ecosystems. In some cases, this can mean the reduction of communities or the disappearance of certain populations; in other cases, populations may be able to expand their communities and extend their range. Climate change will add to the pressures on ecosystems and biodiversity already exerted by human activities. Determining the most vulnerable elements of the natural environment and putting in place adaptation measures to minimize these pressures will be indispensable if we want to help protect the natural wealth of the planet and thus preserve the ecological services on which the survival and well-being of our society depend.

7. Climate change adaptation means envisaging numerous solutions that will substantially reduce negative impacts.

Human societies have always shown a great capacity for adapting to climate variability. Consequently, they should be able to surmount the obstacles standing in the way of climate change adaptation, which depends on the following elements:

- determining and understanding the priority issues;
- acquiring and sharing the data and information required by the various players in adaptation;
- developing and implementing the best techniques and technologies;
- modifying or adapting policies, standards and organizational structures;
- being mindful of uncertainties in the course of decision-making.

Quebec possesses a great adaptive capacity, especially thanks to an ever more diversified knowledge economy. The natural environment will adapt in its own spontaneous and independent fashion, but human society has a responsibility to facilitate this process. Although adaptation is an incontrovertible option, more economic studies to determine its limits and costs are a necessity. Meanwhile, adaptation measures must be accompanied by reductions in greenhouse gas emissions to attack the problem at its source and minimize the costs of adaptation.

Photo: Alain Dumas

Introduction

In 2004, the Ouranos consortium published a first report on knowledge regarding the impacts of climate change for Quebec, and the strategies of adaptation. The report was called *Adapting to Climate Change*. At the time, research work on this vital topic was in its early days in Quebec, in most sectors.

Since then, many more research studies have been completed, a number of them thanks to the effort and participation of Ouranos. Our knowledge concerning the potential impacts of climate change is now much more precise and detailed. As a result, we now have access in most realms of concern to a preliminary assessment of the expected impacts, with a measure of the confidence level for many of them. In some fields, strategies and adaptation measures have already been developed, some of them accompanied by assessments of the monetary costs; a few have even been implemented.

More recently, the Canadian government published a document called *From Impacts to Adaptation: Canada in a Changing Climate 2007*. The chapter devoted to Quebec, which was prepared by Ouranos, provided an update on the knowledge available. Many other studies have been completed since and now seems like the right time to gather the current knowledge into a new document called *Learning to Adapt to Climate Change*, which is devoted entirely to Quebec.

This document describes the main climate changes that are anticipated and their consequences for the most sensitive sectors of Quebec society. The document's title underlines the importance of knowledge in the assessment of vulnerabilities and the development of appropriate strategies for adaption. The document is based on research efforts that for the most part were carried out within Quebec, and in most cases by researchers working at or associated with Ouranos.

Part One of this document deals with the human, economic and environmental characteristics of Quebec. It also contains the most recent temperature and precipitation scenarios, within the context of climate change, for Quebec for various time horizons. Part Two describes the anticipated impacts and the possible adaptation strategies for the built environment and various human activities, as well as the health of populations and of ecosystems and biodiversity. The conclusion, in addition to reviewing the main issues relating to climate change impacts and adaptation includes a table of examples of adaptation measures applied in Quebec communities and in various realms of activity.

PART I

Portrait of Quebec

Relief of Québec (MRNF)

The nature and magnitude of Quebec's vulnerability to climate change depend on the type and extent of those changes, but also on the attributes of its natural environment, economy and society that the projected changes in temperature, precipitation, humidity and other climate variables will affect. In this connection, it is worth reviewing the main characteristics of Quebec and the changes that are anticipated in the coming decades.

THE TERRITORY AND THE NATURAL ENVIRONMENT

The most obvious characteristic of Quebec's natural environment is the sheer immensity of its territory, which covers 1,667,441 km^2. Quebec extends nearly 2,000 km from north to south between the latitudes of 45° and 62° North, and almost 1,500 km from east to west. Its vast expanse means that Quebec contains several and very diverse climate zones and ecosystems. In the far north the vegetation consists of tundra, the soil is composed of nearly continuous permafrost, and the harsh climate is marked by strong winds. Further south, dense boreal forest predominates, covering nearly half the total territory and providing habitat to a large fauna and a great variety of bird species.

Mixed forests – a combination of deciduous and coniferous trees – cover the St. Lawrence Lowlands and are home to an even larger diversity of plant and animal species. Quebec also has a sizeable coastline, encompassing the Gulf of St. Lawrence in the east, Hudson Strait and Ungava Bay to the north, and Hudson's Bay and James Bay to the north-west. The landform of the territory is relatively flat, and rarely exceeds 900 m in altitude. In addition, thanks to its considerable river system and thousands of surveyed lakes and rivers, Quebec has – according to estimates – 3% of the planet's renewable water resource. Finally, a third of Quebec's territory lies within the watershed of the St. Lawrence, in which live 80% of the population (MRNF, 2006b).

QUEBEC'S CLIMATE AND THE PROJECTED CHANGES

Quebec's climate is in one regard typically continental, marked by large seasonal contrasts and an average variation in temperature of about 30°C between winter and summer in any given region. However, as a result of its great north-south expanse, Quebec contains both temperate climate zones and others characterized as sub-arctic and polar. Overall it is anticipated that temperature and precipitation will increase, but because Quebec is so vast, the changes will differ between the north and south, and also in terms of the seasons.

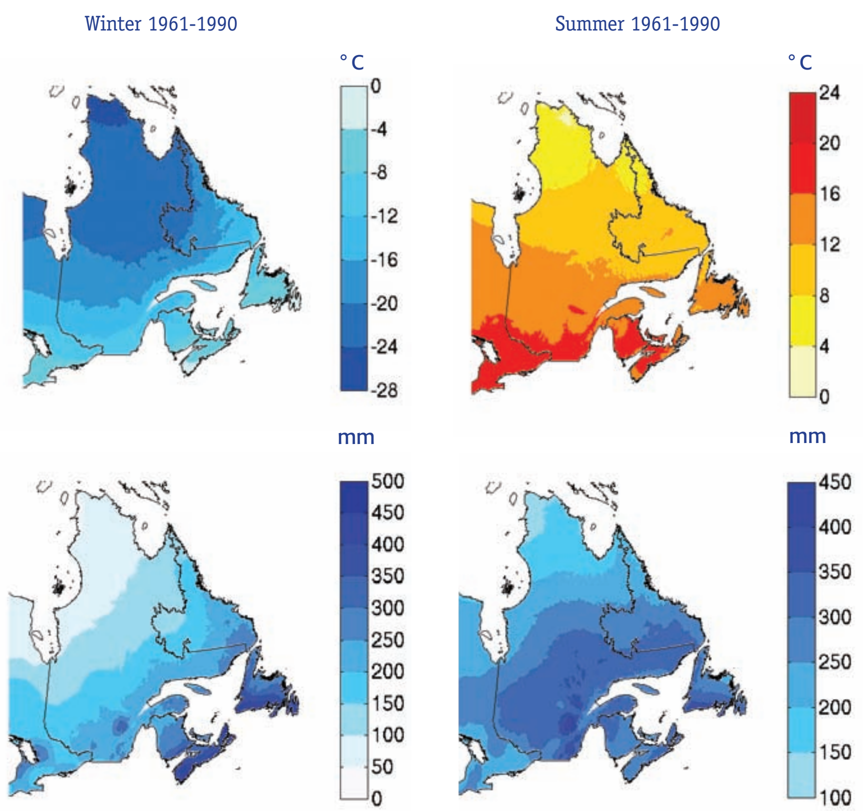


Figure 1 : Mean of observed winter and summer temperatures (above) and precipitations (below), 1961-1990, according to the databank of the National Land and Water Information Service (NLWIS) at Agriculture and Agri-Food Canada, based on weather station observations from the archives of Environment Canada, interpolated on a grid with 10 km resolution.

The climate today

In recent decades, the average summer temperature for the whole of Quebec ranged from 20°C in the South to 3°C in the North, while average winter temperatures in the South and North were -8°C and -25°C respectively (see Figure 1).

Average precipitation in summer shows a steep north-west/south-east gradient with nearly 450 mm in the South and barely 120 mm in the north. In winter, while some mountainous regions in the South received 350 mm of rain and snow in water equivalent, the far north of Quebec receives only 50 mm of snow water equivalent (see Figure 1).

In the recent past (1960-2005), the climate of Quebec has changed significantly. Daily mean temperatures in southern Quebec increased by 0.2°C to 0.4°C each decade (Yagouti *et al*., 2008). This warming was greater for average night-time temperatures than for daytime temperatures (Zhang *et al*., 2000; Vincent and Mekis, 2006; Yagouti *et al*., 2008). The increase in temperatures was also evident in related climatic variables, such as a shortened frost season, an increase in the number of growing degree-days, and a decrease in the number of heating degree-days (Yagouti *et al*., 2008).

In terms of precipitation, we have experienced an increase in the number of days with low-intensity precipitation (Vincent et Mekis, 2006) as well as changes in solid precipitation, which has diminished in southern Quebec, but increased in the North (Brown, in press).

The projected climate

According to the climate models, climate change will involve both changes in the average temperatures and average precipitation and modifications in their distribution, especially for certain extreme values.

In general, the temperatures throughout the territory of Quebec is expected to rise, and more so in winter than in summer (Christensen *et al*., 2007, Plummer *et al*., 2006). This means that by the winter of 2050 (see Table 1), temperatures will have increased by from 2.5°C to 3.8°C in the southern part of Quebec and by 4.5°C to 6.5°C in the North. By the summer of 2050, temperatures would be higher by 1.9°C to 3.0°C in the South and by 1.6°C to 2.8°C in the North.

Increases in precipitation — from 16.8% to 29.4% in the North and from 8.6% to 18.1% in the South — are expected in the winter season by 2050. This increased winter precipitation would bring about an increase in snow accumulation on the ground in the North. In contrast, central and southern Quebec would experience a decrease in the amount of snow on the ground. In the summer, precipitation in the North could increase by 3.0% to 12.1% while in the South, little change in precipitation is expected.

The ensemble of regional simulations (at a resolution of about 45 km) produced by Ouranos enable us to create a picture of the resulting climate by 2050. As shown in Figure 2, in winter, the temperature in the coldest regions would be around -19°C, while in the South, we can expect average winter temperatures of -4°C. In the summer season, the average temperature could range from 23°C in the South to 5°C in the North.

As for precipitation, the climate by the 2050s is expected to bring a total of 150 mm of precipitation to the North in the summer, while in the South, summer precipitation would remain at about 450 mm in the more humid mountainous regions. In winter, the far north of Quebec could receive 65 mm of snow water equivalent, and the South could accumulate 380 mm of precipitation (see Figure 2).

Thus, although the relative increase in precipitation will be greater in the North than in the South (see Table 1), the south-east/north-west precipitation gradient will remain very pronounced.

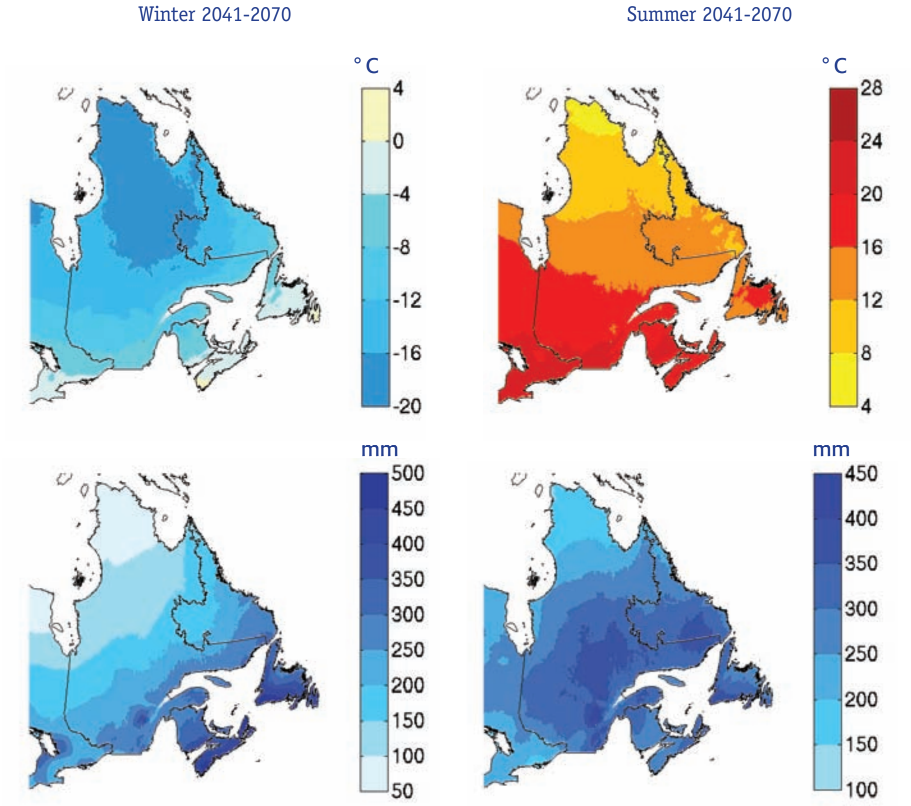


Figure 2 : Scenarios of winter and summer temperatures (above) and precipitations (below) for 2041-2070. The scenarios are based on 1961-1990 climatological normals from NLWIS data, and applying the projected mean seasonal changes (2041-2070 vs 1961-1990) from an ensemble of 17 simulations using the Canadian Regional Climate Model (CRCM) (from Elía and Côté, 2009).

The changes in temperatures and precipitation have to be considered in combination in order to elucidate some of the variables of interest for assessing the impacts of climate change. This is certainly the case regarding changes in snow accumulation, which is of major significance in terms of hydrology, the natural environment, and winter road serviceability in Quebec. As Figure 3 shows, despite the increased winter precipitation throughout the territory, it is projected that by 2050, the accumulation of snow on the ground in the extreme south of Quebec will decline as a result of the abbreviated cold season. On the other hand, in the North, a significant increase in winter precipitation is projected, which would create a greater accumulation of snow despite higher temperatures.

Although global climate models do not have as high a spatial resolution as the regional models used earlier in the section, their analysis is useful because the very large ensemble of simulations available provides us with a greater range of uncertainties in considering several greenhouse gas emission scenarios. Table 1 shows the seasonal changes in temperatures (°C) and precipitation (%) projected for three time horizons for 4 Quebec regions (these regions are shown in Figure 4).

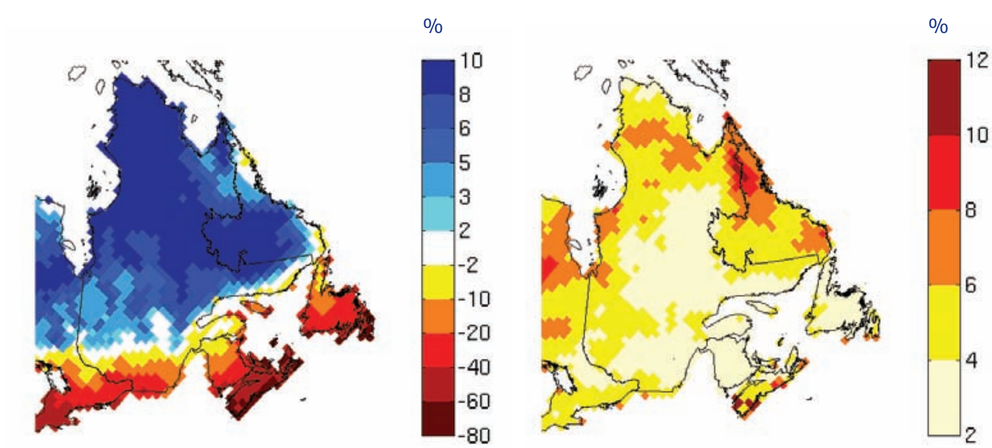


Figure 3 : Mean change (left) (2041-2070 vs 1961-1990) and standard deviation of changes (right) of the snow water equivalent (SWE) accumulated on the ground in March. The changes were estimated using an ensemble of 5 CRCM simulations driven by 5 different simulations of the coupled global climate model (CGCM3) and the A2 (SRES A2) scenario of greenhouse gas emissions.

NORTH				
Season		Changes by 2020	Changes by 2050	Changes by 2080
Winter	Temperature	2.4 to 4.0 °C	4.5 to 6.5 °C	5.8 to 9.5 °C
	Precipitation	6.2 to 17.9 %	16.8 to 29.4 %	24.0 to 43.8 %
Spring	Temperature	1.1 to 1.9 °C	1.9 to 3.3 °C	2.8 to 5.4 °C
	Precipitation	2.2 to 11.8 %	6.3 to 19.0 %	12.1 to 29.4 %
Summer	Temperature	0.9 to 1.7 °C	1.6 to 2.8 °C	2.1 to 3.6 °C
	Precipitation	1.6 to 8.2 %	3.0 to 12.1 %	5.8 to 17.9 %
Fall	Temperature	1.2 to 2.3 °C	2.3 to 3.7 °C	2.8 to 4.6 °C
	Precipitation	5.5 to 12.0 %	9.8 to 20.1 %	16.2 to 29.5 %

CENTRAL				
Season		Changes by 2020	Changes by 2050	Changes by 2080
Winter	Temperature	1.8 to 2.9 °C	3.5 to 4.9 °C	4.5 to 7.1 °C
	Precipitation	5.6 to 14.3 %	12.0 to 22.9 %	19.7 to 35.5 %
Spring	Temperature	1.0 to 1.7 °C	1.8 to 3.0 °C	2.4 to 4.7 °C
	Precipitation	3.6 to 9.6 %	7.0 to 14.3 %	12.6 to 26.0 %
Summer	Temperature	0.9 to 1.8 °C	1.8 to 3.0 °C	2.3 to 4.1 °C
	Precipitation	0.4 to 5.2 %	1.1 to 6.9 %	3.4 to 9.3 %
Fall	Temperature	1.1 to 2.0 °C	2.1 to 3.2 °C	2.6 to 4.3 °C
	Precipitation	1.5 to 7.6 %	4.5 to 13.1 %	9.7 to 18.5 %

MARITIME				
Season		Changes by 2020	Changes by 2050	Changes by 2080
Winter	Temperature	1.4 to 2.2 °C	2.5 to 3.8 °C	3.4 to 5.0 °C
	Precipitation	2.8 to 9.7 %	6.5 to 5.4 %	12.6 to 22.9 %
Spring	Temperature	0.8 to 1.5 °C	1.6 to 2.7°C	2.2 to 4.1 °C
	Precipitation	0.3 to 8.1 %	3.1 to 11.5 %	8.8 à 18.5 %
Summer	Temperature	0.9 to 1.6 °C	1.7 to 2.7 °C	2.2 to 3.8 °C
	Precipitation	-1.9 to 5.2 %	-1.4 to 5.7 %	-4.0 to 7.1 %
Fall	Temperature	1.1 to 1.6 °C	1.9 to 2.8 °C	2.3 to 4.1 °C
	Precipitation	-2.8 to 3.6 %	-2.0 to 7.1 %	-0.9 to 10.1 %

SOUTH				
Season		Changes by 2020	Changes by 2050	Changes by 2080
Winter	Temperature	1.3 to 2.3 °C	2.5 to 3.8 °C	3.6 to 5.7 °C
	Precipitation	3.7 to 11.1 %	8.6 to 18.1 %	14.5 to 27.6 %
Spring	Temperature	1.0 to 1.7 °C	1.9 to 3.0 °C	2.7 to 4.3 °C
	Precipitation	2.0 to 8.6 %	4.4 to 13.1 %	8.9 to 22.2 %
Summer	Temperature	1.1 to 1.7 °C	1.9 to 3.0 °C	2.6 to 4.4 °C
	Precipitation	-1.5 to 4.4 %	-1.8 to 5. 4 %	-4.9 to 6.0 %
Fall	Temperature	1.2 to 1.9 °C	2.0 to 3.1 °C	2.7 to 4.5 °C
	Precipitation	-2.7 to 3.6 %	-0.7 to 7.7 %	0.4 to 12.8 %

Table 1 : Seasonal changes in temperature and precipitation for 4 Quebec regions based on the results of an ensemble of 126 global climate simulations. The changes were calculated in relation to 1961-1990 climate; the values correspond to the 25th and 75th quantiles of projected changes. The ensemble included 3 greenhouse gas emission scenarios (SRES A1B, A2 and B1), 20 global climate models (GCMs) and several combined simulations (GCM/SRES) (Meehl *et al.*, 2007).

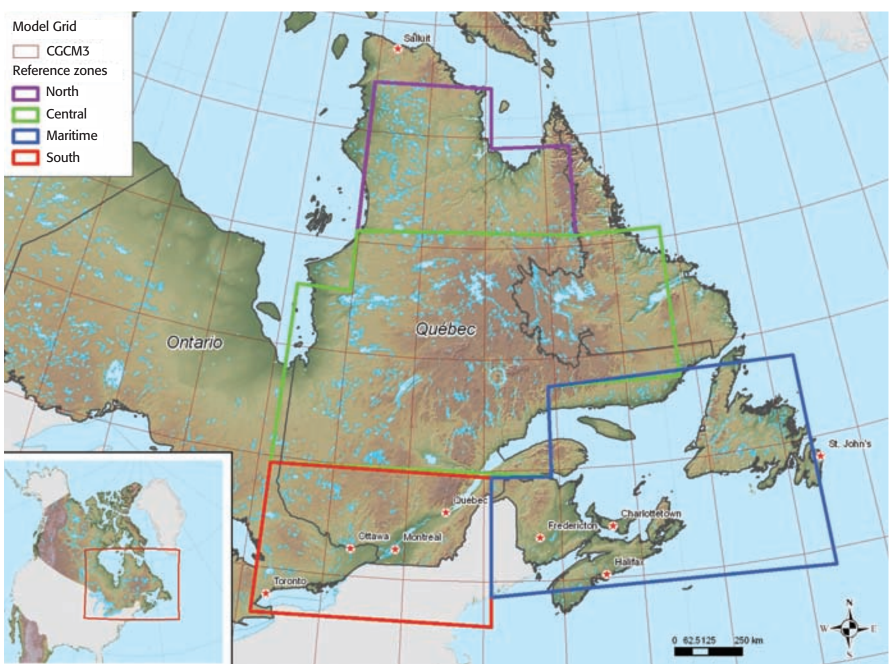


Figure 4: Boundaries of the 4 zones described in Table 1.

By and large, when there is a change, it becomes more pronounced over time, as does the associated range of uncertainty. On the other hand, when there is no change, this persists to the 2080 time horizon. For example, in northern Quebec in winter, the temperature is expected to rise between 2.4°C and 4.0°C by around 2020 and these increases would be as much as 5.8°C to 9.5°C by 2080; the projected range of changes, based on 50% of available global simulations, is between 1.6°C and 3.7°C. In contrast, in southern Quebec in summer, the ensemble of projections suggests that the quantity of precipitation will change very little.

Changes in variability and climate extremes

The anticipated changes in climate averages may well be accompanied by changes in variability and the range of extremes. Figure 5 shows the simulated distribution of daily mean temperatures for the recent past and the projections for the 2041-2070 time horizon based on an ensemble of 5 regional simulations using the Canadian Regional Climate Model (CRCM).

These distribution curves show that changes in variability will differ depending on regions and seasons. As we can see in Figure 5, in winter, both the South and the North would experience higher averages and diminished variability. In the summer, the South would see an increase in variability while in the North, only the averages will change. The reduction in standard deviation of winter distribution results mainly from a lower frequency of intense cold while extreme high temperatures in winter will increase slightly. On the other hand, in summer, in the South, the distribution tail shifts farther to the right, which indicates a more significant increase in the frequency of days with very high temperatures.

As for changes in the distribution of precipitation, the results published by Mailhot *et al*. (2007b) indicate a lengthening of the season conducive to thunderstorms as well as an increase in intense rainfall events. These changes will occur even in regions where the average precipitation remains unchanged.

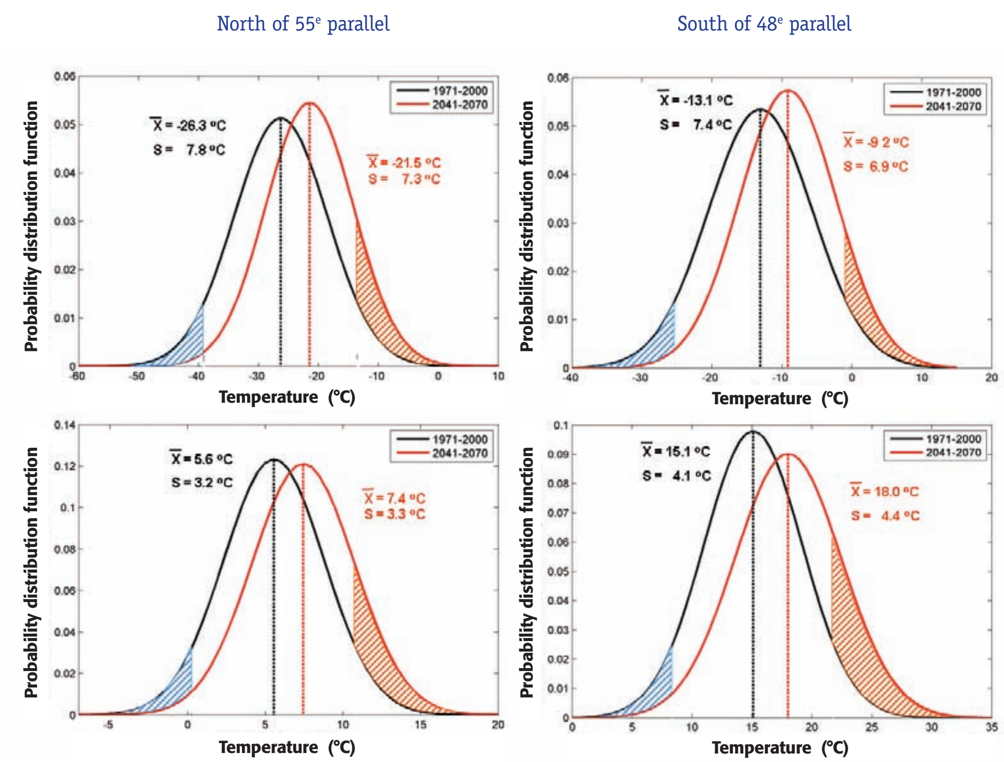


Figure 5: Winter (DJF; above) and summer (JJA; below) probability distribution of daily mean temperatures simulated for the current climate (1971-2000) and projected for 2041-2070 from an ensemble of 5 CRCM4.2.3 simulations driven by 5 different CGCM3 simulations using the A2 scenario. The cross-hatched areas represent the 10th and 90th percentiles based on current climate. $\bar{X}$ and S refer to the mean and the standard deviation respectively.

THE POPULATION

The population of Quebec has reached 7.7 million people (2006). Most of this population (82%) is concentrated in the southern part of the territory and along the St. Lawrence River. In the other regions (18% of the population), the economy depends largely on the exploitation of natural resources. Quebec is relatively urbanized, with 75% of the population residing in 73 towns with populations of 10,000 or more, of which 54% reside in cities with more than 100,000 inhabitants – Montreal, Quebec City, Lévis, Gatineau, Sherbrooke, Laval, Longueuil, Saguenay and Trois-Rivières. Rural areas, which account for 80% of the inhabited territory, are home to 1.6 million people (22% of the population) spread across nearly 1,000 communities. As for the aboriginal population, it comprises around 87,000 individuals (77,000 Amerindians, 10,000 Inuit) (Secrétariat aux affaires autochtones, 2007).

According to the most recent reference scenario from the Institut de la statistique du Québec, the population will have grown from 7.7 million in 2006 to nearly 9 million in 2056 (see Figure 6). A less favourable demographic situation would see the population levelling off at nearly 8.3 million people in 2029, followed by a decline that would result in an estimated 7.7 million people in 2056. On the other hand, high population growth could bring the number to 11 million by 2056.

Eleven of Quebec's 17 administrative regions should continue to grow until 2031. The Lanaudière and Laurentides regions are likely to see the greatest growth (38% and 34%, respectively), with the notable result of increased demand for water resources.

In 2031, the Montreal administrative region would still be the most populous, with 2,101,000 inhabitants, or 227,000 more than in 2006. The other regions, meanwhile have already experienced some population decline or will do so by the year 2031 (between -1.3% and -12.0%), with internal migration to the large centres playing an important role. An exception is Northern Quebec, which includes Nunavik, and where the population is likely to increase considerably by 2031. These variations in regional population changes may aggravate land occupancy problems resulting from climate change, especially in the North where it will be even more difficult to find suitable land on which to build.

The dramatic growth in the number of seniors throughout Quebec is another conspicuous phenomenon (see Figure 7). In 2031, the number of people aged 65 and older could surpass 2 million, and make up 20% of the population in all regions except Northern Quebec and more than 30% in the Bas-Saint-Laurent and the Saguenay–Lac-Saint-Jean regions. By comparison, in the Mauricie, the region with the highest average age in 1996, less than 15% of the population was 65 and older. Thus, we would see a growing proportion of the population in the age group that is potentially most vulnerable to climate change.

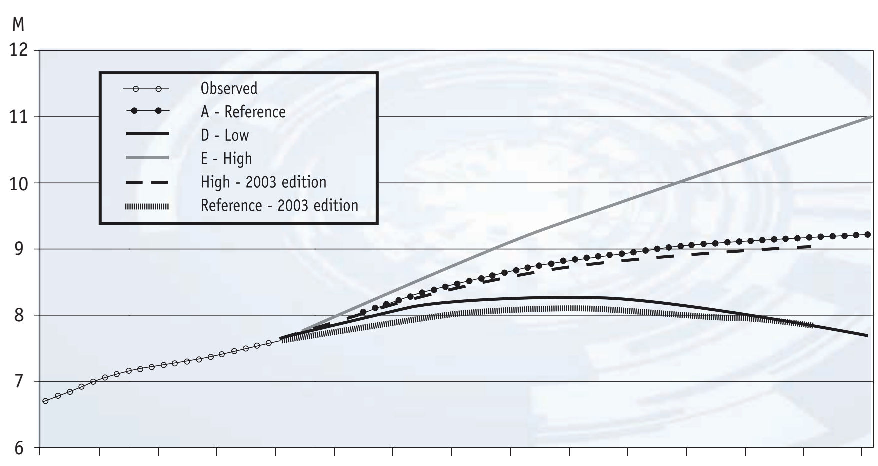


Figure 6:
Scenarios of Quebec population growth in millions, by 2056 (ISQ, 2009a).

All of these changes would have implications for the vulnerability of society, and especially for Quebec's ability to finance the ever growing demand for health services (Godbout *et al*., 2007). This aging of the population has to be analyzed in combination with the changes in the health status of the Quebec population, which, according to the Institut national de la santé publique du Québec (INSPQ, 2006), is changing in a positive direction in the different administrative regions of Quebec. In essence, most socio-economic and health indicators show a gradual and constant improvement in health, the opposite of their earlier report which showed a potential increase in the number of individuals at risk for various reasons (sedentary lifestyle, overweight, elderly people living alone).

A final observation is that the number of households is expected to increase more rapidly than the population, bringing a progressive shrinking of household size, and stabilizing at 4.2 million around 2046 (ISQ, 2009a).

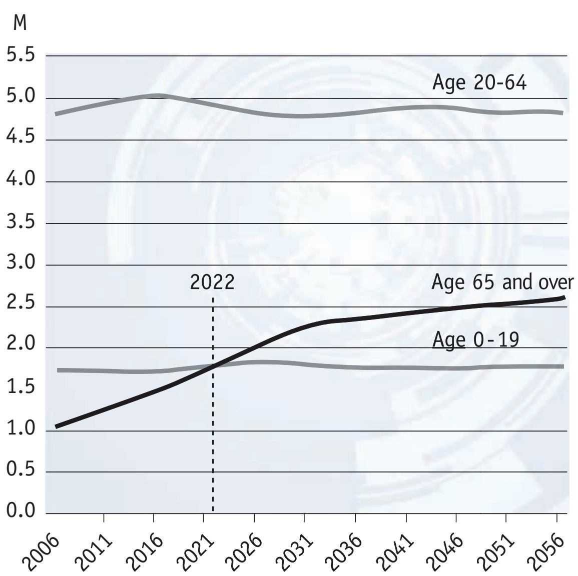


Figure 7:
Evolution of different age groups of the population, in millions, scenario A – Reference, Quebec, 2006-2056 (ISQ, 2009a).

THE ECONOMY

The gross domestic product (GDP) of Quebec stood at close to $278 billion in 2007 (see Table 2), making it the 44th largest in the world. The economy is highly diversified, ranging from production of commodities from natural resources to high technology goods, financial services and products of the cultural industries. The economy is also heavily oriented towards external trade, with a relatively high ratio of imports and exports to the rest of Canada and other countries.

This makes Quebec particularly sensitive to changes that its trade partners undergo, and these trade partners would also be affected by climate change. The per capita production of goods and services in Quebec is among the highest in the world, which means that it is endowed with significant technical and financial resources to address the potential impacts of climate change.

The economy is heavily skewed towards the service sector. Indeed, this sector (the tertiary sector), comprised of commercial and financial activities, health and education, recreational activities and public administration, makes up close to 70% of GDP, as against 30% for the production of goods (primary and secondary sectors) (ISQ, 2009b). All indications are that the tertiary sector will continue to grow, especially due to growth in knowledge-based industries, recreation and tourism, and health services.

The current structure of the Quebec economy suggests that overall, the economy is only moderately vulnerable to climate change. Basically, the most vulnerable sectors to climate change are the agricultural, forestry, and hunting and fishing industries, and in 2007, these represented only 1.6% of GDP. However, one should also consider electricity production, which is grouped with public services, and represents 4% of Quebec's GDP. This production being 96% hydroelectric, it is obviously highly sensitive to climate variations.

Strong growth in hydroelectricity production is expected through the coming decades. Likewise, it is expected that wind energy production, already in rapid development, will grow in capacity from 100 MW to 4,000 MW by the year 2015 (MRNF, 2006a).

Table 2: Gross domestic product at base price for various economic activities in Quebec, 2002-2007, in millions of dollars (ISQ, 2009b).

	2002	2003	2004	2005	2006*	2007*
ECONOMIC ACTIVITY						
Industry and production of goods						
Agriculture, forestry, fishing and hunting	4,173	4,376	4,818	4,400	4,184	4,449
Mining and oil and gas extraction	1,232	1,410	1,645	2,012	2,285	2,673
Public services	9,479	9,936	9,695	10,108	10,709	11,249
Construction	11,183	11,859	13,598	13,747	14 479	16,501
Manufacturing	47,482	46,279	48,243	47,879	48,204	48,827
Service industries						
Wholesale trade	11,365	12,025	12,896	13,13 3	13,823	14,883
Retail trade	13,325	14,239	14,926	15,682	16,601	17,291
Transport and storage	9,589	9,944	10,177	10,776	11,330	11,586
Information and cultural industries	8,912	9,027	9,167	9,571	10,191	10,943
Finance, insurance, real state and rental services business management	36,513	38,264	40,774	42,198	44,660	47,185
Professionnal, scientific and technical services	9,141	9,913	10,546	10,916	11,753	12,336
Administration and support services, waste and sanitation management	5,659	6,132	6,413	6,878	7,440	7,921
Education services	11,789	12,315	12,674	12,916	13,504	14,377
Health care and social assistance	16,244	17,404	18,245	18,999	19,731	21,955
Arts, entertainment and recreation	2,478	2,642	2,735	2,754	2,945	3,144
Accommodation and restaurant services	4,944	5,259	5,659	5,994	6,273	6,541
Other services, except public administration	5,784	6,072	6,356	6,709	7,095	7,618
Public administration	14,559	16,884	16,625	16,978	17,682	18,489
Gross domestic product at base price	**223,850**	**232,980**	**243,389**	**251,650**	**262,789**	**277,967**

* estimate

The manufacturing sector also includes a number of industries that might be affected by climate change, to the extent that they are based on the transformation of natural resources. Among the most vulnerable are agri-food industries and wood processing. The latter industry represents close to 3% of Quebec's GDP and a significant proportion of its exports.

Service industries are a priori less sensitive to climate change, with the exception of the tourism and recreation industry (lodging and food services), where demand is based partly on climate, and health services, which may suffer from the impact of climate change on public health. The insurance industry falls into this group as well, because of the increasing number of events with violent winds or heavy precipitation that result in increased damages and claims.

However, this overall picture hides some deep regional differences. In some regions, a significant proportion of direct jobs (12% to 20%) will continue to be offered by the agriculture, forestry, hydroelectricity, mining and natural resource industries. In total, several hundred communities will continue to depend directly on the exploitation of one or more local natural resources – and these may be more seriously affected by climate change.

Obviously, this portrait of the Quebec economy may change dramatically over the coming decades. Based on current demographic trends and labour productivity, Quebec would experience sustained economic growth and could double its output over the next 50 years (MFQ, 2005).

Households and individuals could also see substantial increases in revenue, which would result in higher disposable income to meet their needs. Increased schooling and urbanization are also anticipated (ISQ, 2003). Regionally, demographic changes could create some significant differences in terms of total and per capita economic growth in tandem with the effects of differential growth in the resource industries in comparison with other economic sectors.

Meanwhile, the evolution of international trade, (trade agreements, growth of emerging economies), changes in technologies (new products, improved production processes) and in the availability and cost of supplies, could also have considerable impacts on the various production activities of goods and services. In this context, even though it might be possible to evaluate overall changes in the economy for the mid-term, it is very risky to make any pronouncement on the future situation of a particular industry (for example, pulp and paper, wood processing, agro-processing) and on the effects that climate change might have on the size or nature of these activities in 50 or 100 years.

Demographic and sociocultural changes will produce noticeable impacts on the demand for goods and services, such as a higher demand for health services from an aging population, or greater recreational demand among the retired, in combination with increased technological means for meeting these needs. In sum, the socio-economic context will be very different than it is now.

THE SOCIAL EVOLUTION

In addition to the actual physical and economic impacts which are easier to measure their real values will be influenced by changes in social preferences and perceptions. Significant socio-economic gains, the growing level of education, increasing sensitivity to the value of the environment, better information and growing awareness of the complexities of the issues will increase the evaluation of those impacts and influence the decisions concerning adaptation enabling us to cope with them. (Bryant *et al*., 2007).

It is clear that Quebec society will in future be far more concerned with the quality of the environment, as evidenced by the many governmental policies and decisions in recent decades on matters related to waste management, energy, water management and sustainable development. In particular, in 2006 Quebec established the 2006-2012 Climate Change Action Plan (MDDEP, 2006b) and adopted the Sustainable Development Act (MDDEP, 2006a).

Although it is hard to predict exactly how much consideration will be given to environmental issues in the future, it seems clear that there is a heightened awareness of the ecological benefits of the environment to society, increasing its value.

The Inuit of Nunavik and the First Nations people in other regions maintain a relationship with the natural environment that is closely intertwined with community identity and the foundations of their cultures. In these communities, fishing and hunting are of great consequence both economically and culturally. These populations, which in many cases are experiencing strong growth, are grappling with major adjustments brought about by economic development and technological and communications changes. Climate change will add yet another dimension to the panoply of changes that these societies are trying to accommodate.

At another level, the proportion of Quebec's population that lives in precarious socio-economic circumstances is not negligible (INSPQ, 2006). This population, which is concentrated in the large cities, faces particular challenges in terms of climate change, especially because they are vulnerable to heat waves. The progress made over the coming decades to reduce the number of low-income individuals through different revenue support and aid measures will have a direct impact on this kind of vulnerability.

THE BUILT ENVIRONMENT

The built environment in Quebec has undergone astonishing growth since the early 20th century. This is due to urbanization, increased wealth, technological developments, population growth and urban expansion, and the growing complexity and interdependence of socioeconomic activities. Because the built environment is generally exposed to climate, its vulnerability is expressed in terms of critical cost/risk thresholds. These are established on the basis of historic climate data, mostly from recent decades, and on the assumption of a stationary climate. The non-stationarity involved in climate change is likely to change the effectiveness, life-span and structural safety of buildings and infrastructure.

The built environment is composed of diverse types of infrastructures and buildings such as transportation infrastructure — land-based (road, rail), maritime, and air traffic — and the infrastructures connected to water resources — dams, canals and ports. Other infrastructures are connected to energy and geology, making it possible to exploit natural resources. Municipal infrastructures are essential for water treatment and distribution, managing surface water, and waste management. Many buildings, whether publicly or privately owned, supply various services to the population. Seawalls and similar installations, sometimes considered as essential infrastructures, serve to safeguard populations, socioeconomic activities, and the natural and built environment.

In recent years, a great deal of attention has been devoted to the problems of aging infrastructure, especially in the municipalities, where some have outlived their useful lifespans (Infrastructure Canada, 2004; Villeneuve *et al*., 1998). In this context, new infrastructure needs and the refurbishment of existing infrastructures are and will continue to be of great concern, and the massive investments anticipated and forecast for the coming decades have already been set in motion (Statistics Canada, 2006). Climate change will only add to the needs for infrastructure repair to the extent that these infrastructures cannot meet the service life for which they were designed. These trends seem to indicate that integrating new climate data and/or new approaches, when relevant, at the moment of designing or refurbishing infrastructure is an important consideration when it comes to the future vulnerability of Quebec's built environment.

PART II

Vulnerabilities, impacts, and adaptation options

INTRODUCTION

Our world is sensitive to climate change in multiple ways, both directly and indirectly. This sensitivity varies by region, population groups, natural environments and the structures of the local economies. Likewise, people and ecosystems have different capacities for adaptation, depending on the region of the world or the structure and wealth of the economy. Some countries will be at a far greater disadvantage than others.

Like other parts of the world, Quebec will experience both positive and negative impacts from climate change. As the following pages will show, the projected impacts depend in large part on the time horizon under consideration – 2020, 2050, 2080 or 2100 – and the greenhouse gas scenario considered. But basically, the longer the timeline and the greater the concentrations of greenhouse gases, the greater the impacts will be; and some impacts that in the short term are slightly positive will become, over time, extremely negative.

The following pages describe the expected impacts, based on the research findings to date, of climate change for Quebec as well as adaptation measures that might be implemented. These impacts and adaptation measures fall into four general areas: impacts on the built environment, on economic activities, on human populations and on natural systems.

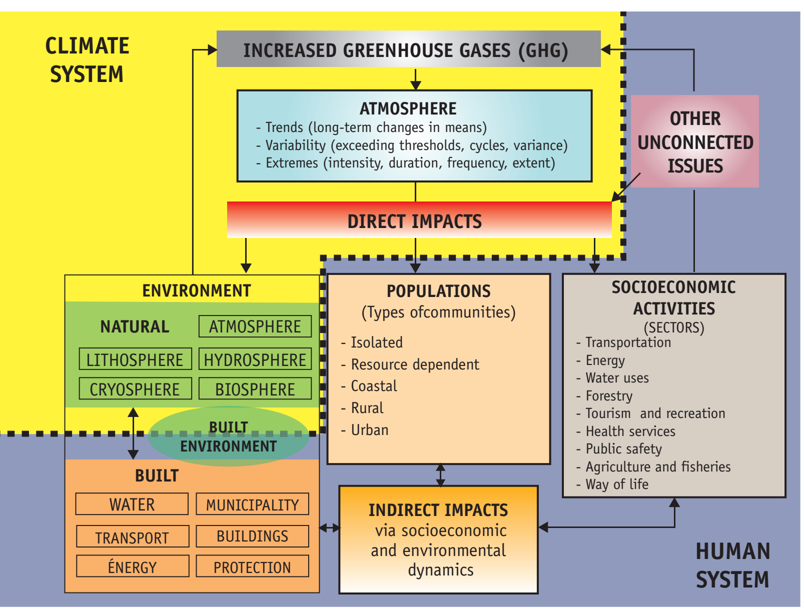


Figure 8: Direct and indirect impacts of climate, its variability and extremes on the natural and built environment, populations and socioeconomic activities.

- The first category includes impacts on the built environment, comprised of residential and non-residential buildings and both public and privately-owned infrastructures. These buildings and infrastructures were designed for particular climatic conditions, and changes to these conditions compromise their capacity for meeting their intended purposes and – in some cases – the safety and wellbeing of populations. Quebec's Arctic and coastal areas are particularly vulnerable in this regard. Rising temperatures in the Far North will cause the thawing of the permafrost, on which many buildings and infrastructures have been constructed. Meanwhile, coastal erosion will increase due to rising sea levels and reduced protection from winter ice and threaten infrastructures and buildings over a vast area. All the infrastructures in southern Quebec are likely to be affected also, especially due to changes in temperature and precipitation regimes.

- The second area of concern relates to the impacts on economic activities that could bring changes in productivity, demand, and the price of goods and services. In this regard, Quebec is slightly more sensitive to climate change than some other parts of the developed world where the economy is not so closely tied to climate. This is mainly due to the predominance of hydroelectricity production, which provides about 96% of the electricity supply in Quebec and is entirely dependent on precipitation in the form of rain or snow. For Quebec, any increase or decrease in the water balance will mean either significant gains or increased costs. Also because energy demand for heating and air conditioning represents a significant proportion of total costs for both households and businesses in Quebec, climate warmingwill influence the demand for all forms of energy bylowering heating needs and increasing the need for air conditioning.

Management of water resources, meanwhile, will play a central role in the magnitude of climate change impacts. The water supply is a key element in the adaptive capacity of several economic activities in the face of climate change, especially agriculture and tourism; moreover, it is critical to human health and the maintenance of ecosystems.

Other industries are also largely dependent on climate, including forestry, agriculture, as well as hunting and fishing. Meanwhile, various processing industries, including agri-food, the timber industry, metal fabrication, and the pulp and paper industry, could be affected indirectly by changes in the availability of resources and procurement costs.

In addition to resource-based industries, several service industries are sensitive to climate change, especially tourism – which could benefit or suffer depending on its capacity to adapt to changing conditions. Likewise, health-care services and facilities will be faced with new needs. Other sectors will also have to adjust, such as road and marine transport as well as the insurance industry.

In sum, a significant portion of the Quebec economy will be affected directly or indirectly. The repercussions could be even more significant in resource-based and rural communities where the economy centres more on industries that are climate-dependent, such as forestry activities, tourism, hunting, fishing or agriculture. Thus, the impacts of climate change will be felt unevenly throughout the territory, and in some communities, the capacity to adapt effectively to a new climate context could mean both a challenge and possibly a new source of wealth.

The sectors that will experience the most direct impacts are discussed in greater detail in later sections.

- The third area where climate change impacts are of concern involves public safety and the health and well-being of Quebec's citizens as well as its ecosystems. Extreme climate events such as droughts, intense rainfall, storms, cold spells and heat waves represent real dangers to health and even survival in various groups, especially the most vulnerable among us.

Finally, the integrity of the natural environment is likely to be affected by the rising number of extreme climate events, as well as by changes in average temperature and precipitation. Again, it will be the most vulnerable species, already at the margins of their natural ranges, that will be highly affected.

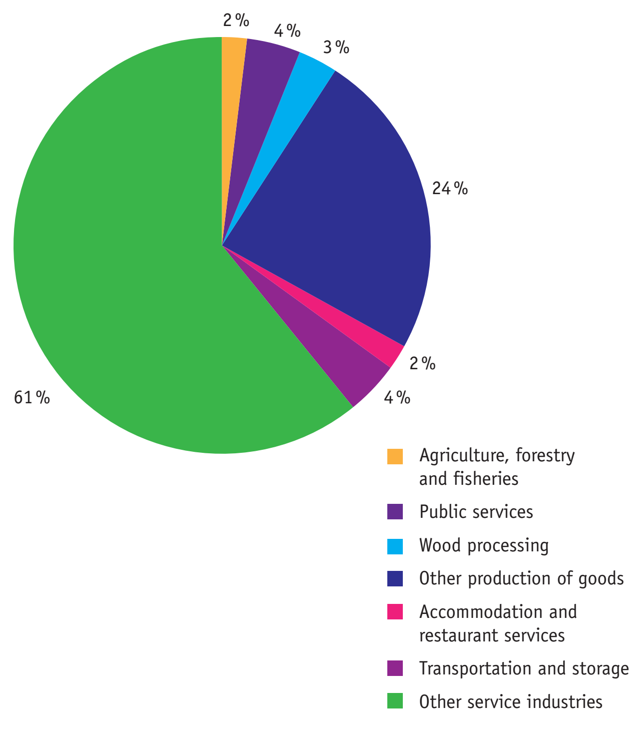


Figure 9: Percentage of the GDP of various economic activities that are sensitive to climate change, from Quebec 2007 GDP, at base prices (ISQ, 2009b).

BUILT ENVIRONMENT

The North

The territory of Nunavik lies north of the 55th parallel, and its polar climate regulates the dynamics of the physical and human environment. Winter lasts 9 to 10 months of the year, so that snow and ice dominate the landscape for much of the year, and this has had a profound effect on the traditional way of life of the indigenous people. Quebec is the only one of the 10 Canadian provinces with an Arctic environment in its territory. The treeline cuts across Nunavik, and north of it stretches the tundra. The soil, often rocky and stony but with areas of finer materials, are mostly frozen permanently: this is the permafrost. The abundant fauna is composed of large populations of animals, including the largest caribou herds in the world. A great number of lakes and major rivers spill into the territory's three watersheds (Hudson's Bay, Hudson Strait and Ungava Bay) and are home to significant ichthyic populations, including the salmonidae – among which is the Arctic char (*Salvelinus alpinus*), a species closely intertwined with Inuit life. The population, predominantly Inuit, is distributed among 14 coastal communities (see Figure 10) where infrastructures are also concentrated.

In three generations, the northern communities have seen rapid demographic growth, and socioeconomic activity has been dramatically transformed. In earlier times, these activities revolved around a traditional way of life, but now, only a few traditional activities (subsistence harvesting, hunting and fishing, fur sales on the international market) play an important role in the local economy.

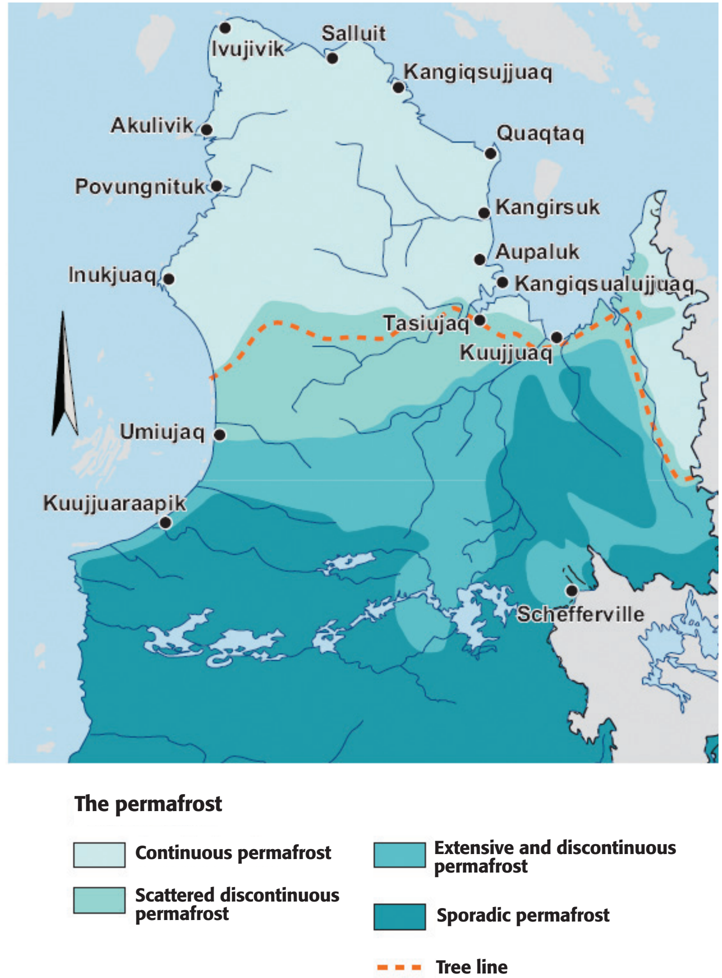


Figure 10: The permafrost (Allard and Seguin, 1987).

Environmental impacts

In tandem with recent climate change, the temperature of the permafrost at depths of 4 m and 20 m throughout the territory increased by an average of 1.9°C and nearly 1.1°C respectively between 1994 and 2007 (Allard *et al.*, 2008). As one can imagine, this warming of the permafrost has led to a significant increase in the depth of the active layer, which is the topmost layer of soil that thaws in the summer (Allard *et al.*, 2002a).

Already, the Inuit have reported substantial changes in their environment, and even experienced hunters say that they find it difficult to predict weather conditions or the condition of the snow or the sea when they are traveling by snowmobile or boat (Tremblay *et al.*, 2006). These recent changes mean that traditional Inuit knowledge about local conditions no longer seems to be as reliable, and there have been numerous reports of accidents involving even experienced individuals (Nickels *et al.*, 2005).

Moreover, it is anticipated that Nunavik will undergo the most significant climate change – in absolute terms – in Quebec, particularly due to a climate feedback loop involving the snow and ice as well as the presence of Hudson's Bay to the west.

In the coming decades, the temperature increases in the North due to climate change could, by 2080, be as much as an average of 2.6°C higher in the summer and 7.0°C higher in the winter.

The transfer of heat in the soil that follows this climate warming would inevitably trigger a partial thawing of the permafrost (Lawrence and Slater, 2005). Due to the degradation of the permafrost, which has already led to some ground subsidence and the creation or expansion of small lakes known as thermokarst (Seguin and Allard, 1984), ecosystems will be seriously disrupted. Furthermore, the drainage networks in sensitive soils are susceptible to change through the drying out and expansion of wetlands and peat bogs (depending on local topographic and soil conditions) as well as from gully erosion and rill wash (Payette *et al*., 2004). Meanwhile, ongoing research indicates that the numerous small thermokarst lakes resulting from the degradation of the permafrost will begin to produce carbon dioxide and methane as a result of the biological activity that will develop in them.

Shrub populations have already begun to expand as a result of more temperate summers and the protection provided by greater snow accumulations in winter on the tundra, and this trend will continue to transform ecosystems in major ways, increasing their primary productivity, a phenomenon that will have repercussions for the animal kingdom. The natural range of animal species that normally live further south will also move northward following the pace of climate change. The impact of these changes on the behaviour of migratory populations, including caribou, Arctic char, geese, ducks, seals and whales, among others, is still unknown.

To the extent that precipitation, evapotranspiration and groundwater flow regimes are affected, the hydrological regimes of rivers will change and water temperature will increase. The deterioration of the permafrost may result in increased sediment transport in rivers, although the magnitude remains to be determined. The impact of all these changes on regional aquatic fauna will not be minor.

Socioeconomic impacts

Already in many places, the discontinuous permafrost, where the soil temperature is close to the freezing point, has become much less cold and is close to the thaw temperature. Predicted regional warming will have its first impacts at the southern margins of the permafrost, and then move progressively northward throughout the territory.

Residential, commercial and institutional buildings

Deterioration of the permafrost presents risks for a number of Nunavik communities. These risks vary depending on local geomorphology (rock masses, ice-laden granular or clay soils, thawing destabilizing factor) and the size of the structures in question. In zones where the soil is composed of ice-rich superficial deposits, the thawing of the permafrost results in soil settlement and distortions that are likely to damage infrastructure. To date, urban planning in each community has, whenever possible, taken into account the nature of the terrain. In addition, most institutional buildings (schools, hospitals) and houses are constructed on piles or trestles, which allow for air circulation under buildings and maintain the soil at a temperature close to the air temperature (Fortier and Allard, 2003a and 2003b). Nonetheless, some major infrastructures (airports, roads) are of necessity constructed partially or totally on sensitive terrain, and as a consequence, are vulnerable to permafrost degradation.

Airport infrastructure

Such is the situation with 13 community airports in Nunavik under the responsibility of the Quebec transport department (Ministère des Transports du Québec, MTQ), where the safety and integrity of the installations has become a concern (Grondin and Guimond, 2005). Already, thawing permafrost has caused settling and cracks, and produced signs of obvious deterioration for a number of runways as well as the access roads connecting the airports to the communities (Beaulac and Doré, 2005). Current maintenance measures have so far been sufficient to maintain safety; however, the increasing rate of damage and maintenance requirements, along with the greater frequency and costs of repairs, has led the MTQ and Ouranos to launch a research programme to study the characteristics of the permafrost beneath and alongside these infrastructures (thermal profiles, soil settlement, climatic conditions), to assess how the infrastructures perform in the years following their construction, to predict how this might evolve and to develop adaptation measures (Beaulac and Doré, 2005; MTQ, 2006a; Allard *et al*., 2007a).

Access to resources

In Nunavik, hunters and gatherers use mainly watercraft in summer and snowmobiles in winter to travel from one place to another. Navigable waterways and ice roads provide important access to various traditional resources obtained by hunting, trapping and fishing, berry-picking and egg gathering; they also serve as routes for people and goods to travel between the communities for economic, family, cultural and social activities. Not only are these trips critical in terms of providing food, they also serve to maintain social cohesion that is an essential part of safeguarding a culture already made fragile by various stress factors (Lafortune *et al*., 2005). Thus, new climate conditions (increased uncertainty of weather forecasts, delayed freeze-up and early break-up) which makes travel more risky will have an influence not simply on various socioeconomic activities, but will also affect the transmission of traditional knowledge, and have repercussions on individual and collective identity in a society that is already in the midst of change (Tremblay *et al*., 2006).

New activities

Nunavik is increasingly open to resource exploitation, especially in the mining sector. To some degree, climate change would facilitate this development, for example, by extending the season when the waters are navigable, which reduces the costs of transportation of minerals. On the other hand, climate change may create new conditions that are less favourable to resource exploitation; for example, thawing of the permafrost would affect surface drainage and may complicate the application of measures designed to protect the environment from contamination. Mining companies may also be obliged to take measures against environmental pollution years down the road, if it cannot be guaranteed that mining residues will remain frozen.

It is also possible that in the long term, the exploitation of the rivers into Ungava Bay for hydroelectricity production may become commercially and socially feasible; in this regard, increased precipitation and the repercussions for the hydrological regime could be advantageous. Given the high potential for wind power in the region (Environment Canada, 2007a), it is also possible to envisage the development of wind turbine systems that could complement the municipal diesel-powered generating stations in some communities, which would both serve to diversify the energy supply and reduce dependence on expensive fossil fuels, delivered by boat.

Adaptation strategies

During a workshop that took place in Montreal on October 6, 2005 on the status and condition of regional projects, participants identified education and the tools for raising awareness and disseminating information as essential means for reducing the vulnerability of regional infrastructure to climate change. Participants also stressed the importance of improving meteorological information and increasing the capacity to predict extreme events, especially blizzards, storms, and gale force winds, as well as rapid snow melt events and fog. The Inuit representatives mentioned that one of their concerns was the need for a better analysis of the impacts of climate change for their ecosystems and fauna. So far, most research has focussed on finding methods for adapting to threats to the built environment or to town planning and development, and to a lesser extent, understanding the most significant changes affecting resources and the traditional activities of hunting, fishing and gathering.

In order to reduce the potential risks for residential, commercial and institutional buildings, large-scale maps showing the condition of the permafrost in each community are an essential tool for urban planning and long-term adaptation (Allard *et al*., 2007b) (see Figure 11). Furthermore, it is important that construction standards and urban land-use plans be adapted to take climate change into account (Allard *et al.*, 2004) so that vulnerabilities do not increase.

As for consolidating and maintaining the integrity of infrastructures that must of necessity be constructed on the permafrost, various solutions are being tested or have already proven to be useful. In this regard, expanding our knowledge about the permafrost beneath this infrastructure, in combination with solutions and practices from civil engineering, will help to manage the impacts of climate change for airports, roads and buildings (Allard *et al*., 2002b). For example, the problem of heat penetrating into the fill can be counteracted by using air convection or with insulation techniques or reflective surfaces; another technique is to extract heat from the fill using thermal drains. Installing geotextiles or stabilizing and raising infrastructures at risk is another option for limiting their vulnerabilities (Beaulac and Doré, 2005). Modifying the cross profiles of runways and road fill to render them more aerodynamic serves to limit the accumulation of snow against the shoulders, which is currently the main local warming factor responsible for deterioration of the permafrost underneath these infrastructures.

From impacts to adaptation: a case study of Salluit

In support of adaptation to climate change in the community of Salluit, which is constructed on permafrost soil that is ice-rich and presenting stability problems, the CEN, the Quebec government, and Ouranos have mapped the geotechnical properties of the permafrost in a first phase of research work (Allard *et al*., 2004). The second phase is now in progress, focussing on predictive analyses of the thermal regime and of the behaviour of the permafrost that will help guide the selection of the best choices of foundations for infrastructure and buildings.

The climate scenarios produced by Ouranos using the CRCM output serve as input for simulation models of the thermal regime of the permafrost. The Quebec government also formed a technical committee to work together with the community and regional government to provide advice and guidance on community decisions for adapting to current problems and planning local development for future conditions.

The Salluit research serves as a source of technical information and as a laboratory for expertise that can be transferred to other Arctic communities confronted with climate change in combination with the needs generated by rapid demographic growth. In all these communities, current development and maintenance practices, including urban drainage, snow removal methods, road design and foundation techniques, need to be revised with a view to limiting the effects of climate change on the ground. A variety of adaptive measures from civil engineering, such as convection embankments, heat drains, reflective surfaces and changing the embankment slope, are being tested in Salluit and at the Tasiujaq and Puvirnituq (Povungnituk) airports as part of a project to evaluate the cost-effectiveness ratios given the harsh conditions in the study zones (Beaulac and Doré, 2005).

Classification map of land development potential, Salluit

Figure 11: Map showing relative vulnerability and suitability of land for infrastructure construction: the case of Salluit in Nunavik, Quebec (Solomon-Côté, 2004).

Access to land and resources for traditional harvesting activities has been the object of particular attention on the part of local authorities such as the Kativik Regional Government; their concerns include safety along the ice roads and on navigable waterways (Bégin, 2006). A study is underway with local communities to determine the best means for predicting and adapting to new winter snow and ice conditions, using the network of weather stations in the North (Lafortune *et al*., 2005).

Currently, the small number of stations and the poor quality of chronological data sets makes it difficult to validate models, but this problem is in the process of being resolved as Environment Canada installs new weather stations and thanks to the SILA network of environmental telemetry established by the Centre d'études nordiques (CEN).

In brief, in Quebec's North, rapid demographic growth, the resulting urban development as well as changes in access to resources and in traditional hunting, fishing and gathering have led to some delicate and multi-faceted socioeconomic changes. To this must be added the probable development of numerous mines in response to changing world demand for metals, as well as eventual large-scale hydroelectric development. Increased climate change, the most obvious effects of which will be accelerating thawing of the permafrost and an extended navigation season, will add to these factors and at times intensify the pace of change.

The Coastal Zone

Quebec has some 3,000 km of coastline along its eastern edge, extending from the Gulf of St. Lawrence to the river estuary. This maritime region includes the Côte-Nord, Bas-Saint-Laurent, Gaspésie, the Îles-de-la-Madeleine and Île d'Anticosti.

The 395,000 inhabitants (Statistics Canada, 2005) of this maritime region are distributed among 239 municipalities, 110 of which are located on the coast. The largest communities include Sept-Îles, Havre-Saint-Pierre, Baie-Comeau, Forestville, Chandler, Sainte-Anne-des-Monts, Percé, Gaspé, New Richmond, Carleton-sur-Mer, Rivière-du-Loup, Rimouski, Matane and La Pocatière. More than a quarter of the population lives within 500 m of the shoreline (Dubois *et al*., 2006), and more than 90% within 5 km. Many of the main industries – such as fisheries, tourism, and aluminum smelters – are also located within this narrow coastal strip along with major portions of land and maritime transport infrastructures including provincial highways 132, 138 and 199 and harbour facilities. A significant proportion of the population is thus exposed to the erosion that threatens built assets and some essential infrastructures.

The geology of the maritime region is marked by the presence of up to 60% unconsolidated friable deposits, which are easily eroded under the action of low-to medium-energy hydrodynamic processes (Bernatchez *et al*., 2008). The Côte-Nord is covered with postglacial argillaceous silts overlain with deltaic sand, all resting unconformably on Precambrian granite formations of the Canadian Shield (Dubois *et al*., 2006).

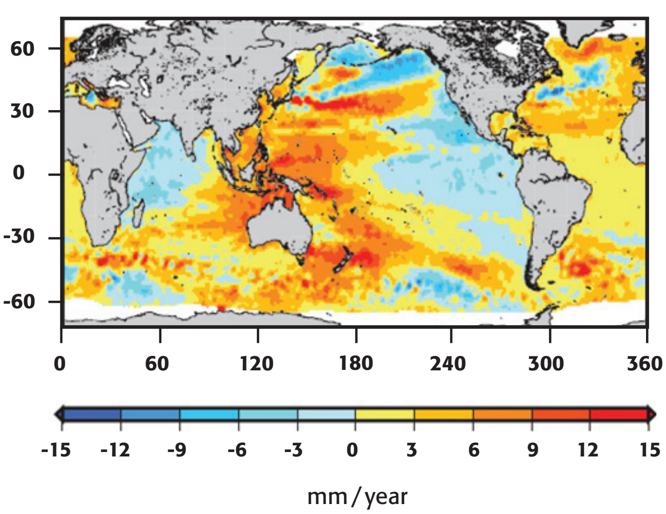


Figure 12: Geographic distribution of short-term linear trends for average sea level (mm/year) for 1993-2003, based on altimetric data from the Topex-Poseidon satellite (IPCC, 2007a).

These unconsolidated loose deposits, which can be up to a hundred metres thick, protrude into the Gulf and form estuary deltas, terraces and beaches. In Gaspésie and the Îles-de-la-Madeleine, the rocky Appalachian formations are composed of sandstone and poorly consolidated argillaceous shale, which erode easily when exposed to freezing, thawing, rain, wind and hydrodynamic processes that attack the base of the banks, regularly triggering rock falls and landslides. Fluvial and marine erosion of these friable rocks releases sand and gravel, the genesis of numerous beaches and the sand spits that shelter lagoons and tidal bays. The sensitivity of the coastal system to erosion is determined by the equilibrium between the sediment contributions resulting from the erosion of the coastal cliffs and embankments and the sediment losses from the beaches and marshes due to the influence of waves, coastal currents and ice. In deltaic zones, the contributions of sand from the rivers and coastal estuaries can account for a significant portion of the sand balance of beaches.

Climatic factors

In this particular geological environment, climate warming can modify the rhythm of shore erosion and augment the risks of submergence. The coastal zone of the Gulf of St. Lawrence will be affected by several climatic factors linked to rising temperatures (Savard *et al*., 2008), such as:

- a rise in sea level;
- changes in the frequency of:
  - winter rains and storms;
  - mild spells and freeze-thaw cycles;
- the disappearance of sea ice and shore ice.

The rise of sea level

According to the Intergovernmental Panel on Climate Change (IPCC, 2007a), average sea level rose by 1.8 ±0.5 mm per year over the course of the 20th century, and by 3.1 ±0.7 mm/year in the 1995-2006 decade. The IPCC estimates the probable rise in the level of the oceans at 3.8 ±2.0 mm/year in the 21st century. However, many experts believe this assessment is too conservative because it underestimates the loss of polar ice cap mass. With this loss considered, Pfeffer *et al*. (2008) place the average rise in sea level at around 0.8 m between now and 2100. However, the geographic distribution of this rise is extremely variable, as is shown by the satellite altimetric readings in Figure 12. The rise in sea level has varied by 15 mm/year, more or less, depending on the study region, for the 1993-2003 period; the average rise for the period was 3.1 mm/year. This great spatial variability constitutes a daunting challenge when trying to determine the future average level on a regional scale.

At the scale of the Gulf of St. Lawrence and the North-West Atlantic, large relative variations in sea level can be observed, caused by phenomena of geological origin (postglacial isostatic adjustment) and atmospheric origin (North Atlantic Oscillation [NAO], dominant winds, etc.). This means that over the short term, the average annual level of the Gulf of St. Lawrence may vary by 15 cm over a decade in response to fluctuations of atmospheric pressure and of winds at the regional scale or the scale of the North Atlantic. Postglacial readjustments of the Earth's crust are causing subsidence in the south of the Gulf of St. Lawrence (Daigle *et al*., 2005), while in the northern part, they are causing slight emergence (Tarasov and Peltier, 2004; Bernatchez and Dubois, 2004). The result is that the sectors of the Îles-de-la-Madeleine and the Baie des Chaleurs will undergo the conjugated effect of coastal subsidence and the global rise in ocean levels (Savard *et al*., 2008). The lagoon systems and beaches of Îles-de-la-Madeleine already show signs of a serious sedimentary deficit that is causing the subsidence of beaches and a significant erosion of the coastal embankments (Bernatchez *et al*., 2008).

Rains and winter storms

Storms produce large waves, heavy rains and variations in the water level. Changes in the intensity and frequency of storms will modify storm surges associated with low pressure and wind; this will create variations in both the waves and water level. The combination of higher levels and heavy seas is one of the main causes of damage to infrastructure and shore erosion. Diaconesco *et al*. (2007) have demonstrated that the wind regime in the Gulf has changed in the 1960-2004 period. Savard *et al*. (2008) have described the storm regime that affects certain sectors of the Gulf of St. Lawrence. Their study has revealed that the storms affecting different parts of the Gulf have different trajectories and behaviours. The storms in the south of the Gulf produce higher water levels and waves from the east, while storms centred over Newfoundland cause the water levels to drop and waves from the west and north-west.

It has been shown that storms vary depending on climate conditions; preliminary climate simulations (Savard *et al*., 2008) suggest that the total number of storms in the Gulf of St. Lawrence will decrease, while the total number of storm waves will increase. This apparent contradiction is a result of the rapid disappearance of sea ice.

Winter mild spells and the freeze-thaw cycles

A third phenomenon linked to warmer temperatures would also include a change in winter mild spells and freeze-thaw cycles. That being the case, the clayey slopes of the Côte-Nord and the friable sandstone cliffs of Îles-de-la-Madeleine and Baie des Chaleurs are especially susceptible to gelifraction (frost shattering). An increase in the number of winter warm periods speeds the erosion of these cliffs (Bernatchez et Dubois, 2004). Bernatchez *et al*. (2008) have demonstrated correlations between the rate of cliff retreat (of sandstone, of schists and of clayey shale) and the number of freeze-thaw cycles, winter mild spells and other winter climate factors such as the presence of snow on the cliffs, the percentage of sunshine and the frequency of winter rains.

Photo: Christian Fraser, UQAR

The disappearance of sea ice and coastal fast ice

One of the most direct impacts of climate change is related to the effect of rising temperatures on the duration and magnitude of sea and coastal ice. When the concentration of sea ice is greater than 30% of the water surface, it inhibits the formation of waves caused by storm-winds. That said, about 30% to 40% of these storms occur in the winter months (Savard *et al*., 2008). Data collected by an expert panel on shore erosion on the Côte-Nord (Dubois *et al*., 2006; Bernatchez *et al*., 2008) showed that the rate of erosion increased dramatically over the last 10-year period in the region of Sept-Îles. Savard *et al*. (2008) established a link between these elevated rates of erosion and the conjugated effect of a greater number of winter storms bringing waves from the southeast and a reduction in the ice cover. From 1994 to 2005, the ice cover in the Gulf was much lower than average (Environment Canada, 2007b).

Senneville and Saucier (2007) calculated, using climate scenarios, that the sea ice season will be reduced by two-thirds between now and 2050, and that by the end of the century, sea ice will have completely disappeared in the Gulf of St. Lawrence. This is why, as mentioned earlier, despite a probable decreased number of storms, we can expect an increase in the number of strong waves reaching the coastline.

Socioeconomic factors

Some socioeconomic factors contribute to increasing the vulnerability of communities to coastal erosion. As noted by Morneau *et al*. (2001), the first of these factors has been an increase in the number of constructions along shorelines since 1970, resulting from a growing enthusiasm for coastal areas and the greater availability of shoreline protection methods to safeguard infrastructures and residential and industrial buildings. However, the technologies used for bank protection, which consist for the most part of linear protection with large stones or the construction of vertical walls (concrete, sheetpiles, rocks and timber cribs), are often poorly adapted, with the result that they have significant residual environmental impacts.

One of the largest repercussions is a deficit of granular materials, such as sand, in the areas protected by these structures. Bernatchez *et al*. (2008) noted that some 80% of the beaches in front of these protective structures have suffered serious damage or disappeared entirely. Using heavy, massive structures to protect the coast aggravates the impacts of climate change by rigidifying the coastal stretch, which can no longer adjust to the rise in sea level and other hydrodynamic changes. In the medium term, protection structures often become useless and crumble, exposing infrastructures that then must be protected from even more severe erosion. What is more, most protection structures do nothing to hinder the process of submergence and may even serve to aggravate it.

Anthropogenic activity can therefore have an impact on natural processes that act to erode the shore. The interactions between coastal processes and various anthropogenic activities (dams, dikes, jetties, quays, wood clearing, trampling on beach grasses, removing sand from beaches, etc) are too numerous to list here. It suffices to say that management of coastal zones must take into consideration not only natural factors, but the full range of human activities than can affect the dynamic of coastal systems.

Two studies (Bernatchez *et al*., 2008; Drejza *et al*., 2009) estimated the cost of erosion between now and 2050 at Sept-Îles, the Îles-de-la-Madeleine and Percé at $71 million – for a total length of coastline of 188 km. This estimate includes only the value of the land and buildings, and includes no associated costs for the demolition of housing, compensation paid out, loss of natural habitats, etc. A study by Tecsult (2008) in the area of Sept-Îles and Gallix estimated that the financial cost of bank erosion over the next 25 years will amount to $33.9 million. For the entire Gulf of St. Lawrence and the estuary, potential losses can be estimated in the hundreds of millions. To this amount must be added the costs associated with the loss of critical habitat for avian and marine life.

For example, the natural habitat of the snow goose population that regularly stops in the St. Lawrence estuary is currently shrinking rapidly. Meanwhile, the disappearance of coastal marshes and beaches means a loss of habitat for numerous animal and plant species, some of which are of critical value for fauna or flora (capelin, eelgrass, American bulrush, etc.), and – very often – have commercial or heritage value (soft-shell clam, algae, waterfowl). All this makes shore erosion economically significant.

Finally, at a social level, the constant threat to the built heritage, public and private, is an ongoing source of anxiety and frustration, and sometimes constitutes a risk to public safety when erosion or submergence threatens essential infrastructure. In some communities, urban development is hindered because a large portion of the population must be relocated or because essential infrastructures (roads, wharfs, piers, etc.) are at risk.

Adaptation solutions

There are many different possible solutions for adapting to coastal erosion. They range from appropriate zoning (see Figure 13) aimed at limiting future vulnerabilities, to the pre-emptive withdrawal of infrastructures and buildings that are at risk in the short to medium term, and including protection work such as the replacement of beach sand, protection jetties, groins, sea walls and various sediment retention systems. The choice depends on both the cost of the available technical solutions and the socioeconomic and environmental stakes at issue.

The complexity of the factors that regulate the coastal dynamic requires a multidisciplinary and integrated approach on the part of all the players involved in adaptation. The Quebec government initiated studies on this topic in 1998 (Dubois, 1999); since 2005 Ouranos (Savard *et al.*, 2008) and the Université du Québec à Rimouski (UQAR) Bernatchez *et al.*, 2008) have been continuing this research. Their goal is to develop a preventive approach to evaluating coastline risks and to adjust management and coping strategies that will take account of the impact of climate change.

These studies incorporate three elements: tracking the evolution of the Gulf of St. Lawrence shoreline historically; a detailed analysis, using numerical modelling on a regional scale, of climate and the hydrodynamics of the Gulf; and an integrated management framework for coastal zones that involves communities and local and regional decision-makers and the support of scientists. An in-depth review of government policies and connected regulation, based on the results of these studies, will look at municipal zoning, urban development plans, critical infrastructure management, public safety policy, regulatory control, protection methods and other strategies for managing risk. The final adaptation choices will be made in concert with coastal community representatives and the relevant government departments on the basis of critical cost-benefit analyses.

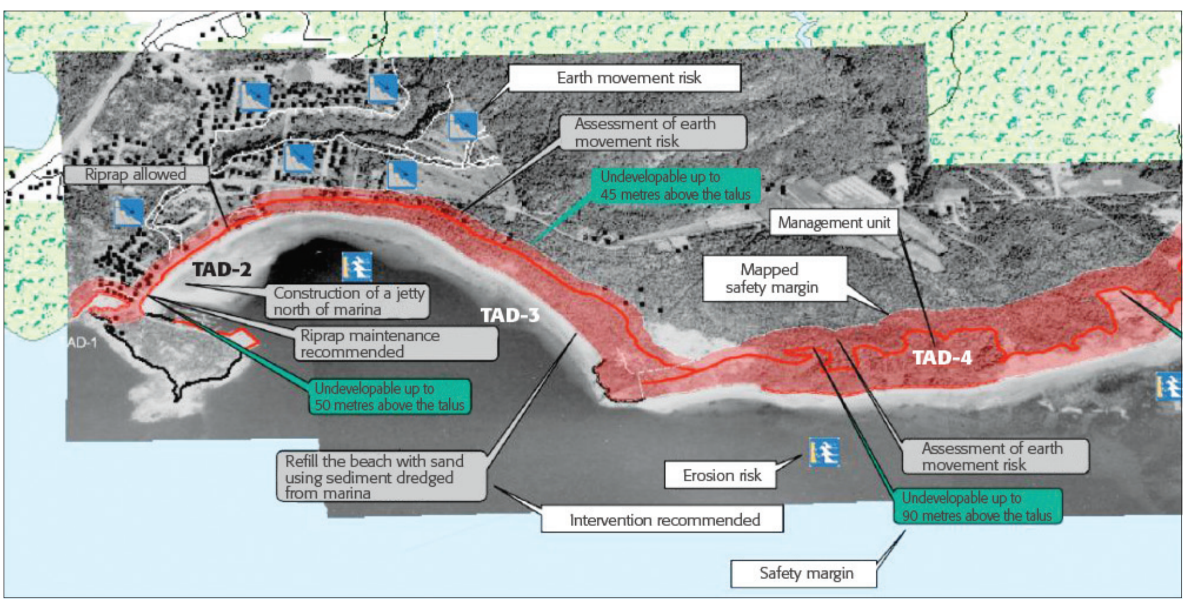


Figure 13: Zoning map of erosion risk and shoreline management measures for the Côte-Nord (Dubois *et al.*, 2006).

The South

In western societies, the built environment is extremely important, especially in urban centres where structures and networks are relatively complex and closely interconnected (for example, a power supply is necessary to produce and distribute potable water). Quebec's infrastructures in this regard represent a considerable collective investment (for example, according to MAMROT, the underground infrastructures for drinking water and wastewater alone are worth about $60 billion) and are essential for the wellbeing and health of communities. Quebec's infrastructures include transportation, communication and energy networks as well as municipal infrastructures such as water supply, sewage treatment and waste management. We can also include buildings – residential, agricultural, industrial, commercial and institutional – in this definition. All these infrastructures form a highly interdependent web that is essential to our way of life (Ruth, 2003).

That said, the vast majority of the infrastructure built in recent decades has involved design criteria based on the statistical analysis of past climate events. However, climate change now calls into question the assumption that past climate conditions are representative of future conditions. This is especially the case in regards to the effectiveness and safety of infrastructure, which is usually designed to last several decades, during which time the effects of climate change would be noticeable.

In a highly service-based economy such as Quebec's, the development of communities and economic activities relies heavily on infrastructure operating properly. The interdependence between infrastructures makes Quebec especially susceptible to failures caused by climatic events (Bruce *et al*., 1999; Kirshen *et al*., 2007; Chang *et al*., 2007). We have already seen examples of the degree to which a climate event can lead to the destruction of infrastructure and disrupt populations and economic activity, including, most notably: the Saguenay floods of 1996 (MSP, 1996; MTQ, 2000), the ice storm of 1998 (MSP, 1999) and landslides (Lebuis *et al*., 1983) and avalanches (Lied and Domaas, 2000; Public Safety Canada, 2006) resulting from heavy precipitation. The damages and losses resulting from such climate events have been considerable and appear to be increasing (Bruce *et al*., 1999; McBean and Henstra, 2003).

The impacts

For Quebec, the greatest concerns related to the effects of climate change on infrastructures are connected to changes in the duration, frequency and intensity of rainfall events (Mailhot, 2007a), whether they take place in urban or rural environments. These events, which can cause flooding such as occurred at the l'Acadie Circle in Montreal in 2006 and the Rivière-au-Renard in 2007, may become more common. Climate change will probably lead to an increase in freeze-thaw cycles in some regions, which will have an impact on the design and maintenance of surface and underground infrastructures (faster degradation of pavement, more pot-holes, breaking water mains and sewer lines, etc.). Meanwhile, soils drying out as a result of higher temperatures and periods without rain, especially in clayey regions such as Montreal and Outaouais, may exacerbate the problem of cracked foundations. As can be seen in more detail in other sections of this document, infrastructures in the North and in maritime regions are also at risk.

There is no question that extreme climate events carry greater risks to infrastructure (IPCC, 2007b; Bruce *et al*., 1999; Auld and MacIver, 2004), but gradual changes also can have profound impacts. Climate change can cause three main types of direct impacts on infrastructure and the built environment (Engineers Canada, 2008; Infrastructure Canada, 2006; Auld and MacIver, 2004; Case, 2008) :

- Structural problems and loss of functionality resulting from loads higher than the design load of a structure, for example: a very high volume and intensity of rain, significant accumulations of snow or very high winds. Such loads can trigger total or partial collapse of a structure or the breakage of some of its components (culverts, roofs, etc.).

- Accelerated wear and tear of materials, which translates as a general reduction in the durability of materials, corrosion, etc. Climate conditions can act as catalysts for certain chemical reactions, which alter the materials and their rate of degradation (for example, increased carbon dioxide degrades mortar and stone). The premature deterioration of infrastructures can also make them much more vulnerable to extreme events.

- The loss of optimal performance of the infrastructure. Even when the integrity of a structure is not at risk, new climate conditions can affect its technical performance. For example, a building that retains a great deal of heat can become extremely uncomfortable during periods of intense heat, especially for vulnerable individuals (see the section "Health of Populations").

The indirect impacts of climate change on the built environment are basically linked to the impacts that these changes have on the natural environment. For example, more abundant rainfall can cause floods, landslides and avalanches that in turn can pose a threat for infrastructures located in these risk zones. Likewise, climate impacts on water can have consequences for certain infrastructures or procedures that depend on raw water at a particular temperature, quality or water level.

Nevertheless, stakeholders associated with the built environment, such as engineers, are more and more aware of the issues (Engineers Canada, 2008; FCM, 2002; CIP, 2007; Ligeti *et al*., 2007; Case, 2008), and the adaptive capacity of communities appears to be increasing (Infrastructure Canada, 2006). In a broader context, considerable effort is now being applied to the construction of new infrastructures and the renewal of aging infrastructures (Statistics Canada, 2006; Mirza, 2007; Larsen *et al*., 2008). This massive investment in infrastructure is the ideal occasion to integrate climate change considerations into the design, management and maintenance of infrastructure.

Adaptation of buildings and infrastructures

In the wake of various major climate events, actions have been taken to limit the vulnerabilities of infrastructures and the built environment (see Table 8). For example, Transports Quebec and the City of Québec now require that certain rainwater management works, such as culverts, be over-designed to account for increasing rain events (frequency and intensity) likely to occur in future climate conditions. A number of municipalities are requiring that all new developments must include retention basins in order to prevent urban drainage problems. The Town of Sept-Îles reviewed its land-use policies and plans, along with its zoning regulations, in an effort to better control development in zones at risk, such as those prone to coastal erosion.

In terms of the main concerns linked to projected climate change, besides the initiatives already taken by Transports Quebec and some municipalities, studies are underway on the impacts of rainwater management in order to determine the actual effectiveness of various adaptation solutions, both technically and economically. Engineers Canada are continuing their work with the infrastructure vulnerability protocol developed by the Public Infrastructure Engineering Vulnerability Committee (Engineers Canada, 2008) and are doing case studies throughout the country to promote the use of vulnerability assessments. The Canadian Standards Association is also looking at risk management as applied to infrastructure within the context of climate change, and is designing tools to assist municipalities.

But despite these experiments and knowledge gains, we are still in the early stages of planning the necessary adaptations to minimize the impacts of climate change. Adapting infrastructure to changing conditions can be more or less difficult (technically, economically, socially, environmentally, etc.) depending on the life span and relative age of the infrastructure, as well as the frequency of maintenance or rehabilitation activities. However as Figure 14 shows, adaptation measures can be integrated into any stage of the life cycle of infrastructure, whether it is:

- pre-construction (for example, choice of location at the planning stage);
- during construction (for example, adding a security factor to the design or the types of materials selected for the construction phase);
- after construction (for example, the modification of the maintenance programme or the rehabilitation method to be implemented).

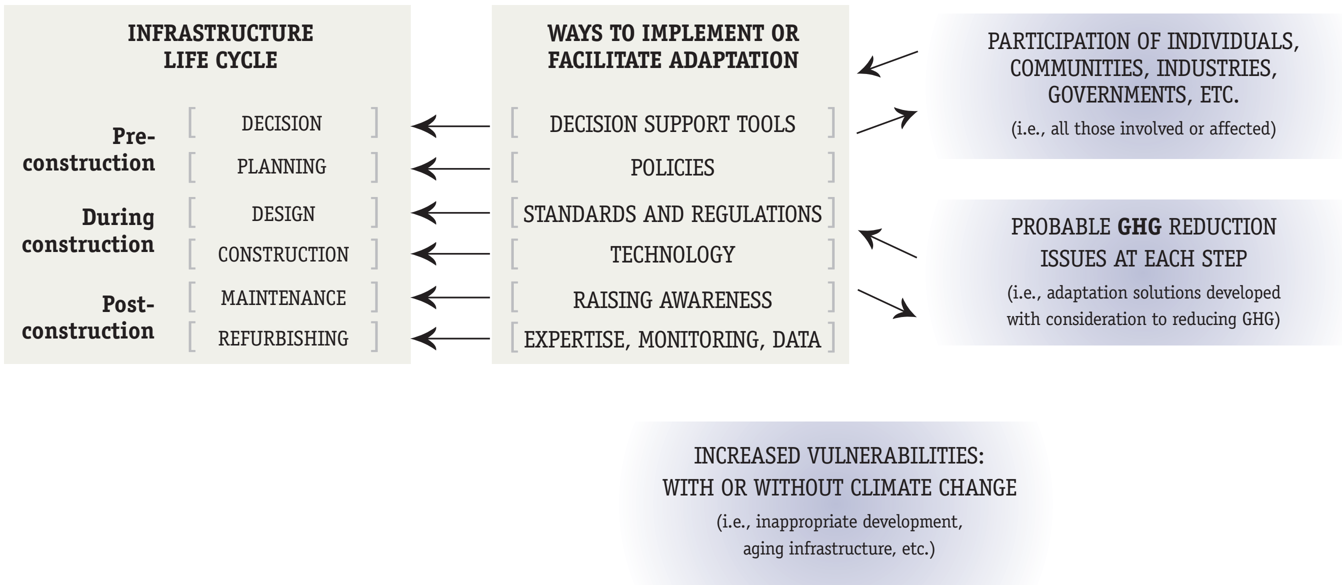


Figure 14: Diagram of different categories of adaptation measures in the infrastructure life cycle (adapted from Larrivée and Simonet, 2007).

Although there are still few studies on this topic, it would be beneficial to consider whatever climate scenarios are available during the design phase for infrastructure, as was done in the case of the Confederation Bridge linking Prince Edward Island with New Brunswick (Canadian Environmental Assessment Agency, 2000). Once built, infrastructures are not easily adapted and their life spans can be long. For projects with shorter life spans, such as roads, it is easier to introduce least cost adaptation solutions at the moment of rehabilitation or maintenance activities. For critical infrastructures related to energy, water, food, health services and transportation, the vulnerabilities must be minimized and palliative measures put in place in case of structural failure.

There are a number of ways to stimulate adaptation, but effective implementation requires multidisciplinary collaboration and a risk management approach (Engineers Canada, 2008; Ruth, 2003). For example, a risk analysis might support the decision to build or rehabilitate critical infrastructures further inland. It might prompt the selection of more resistant construction materials, suggests the revision of design criteria or reshape maintenance programmes based on anticipated problems -- in brief, the decisions that are currently regularly made by engineers in order to resolve or minimize a problem.

There are, however, more than a few factors limiting the implementation of adaptation solutions (Mailhot *et al.*, 2008b; Koch, 2007). Apart from physical space constraints (especially in sectors that are already developed) and geographic constraints (not all technologies are appropriate in a northern climate), economic and particularly organizational considerations can work against adequate adaptation to climate change. In addition, given the professional liability of infrastructure designers and managers, it can be difficult for them to justify trying untested techniques, and the higher costs that often come with them, especially given the uncertainty that accompanies climate change projections or the actual effectiveness of the proposed solutions.

In Quebec, however, the built environment remains fairly robust, because the variability of the climate is already relatively substantial. However, our infrastructures are aging, and as a result, are more and more vulnerable. In this context, infrastructure reinvestments offer the opportunity not only to consider climate change, but also to review the way in which we design infrastructures, challenge the roles that they play and reconsider land management.

ECONOMIC ACTIVITIES

Hydroelectricity generation

The electricity industry in Quebec and Canada could well be one of the economic sectors most directly affected by climate change, in terms of both production – which is largely hydroelectric – and demand. In Quebec in particular, where hydroelectric generation represents about 96% of total electricity production and close to 41% of total energy demand, the impacts of climate change on the hydraulic resource are of major importance.

The impacts

Over the coming decades, climate change will bring about significant changes in precipitation, and as a consequence, in water resources. First of all, this will affect the hydrological regime of harnessed watercourses, putting at risk the capacity to respect all the constraints associated with multiple uses of the water resource (hydroelectric production, drinking water supply, navigation, agricultural irrigation, preservation of wildlife habitat, flood prevention, etc.).

Secondly, it is reasonable to believe that the design of future hydraulic structures will be affected, to the extent that the anticipated climate change could modify the generation capacity of these installations over the course of their lifespan. Taking into account the potential effects of climate change on the hydraulicity of various developable watersheds will make it possible to design installations better and to optimize their operational planning in such a way as to produce the maximum energy while complying with the various constraints that must be accommodated.

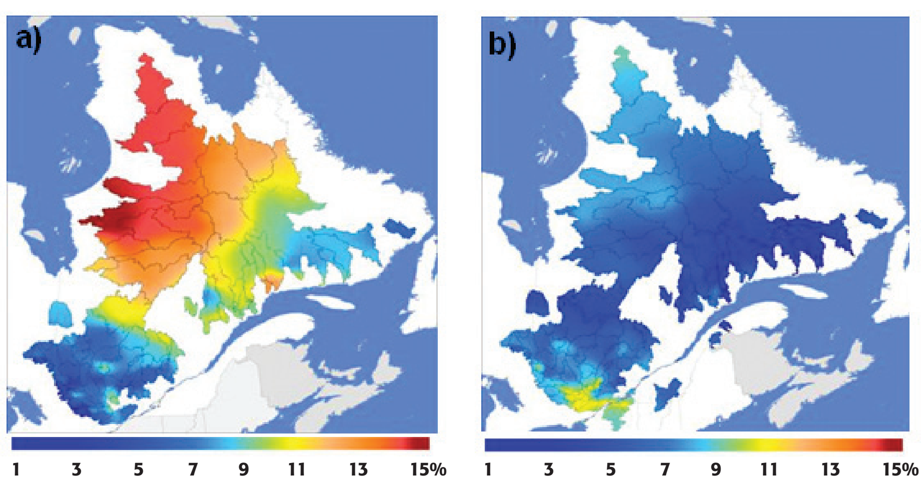
The climate simulation tools developed by Ouranos have led to an improvement in understanding the projected evolution of climate over the coming decades, focussing particular attention on anticipated changes in temperatures and precipitation regimes. These, especially, will have a major impact on the forecasting of energy demand and supply. Improving our knowledge of future climate, in particular the changes to the hydrological regime, the thermal regime and the frequency of extreme weather events, will help us in future to modify various operational strategies or planning and design activities so that they take into account the effects of climate change.

Overall, it is expected that climate change will bring increased rainfall and snowfall on all watersheds, but with significant differences according to regions (Desrochers *et al.*, 2008). As Figure 15a shows, the average change in projected annual discharge by the year 2050 will be between 1% and 15%, depending on the watershed. The increase in annual discharge will be greater in Northern Quebec than in the southwest section. Thus, in the northwest, the increase will be between 10% and 15% depending on the watershed, and between 7% and 10% for Churchill Falls and the Côte-Nord, while the increase in the southwest region will lie between 1% and 8%.

These figures are drawn from 90 simulations based on the combination of different global models and different scenarios of future greenhouse gas emissions. They are based on the perturbation method, which consists of modifying a climate observation set on the basis of climate projections (Music *et al.*, 2008).

Figure 15:
a) Evolution of hydrological regime conditions by 2050;

b) Dispersion between the different projections for the evolution of the hydrological regime by 2050 (Desrochers *et al.*, 2008).



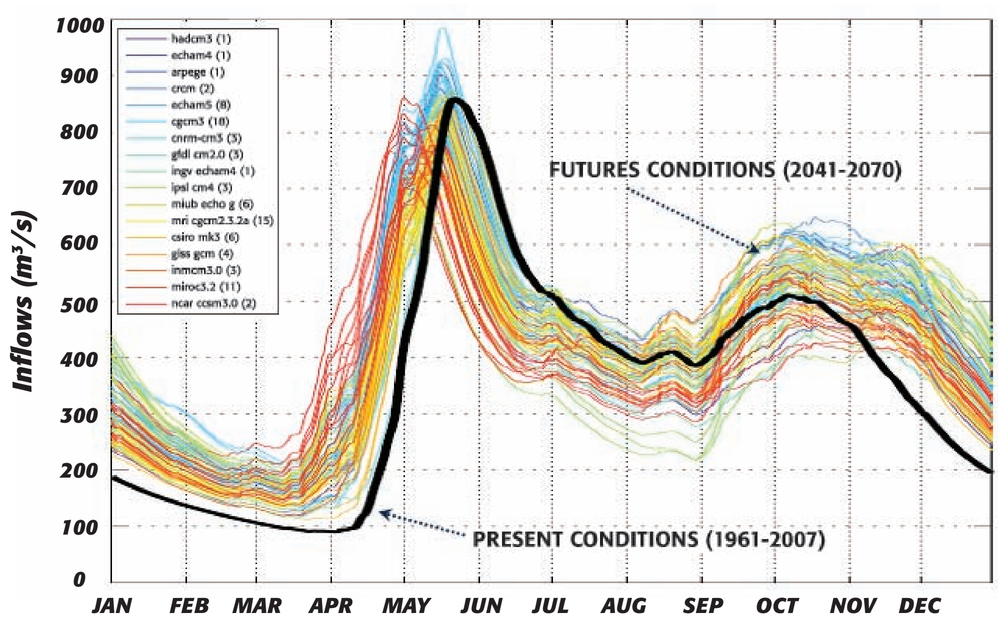


Figure 16: Reconstructed and future mean hydrographs for each of the 90 simulations — Northern Quebec watersheds (Roy *et al*, 2008b)

The two climate time series (reference and disturbed) feed a single hydrological modelling tool, and the simulated discharges for the reference period and the future period are compared so as to assess the impacts of climate change on the hydrological regime by the year 2050. As shown in Figure 15b, which illustrates the variability between the different simulation results, this variability is less than the average relative change in mean annual discharge. Variability is generally greater in the southwest part of Quebec than in the watersheds located further north. It is also worth noting that in the northwest region of Quebec, where a significant amount of hydroelectricity is produced, the change signal in the mean annual discharge is much greater than the dispersion between these simulations, which inspires a degree of confidence in the projected changes for this region. Such is not the case for the southwest region of Quebec, where the dispersion between the various simulations is comparable to the change signal itself.

Changes in the distribution throughout the year seem to be as important, if not more important, than changes in the annual mean (Roy *et al*., 2008b). Figure 16 shows the hydrographs (changes in annual inflows over a year) issued from the 90 simulations for the period 2041 to 2070, overlaid on an averaged reconstructed hydrograph for the current period.

On a seasonal scale, changes, both absolute and relative, would be most significant in the spring. The average outflows in the months of March, April and May would be more significant in the future. This increased outflows are largely explained by the earlier onset of the spring flood.

In the summer period, inversely, a decrease of the natural outflows, is expected for precisely the same reason -- the shift of the flood period. Runoff resulting from the snowmelt currently has a greater impact on the discharge in June, July and August than will be the case in 2050. A, part of this decrease could also be attributed to an increase in evapotranspiration due to the warmer temperatures predicted for 2050. Few changes are expected for the fall period. Finally, an increase in outflows is predicted during winter (defined as December through February) by the year 2050. This will be caused by the increased frequency of above-freezing temperatures, so that in coming decades, a greater proportion of precipitations will fall in the form of rain rather than snow in winter months. More favourable conditions of hydraulicity before winter begins will also lead to more sustained winter low flows.

For all seasons as well as for changes in annual volume, there is a noticeable variability in the results of the different simulations of changes in the hydrological regime by 2050, which underscores the uncertainty of these assessments. Despite these uncertainties, they show some common characteristics, such as a systematic positive change on the annual and winter scales. The projections for autumn, however, do not all concur on the direction of the hydrological regime change, some pointing towards a reduction and others towards an increase of the fall discharges.

The results of simulations have not yet allowed for the quantification of change in the natural interannual variability of discharge, which represents a significant business risk for Hydro-Québec, since years of high or low hydraulicity may have significant consequences for its financial performance. It is, however, reasonable to wonder whether the range of interannual variations in hydraulicity may change in the future. New research has been undertaken to obtain time series longer than the 50-year horizon currently available, so as to better understand this type of variability. Paleoclimatic indicators make it possible to extend energy inflows series into the past, so as to better qualify interannual variation (Nicault *et al*., 2009).

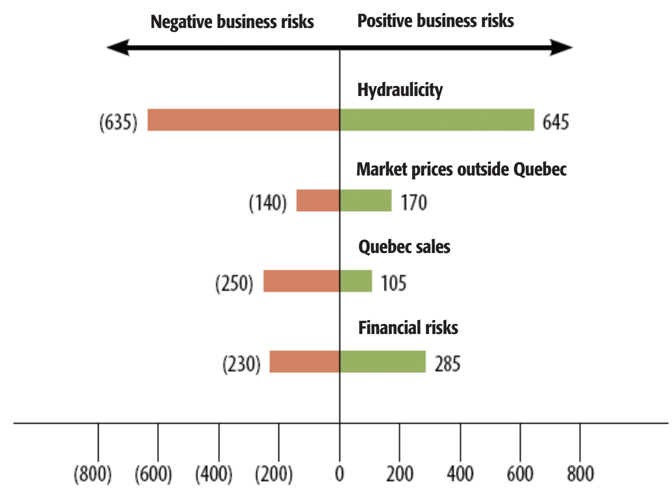


Figure 17: Analysis of net earnings sensitivity to various risks (in millions of dollars) for 2008 (Hydro-Québec, 2006).

The expected changes in average precipitation and its variability could have consequences on the risks faced by the industry. For Hydro-Québec, for example, the "hydraulic risk" is clearly the highest economic risk and its ability to predict hydraulic conditions in the future is essential for assessing the overall risk posed to net earnings by this determining factor. In fact, the risk for Hydro-Québec from hydraulicity conditions alone is as great as all other combined sources of risk. Figure 17, taken from Hydro-Québec's 2006-2010 strategic plan, shows the results of a sensitivity analysis of the main risks identified by the company in its projected net income for 2008. This shows that in 70% of instances, net income would vary between +$645 M with increased hydraulicity and - $635 M with a reduction.

It should be noted that in this graph, the variation in electricity sales within Quebec presents another sizeable element of risk, although to a lesser extent. Such sales are also highly influenced by the climate, and especially by the severity of winter and the resulting heating needs. As emphasized in the following section on energy demand, changes in the thermal regime in the north-eastern part of the continent are likely to significantly modify this demand on both sides of the Canada-US border. Thus, higher temperatures would lead to a decrease in winter energy requirements, while stimulating the electricity demand for air conditioning in summer. A consequence of the reduced electricity demand in winter would be to maintain higher water levels through the end of the winter season.

This new scenario must be taken into account in order to ensure that facilities remain safe during the spring flood period. Similarly, increased demand for air conditioning in summer (whether at home or for export) would require that water levels be kept relatively high.

As for extreme climatic events, the climatic models suggest that extra-tropical cyclones affecting the Quebec territory could be less numerous but much more intense, and, therefore, that the magnitude of future extreme climatic events could be even greater. If we neglect to plan for measures to adapt to these climatic events, the integrity of hydroelectric production, transportation and distribution facilities could be compromised.

The probable increase of temperatures could also modify the cooling capacity of water circulating in hydraulic turbines. Increasing water temperatures could require the use of auxiliary cooling systems. It should be noted that such components are more important for conventional and nuclear thermal power plants that depend on water-courses for cooling, and where higher temperatures could lead to decreased production.

Adaptation

One cannot simply conclude that an increase in mean annual discharge in Quebec would increase hydroelectric production by the same factor. In fact, an increase in the mean annual discharge could, in some cases, mean a decrease in energy production if larger discharges were observed only when reservoirs were filled to capacity, bringing about significant increases in non-productive spills. The reservoir management methods, the distributions of these changes over the year as well as the possible changes in the frequency of floods all have an influence on energy production (Minville *et al*., 2009; Pacher *et al*., 2009).

That is why the analysis of evolving hydrological regimes, as discussed above, must be followed by an analysis of the consequences for water resource management and the planning and design of new hydraulic equipment. These analyses will make it possible to assess potential benefits of various adaptation measures and in time their deployment. Roy *et al*. (2008a) authored a guide on the assessment of the impact of climatic changes and described the advantages of an adaptative management method that takes into account the possible fluctuations of the hydro-climatic regime.

A broad spectrum of adaptation measures is available, including structural and non-structural ones. Table 3 shows a non-exhaustive list of adaptation tools that could allow us to benefit from the benefits or to limit the negative impacts of evolving climatic conditions.

It is important to note that, in general, non-structural adaptation measures are simpler and less costly, while the structural measures are more complex and expensive. These should be considered only if the advantages of their deployment can be predicted with a high degree of certainty. Otherwise, it is more advantageous to adopt the less constraining measures gradually, as climatic changes appear.

Table 3: Tools for adapting hydraulic works to evolving hydroclimatic conditions (adapted from Roy *et al*., 2008a).

Non-structural tools	Structural tools
• Modifications to the operating rules of the installation • Development or improvement of discharge forecasting models • Better coordination of the various uses of water within a watershed • Development or improvement of performance assessment methods (in climatic change conditions) • Modification of design methods	• Diversion of tributaries upstream of the works • Installation of new reservoirs upstream • Modification of the characteristics of the electrical components (generators, transformers, distribution lines, etc.) • Design of “adaptable” hydraulic works (adding groups of turbo-generator units or discharge capacity, expanding dikes, etc.) • Modifying the size of raceways or intake channels • Modifying the number or size of turbines • Increase the spillway capacity

Adaptation prerequisites and limits

The use of adaptation measures seems easy to justify when the expected benefits are substantial. A very long-term vision of business activity is one of the prerequisites to adaptation of business practices. In fact, since the expected consequences of potential climatic change involve time horizons of 30 or even 50 years, decision-makers must consider such timelines. To this end, they must be able to rely on impact studies based on sophisticated climate and hydrological modelling tools producing results with a high degree of certainty. Despite substantial expected benefits, few managers are inclined to put into place adaptation measures, especially if there are associated costs, without understanding the uncertainties linked to projections of the evolving hydroclimatic regime. Finally, an enterprise must be well enough established to be able to cope with the risks associated with the deployment of such measures. According to Stankey *et al*. (2005): "If action in the face of uncertainty must be accompanied by an assurance that nothing will go wrong, then we have a recipe for inaction."

Other limiting factors that could slow the deployment of adaptation measures include the inertia of large organizations and certain technical and legal issues. For example, the best practices to which designers must adhere regarding the security dimensions of spillways (i.e., probable or frequential maximum floods) are based on a hypothesis of stationary hydroclimatic conditions. It is exactly this hypothesis, however, that is being challenged by climatic change. Several scientists are working to adapt existing methods to the context of climate change, but it could be many years before these new methods are recognized and adopted. Finally, one of the main factors limiting adaptation is found in the asymmetric cost/benefit relationship. Adaptation requires that an investment (possibly of considerable sums) be made right away for benefits that may be decades away. Given the current discount rates used by businesses, benefits that may accrue in the very long term have little influence on decisions to invest.

Prospects

The perturbation method on which the above impact analyses are based while being adequate has its limits, notably with respect to the evolving variability of the hydroclimatic regime conditions. Direct methods, with or without hydrological modelling, which allow for the judicious use of regional climate models, are most promising and are currently being studied by several teams around the world (Music *et al*., 2009; Lenderink *et al*., 2007; Rosberg and Andréasson, 2006). A recent World Bank report (2007) concluded that this approach was more pertinent than the more commonly used perturbation method (or so-called "delta method") for analyzing the variability of future hydrological conditions. Thus, research at Ouranos is being oriented towards the use of the direct method and, more specifically, towards projections from high-resolution climatic models (CRCM, ARPEGE-Climate and REMO). The resolutions of these models are closer to the scale of the watersheds for which we wish to assess the evolving conditions of hydrological regimes.

Ouranos also intends to continue assessing the results of the "direct method via a hydrological model" for all the watersheds studied. By comparison to the delta method, the former has the advantage of providing a new climatological sequence that will allow us to study, among other things, the change in variability attributable to climatic changes. The issue of the hydrological model to be chosen requires further attention, notably to refine the analysis of certain parameters other than discharge, such as soil moisture.

Finally, the issue of hydrological variability will become more important. It is in fact of great signification because several consecutive dry or wet years are likely to have major impacts on the planning, design and operation of hydraulic works. Much work remains to be done to better quantify variability in all its aspects, but it is reasonable to believe that ensemble forecasts (a multimodel approach) will improve our knowledge.

Conclusion

The climate is evolving, and the consequences for the hydrological regime of watersheds in Quebec justify research efforts to determine the nature of impacts and, in time, to adapt some of the business practices of the hydroelectric industry. As of now, the methodological bases for climate change impacts assessment on the water resource in Quebec have been established with concern for the main vulnerabilities. There remains a high degree of uncertainty about the results, which must be reduced considerably by using improved climate and hydrological models, among other things. However despite this uncertainty, the results tend to show that Quebec does not really have to fear the effects of climate change on its current annual capacity for hydroelectric production. This conclusion is reinforced by similar findings from several studies on hydroelectricity in other northern countries (Graham *et al*., 2007).

Nonetheless, adaptative management methods must be put into place to handle the inevitable changes in outflows that will occur in the various regions, especially seasonally. By gradually adjusting management methods as our knowledge of the future climate improves, it will be possible to optimize the operation of all existing and future production facilities.

Energy Demand

For Quebec, one of the most economically significant of the anticipated direct impacts of climate change will be the effect of higher temperatures on energy demand.

Quebec's cold winters and relatively warm summers lead to a demand for heating and air conditioning that represents a heavy expenditure for all sectors of the economy. The impact of climate warming on energy demand will obviously lead to lower demand for heating in winter and a greater need for air conditioning in summer. In 2006, these two uses represented 59% of energy demand in the residential sector and 56% in the commercial/ institutional sector. As these two sectors combined account for 35% of total demand (residential, commercial and institutional, industrial and transport sectors), the total energy and economic impact of climate change will be significant, both for electricity demand – which supplies a substantial percentage of heating in the residential and commercial/institutional sectors as well as most of the air conditioning – and for natural gas, which supplies a relatively high portion of heating in the tertiary sector, as we will see below (MRNF, 2009a).

The relationship between temperature, heating and air conditioning has been the subject of a number of analyses in recent decades, especially in connection to energy efficiency studies and demand forecast analysis (MRNF, 2001 and 2005). A more recent study on rising temperature and humidity levels, carried out by Ouranos on behalf of the Agence de l'efficacité énergétique, was also aimed at determining the impact of climate change on the heating and air conditioning of buildings (Sottile, 2006).

In the residential sector, heating requirements are closely connected to the number of heating degree-days, and in general, it is assumed that the relationship is essentially proportional or linear in a given region and type of dwelling. In the case of air conditioning, the relationship is a little more complex and depends on both the variation in degree-days and the distribution of equipments. This last factor is itself a function of changing temperatures, especially when it comes to the use of central air conditioning. For instance, in southern regions where temperatures are higher, a higher percentage of homes are equipped with central air conditioning.

The impacts

According to a 2006 study (Lafrance and DesJarlais, 2006), under a median scenario involving warming of 2.6°C in winter and 2.0°C in summer by 2030 and of 3.5°C in winter and 3.1°C in summer by 2050, the energy requirements in the residential sector would decrease by 6.7% by 2030 and by 6.9% by 2050 (see Table 4) in comparison to a reference scenario of energy demand in the absence of climate change. As Table 4 shows, the impact of the increase in air conditioning on household energy demand would be less than the impact resulting from reduced heating requirements. This is explained in part by the greater increase in winter temperatures than summer ones, and by the fact that the use of home air conditioning is much less widespread. However, it should be noted that the energy requirements for air conditioning would be 4 times higher in 2030 and 7 times higher in 2050, while heating requirements will drop by only 13% and 14% respectively.

Table 4: : Impact (%) of climate change on heating and air conditioning in the residential sector (Lafrance and DesJarlais, 2006).

	On total energy demand (%)			On demand for electricity (%)		
	Heating	Air conditioning	Net	Heating	Air conditioning	Net
Scenario						
2030						
Optimistic	-7.5	3.4	-4.0	-5.8	4.3	-1.5
Median	-11.0	4.4	-6.7	-8.6	5.5	-3.1
Pessimistic	-15.7	6.4	-9.2	-12.1	8.1	-4.0
2050						
Optimistic	-10.5	5.5	-5.1	-8.5	6.6	-1.9
Median	-15.2	8.3	-6.9	-12.3	10.0	-2.3
Pessimistic	-12.1	12.3	-8.8	-17.1	14.8	-2.3

Energy demand in the commercial and institutional sector, meanwhile, would drop by 10% by the year 2050 in a median scenario, as a result of decreased heating demand, while the air conditioning demand would grow by 2.5% – a net reduction of 7.5% in total energy demand. In 2001, air conditioning accounted for a larger share of energy consumption in this sector than in the residential sector.

In the industrial sector, which represents 40% of total energy demand (MRNF, 2009a), energy is used primarily for industrial processes rather than heating and air conditioning. However, there is still a measurable seasonal variation in fuel consumption, which allow us to estimate some limited climate impacts in this sector, especially in light industry. Finally, a review of consumption in the transportation sector (25% of total energy demand) does not establish any significant link between climate and energy consumption.

Overall, energy demand (for heating and air conditioning) in all sectors combined (residential, commercial and institutional, industrial and transportation) would drop by 2.7% by 2050 based on the median scenario. Moreover, this reduction would have a much greater impact on the use of fuels, leading to a significative reduction in greenhouse gases.

Although modest as a percentage of the Quebec economy's total consumption, the annual savings could reach several hundred million dollars based on 2003 prices (see Table 5). In addition, as these savings would affect imported fuels in a larger proportion, there would be a positive impact on Quebec's balance of trade.

The impact on electricity demand in the residential sector and the commercial and institutional sector is equally significant, although the impact is lower because of the relatively high use of combustibles for heating purposes. Using the median scenario, it is estimated that electricity demand in the residential sector by 2050 will be reduced by 2.3%, while in the institutional and commercial sector it will increase by 0.7%. This last case is explained in part by the assumption that air conditioning will be more widely available in health establishments.

It is interesting to note that the impact on peak winter demand would be even greater, given that the reduction in cold waves is expected to be much more dramatic than the reduction in degree-days; as Figure 18 shows, temperatures below -25°C are expected to all but disappear.

Table 5: Potential savings (in millions of 2003 dollars, not including taxes) (Lafrance and DesJarlais, 2006).

	Residential	Commercial	Industrial	Total
Scenario				
2030				
Optimistic	197	77	56	330
Median	329	139	83	552
Pessimistic	453	206	118	776
2050				
Optimistic	229	104	82	415
Median	313	166	117	596
Pessimistic	397	259	163	820

Adaptation strategies

The findings presented in the above paragraphs lead one to conclude that modifications in energy requirements brought on by climate change would not present overall major problems because they would be accompanied by a drop in demand.

A reduction in heating does not in itself require any particular adaptation, and may even result in increased possibilities for electricity exports. However it would translate into a reduction in the demand curve of energy distributors, which could eventually have an impact on their installations mix.

In addition, the growth in demand for the purpose of air conditioning raises the question as to whether there are better ways to satisfy this need. Basically, this demand can be reduced with relatively simple actions that would reduce the heat in buildings – planting trees, installing shutters, using exterior cladding with higher reflectivity, or developing green roof systems. These methods can contribute to reducing the need for air conditioning, and at the same time improve the comfort level of homes and buildings without air conditioning. Cooling systems with low energy consumption, such as fans and self-evaporating air conditioners, make it possible to reduce the use of air conditionning with higher energy requirements, either by delaying their use, or reducing the demand for such systems. Finally, because the life span of dwellings often extends to 50 years and more, it will be important to design them for the anticipated impacts of climate change so that they include the installation of the most energy-efficient air conditioning systems (Lafrance and DesJarlais, 2006).

The level of knowledge regarding energy demand is quite advanced due to the relatively broad concern about energy security, and the modelling is to a large extent satisfactory. However it would still be useful to have a better grasp of the impacts on energy networks that might result from the increased frequency of extreme climate events and to study the consequences of various other climate scenarios.

The forecasts included here take into account the increased penetration of air conditioning systems in the health care sector, but do not include a more advanced adaptation strategy aimed at reducing the impact of expected heat waves on vulnerable populations (elderly and sick people).

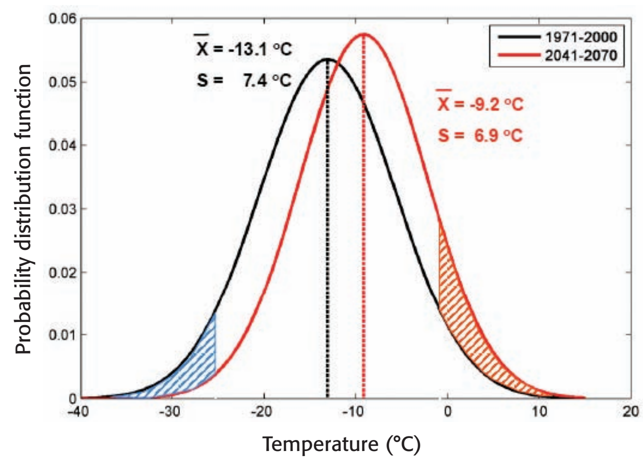


Figure 18: Winter (DJF) distribution of daily mean temperatures south of the 48th parallel simulated for current climate and projected future climate (2041-2070) from an ensemble of 5 CRCM4.2.3 simulations driven by 5 different CGCM3 simulations using the A2 scenario. The cross-hatched areas represent the 10th and 90th percentiles based on existing climate. $\overline{X}$ and S refer to the mean and the standard deviation of the distribution respectively.

Water resources

Quebec's territory contains significant quantities of fresh water, accounting for about 3% of all the renewable fresh water on the planet. These water resources are critical, in terms of both quantity and quality, for the economic, social and environmental well-being of Quebec. It is for the public good that the resource be used with a view to its sustainable development, which includes by definition a forward thinking attitude.

Over the years, many infrastructures have been built to profit from this resource, by individuals and companies as well as by municipalities and other levels of government.

These include infrastructures for water storage (dams, dikes, regulation structures), protection (bank protection, flood protection), water supply (surface water intakes, wells), water movement (drainage, bridges, culverts) and navigation (navigable waterways, locks).

Anticipated climate change suggests that we will see major disruptive effects on the water cycle. As pointed out in the section on hydroelectricity, and particularly in Figures 15 and 16, various climate projections suggest a change in the frequency and amplitude of summer and autumn peak water levels. Meanwhile, snowmelt flood could happen sooner and peak discharge reached during these flood would tend to be reduced. In summer, periods of low flow could be longer and more severe. Overall, we would experience greater variability in water discharge than currently observed, with an increased number of cases of isolated stress on hydrological systems.

As for water quality, increased temperatures and reductions in the amount of discharge during summer suggest a risk of degradation of some parameters linked to water quality. Furthermore, more severe low flows may increase the risk of some types of pollution problems in receiving environments by reducing the beneficial dilution of contaminants.

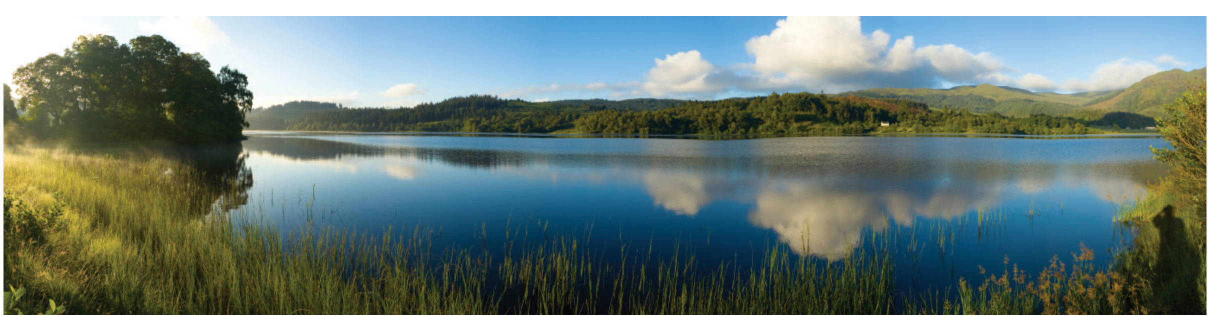
The possible increase in discharge fluctuations, paired with a possible increase in flash floods, increases the risk of bank erosion in different Quebec waterbodies. Finally, changes to the water regime brought on by climate change run the risk of destabilizing the provision from waterbodies to ecosystems.

The large number of infrastructures associated with water and their key role in the Quebec economy are reason enough to devote further study to climate change and its impacts on water resources. Changes expected in the characteristics of the water regime will require adaptations to the operation and upgrading of existing infrastructure related to water resources.

Adaptation may also require new infrastructures. Uses and development of water in Quebec depend to some degree on water availability and its range of variation over time. The infrastructures currently in place for managing and utilizing the water resources were designed to be efficient on the basis of historical data on average hydrological conditions and fluctuations.

In addition to these potential structural adaptations, thought must also be given to possible adjustments in terms of legislation and regulation of land use planning, as well as optimal management of our hydrological systems in the new context created by climate change.

Whether in rural or urban environments, we use water resources in multiple and important ways, among which: bottling, water supply for industry, municipalities, pisciculture, agriculture, and mining; as well as on site usage for hydroelectricity production, water transportation, fishing, sewage disposal and recreational activities. Given these multiple and often conflicting needs, adaptation of water management will have to involve the participation of all end users.



Finally, it is likely that the natural environment and ecosystems that are now in equilibrium – up to a point – with these same average quantities and historic fluctuations will be disrupted, and specific adaptation measures will be necessary.

Water supplies for Quebec's population and economy comes in part from the St. Lawrence River (about 45%), in part from lakes and rivers (35%) and in part from groundwater (20%). The following section begins by addressing the issues related to surface water of watersheds of southern Quebec and especially the St. Lawrence River, and then discusses the issue of groundwater. This will be followed by a discussion on some aspects of adaptation to climate change.

Surface water

Surface water represents about 80% of the total water volume used in Quebec (Mailhot *et al*., 2004; Rousseau *et al*., 2004). Its abundance in all regions of Quebec helps to explain the way of life of its populations as well as land use of its inhabited territory and the nature of economic activities.

Although it cannot expressly be linked to the effects of climate change, an analysis of data from 56 hydrometric stations in southern Quebec, comparing the 15 most recent years with the previous 15 years (Larouche *et al*., 2008), found that periods of low flow were more severe (-11%) and lasted longer (+3 days), peak snowmelt floods were less intense (-8%) and the variability in discharge was greater (standard deviation of +22%). Such behaviour is consistent with changes that climate projections suggest as impacts of climate change. It also appears that summer and autumn floods were higher over the past 15 years (+20%), while annual volumes did not show changes that were statistically significant. It should be added that although the differences between the two 15-year periods are important, they do not necessarily indicate statistically demonstrable trends.

In terms of statistical trends, a study by Jones (2008), looking specifically at the Massawippi river in Estrie, shows that even if some parameters have been significantly modified over recent years (reduction of snow on ground, more liquid precipitation compared to solid precipitation), this has not led to a statistically significant change in discharge.

However, it is expected that over the coming decades water resources will undergo similar impacts due to climate change, including earlier and reduced spring floods, more severe low flows, and changes in the intensity and frequency of summer and autumn floods. Changes in annual volumes of flow are also possible (Rousseau *et al*., 2003; Nantel *et al*., 2005).

To this effect, studies conducted over the past four years on the Châteauguay river watershed provide a good indication of the future impacts of climate change on the surface waters of southern Quebec.

Thus, the HYDROTEL and HSAMI hydrological models applied to the rivière des Anglais (a tributary of the Châteauguay river), made it possible to evaluate the impacts associated with six future climate simulations based on three global climate models (ECHAM4, HadCM3 and CSIRO) and two greenhouse gas emissions scenarios (A2 and B2), using the delta method for downscaling of simulation results (Chaumont and Chartier, 2005). As Figure 19 shows, peak spring floods would occur two months sooner in the future; occurring at the end of April in the period 1961-1990 but at the beginning of March by 2050. Despite increased precipitation, all these projections also indicate a reduction in summer low outflows, due to a more significant increase in evapotranspiration (Pugin *et al*., 2006). The projections diverge with respect to annual volumes of outflow. Those generated with the HadCM3 model show an increased annual volume of outflow, while the projections based on the ECHAM4 model show a significant drop, and those using the CSIRO model a smaller reduction. These differences are explained by different evolutions of projected temperature and precipitation from these climate models.

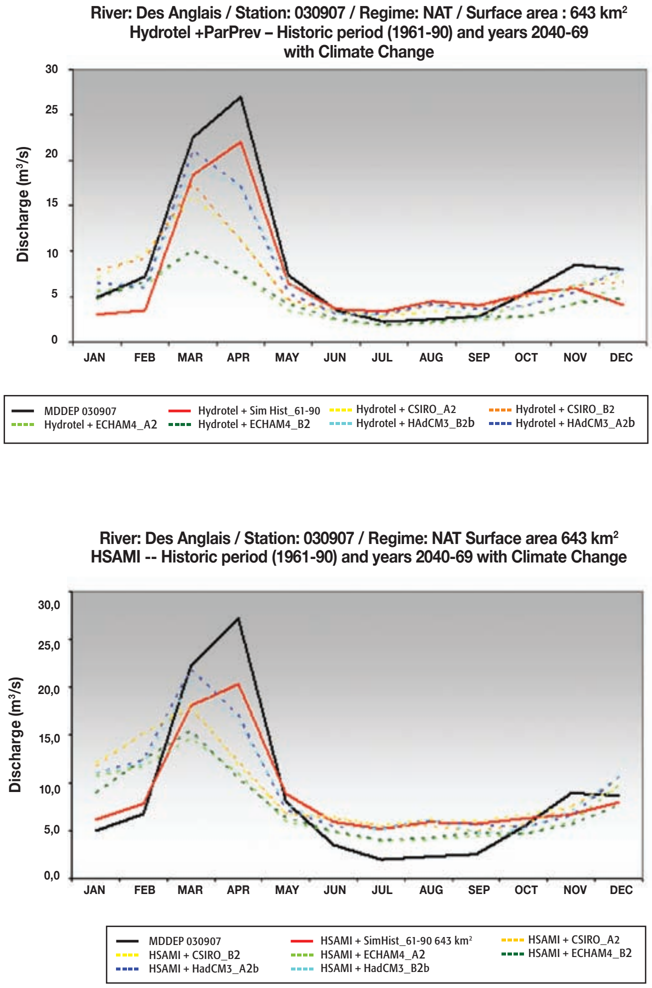


Figure 19: Mean annual hydrographs simulated with HYDROTEL (above) and HSAMI (below) hydrological models at the outlet of the Rivière des Anglais. The simulations are for the years 2040-2069 and the reference period of 1961-1990 (Chaumont and Chartier, 2005).

Similar results, from a larger variety of downscaling methods, were obtained for the Chaudière river watershed (Quilbé *et al*., 2008a). Moreover a study of three different modeling approaches for estimating evapotranspiration in the Chateauguay river watershed indicated an increase in annual evapotranspiration ranging from 79 mm to 141 mm (Vescovi *et al*., 2009).

Three approaches were also tested to estimate evapotranspiration based on climate simulations from the CRCM4 driven by the Canadian global model CGCM3 and based on the HYDROTEL and PROMET models (Mauser and Ludwig, 2002) using precipitation and temperatures from the same climate simulations. The results, which varied according to approaches, led to the completion of a study on the choice of hydrological models for this kind of evaluation under climate change, the first results of which were compiled by Ludwig *et al*. (2009).

On a more local scale, evaluations of the moisture content of the upper layers of soil in the Norton creek watershed (a sub-watershed of the Des Anglais river) using a water-balance model, show an increase in the need for farmland irrigation. This is due primarily to increased evapotranspiration. Given the environmental constraints associated with extraction of surface water, and despite the relative variability in the results of the different climate scenarios that were analyzed, it will likely be necessary to increase efforts at concerted planning of water use. This planning should be based on integrated and holistic management at the watershed scale in order to maintain the proportion of future irrigation needs currently supplied by the sub-watershed streams (Pugin *et al*., 2006).

Inundations generated by high water levels in rivers are among the most damaging (Ashmore and Church, 2001; Brissette *et al.*, 2003; Ouranos, 2004) hydroclimatic events Quebec faces (MSP, 1996). Caron (2005) and Mareuil (2005) conducted modeling experiments on this issue, again looking at the Chateauguay river watershed, and using a stochastic climate generator including monthly temperature and precipitation anomalies taken from three global circulation models: CGCM2, HadCM3 and ECHAM4. The scenarios resulting from the ECHAM4 model for the 2050 time horizon showed a statistically significant reduction in spring water levels for return periods of 2 to 500 years, while the scenarios from the HadCM3 and CGCM2 models produced similar results, but not statistically significant.

For the summer period, the HadCM3 model showed a slight but not statistically significant increase in flood intensities for all return periods while the ECHAM4 and CGCM2 models showed a statistically significant reduction of 8% to 10%. A complementary study (Laforce, 2008) on a different watershed, the Rivière du Nord, produced similar results.

Finally, it should be noted that for the Châteauguay watershed, the anticipated impacts of climate change would take the form of earlier spring floods and more severe low flows, but also of amplified or reduced flooding depending on the fluctuations of water levels in the St. Lawrence River. Indeed, while flooding from ice jams near the municipality of Chateauguay is mostly the result of the hydrological response of the watershed and the presence of ice accumulations on the river (Leclerc *et al.*, 2006), the recurring open water floods the municipality experiences are mostly the result of fluctuation of water levels in the St. Lawrence.

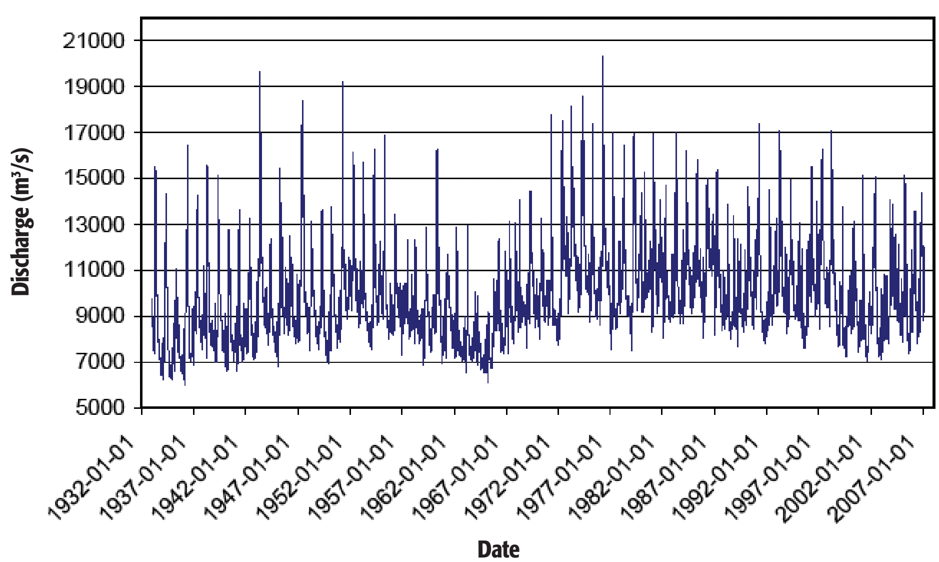
The St. Lawrence River

The St. Lawrence is one of North America's most important waterways. It extends from its source in the Great Lakes to a vast estuary more than 65 km across before emptying into the Gulf of St. Lawrence and the Atlantic Ocean. Dotted with more than 500 islands, it broadens into shallow lakes and reaches into seagrass beds and marshes, flooding riparian forests. It serves as the drainage basin for nearly every river in the inhabited regions of Quebec, and many dozens of tributaries double the river's discharge between the Great Lakes and the estuary.

The Saint-Lawrence is also one of the largest navigable rivers in the world, and the main river artery on the North American continent. In Canada, it has been developed to accommodate navigation along its entire length, forming the St. Lawrence Seaway, which was inaugurated in 1959. By connecting the Great Lakes to the Atlantic, the Seaway opened 3,800 continuous kilometres to navigation, creating maritime access for major industrial centres in Canada and the United States, as well as for the Prairies further west. The St. Lawrence represents more than half of Quebec's surface water and provides the water supply for many of its largest urban centres. It also constitutes an exceptional natural environment, most notably in Lac Saint-Pierre, recognized by UNESCO as a biosphere reserve of which 90% is undeveloped.

Data from the hydrometric network in the St. Lawrence highlight the cyclical behaviour of the river's hydraulicity. Figure 20 shows the evolution of monthly discharge at Sorel for the period 1932-2007. Examined all together, this data set illustrates the magnitude of the river's fluctuations in discharge, varying by some 14,000 m^3/s, from a low of 6,000 m^3/s to as much as 20,000 m^3/s (Morin and Bouchard, 2000).

Figure 20:
St. Lawrence discharge at Sorel, January 1, 1932 to January 1, 2007 (Morin and Bouchard, 2000; J.-F. Cantin, personal communication).



Two main watersheds, both of them regulated, supply the St. Lawrence – the Great Lakes and the Outaouais. The first is the largest, with a mean annual discharge of 7,060 m^3/s and varying between 6,000 m^3/s and 9,000 m^3/s. The second registers even greater fluctuations, with a discharge ranging from 1,000 m^3/s to as high as 8,000 m^3/s in the spring. Without regulation, the fluctuations in the two rivers would be even more pronounced. Streamflow regulation efforts generally reduce springtime discharge and increase it in autumn and winter.

According to a study by Croley (2003), which used the output of four global circulation models, the quantity of water flowing through Lake Ontario towards the St. Lawrence would be reduced by 4% to 24% on a year-over-year basis by 2050 compared to current levels. Fagherazzi *et al*. (2005) used a similar method and concluded that the Outaouais river, the main tributary of the St. Lawrence, would undergo a small reduction in discharge of between 1% and 8%. Lefaivre (2005) combined these two results and concluded that the level of the St. Lawrence in the Montreal sector will be reduced by a maximum of 20 cm to 120 cm depending on the scenario.

A reduction in discharge of this magnitude would have serious consequences for commercial navigation by considerably reducing the open water surface, especially in Lac Saint-Pierre which is quite shallow. Expected impacts on the exceptional natural environment of the lake are also of concern, given that drying wetlands would affect populations of fishes and migratory birds.

The river mouths of St. Lawrence's tributaries were also analyzed. Results along three rivers (Saint-François, Richelieu and Batiscan) indicated that climate change will influence the sediment load and the river profiles. However, a study by Verhaar *et al*. (2009) concluded that the impacts will vary greatly from one river to the next.

These three tributaries have different hydrodynamic characteristics at their mouths and different discharge thresholds at which various types of sediment are transported, while all are at different stages in their geomorphological evolution. It is worth noting that the sedimentary load in the Saint-François will likely decrease while loads in the other two rivers will likely increase.

Groundwater

Groundwater supplies 20% of the potable water in Quebec. Rivard *et al*. (2003 and 2008) determined that the annual recharge of the groundwater resource in Quebec has remained stable or diminished slightly in recent decades. A significant drop in the availability of ground water would have serious repercussions, especially in rural areas, where a sizeable proportion of the population (26% in the Chaudière-Appalaches, for example, as opposed to 10% for all of Quebec) obtain their water from private wells (Régie régionale de la santé et des services sociaux de Chaudière-Appalaches, 2001). The fact that there are still large knowledge gaps concerning this water resource makes the groundwater aquifers in Canada even more vulnerable. In Quebec, the mapping of the Châteauguay river watershed aquifer (Côté *et al*., 2006) and the new Quebec programme for developing knowledge of the groundwater resource (MDDEP, 2008a) are steps in the right direction. In addition, several research projects on this same watershed launched in 2006 and supported by Ouranos and the Natural Sciences and Engineering Research Council of Canada (NSERC) are trying to improve our understanding of systems involving both surface water and groundwater, partly with the aid of coupled modelling. This knowledge will contribute to the study of the vulnerability of aquifers at the local scale.

Adaptation measures

There are many possible adaptation methods to consider when it comes to water resources. These can be grouped into four main categories:

- updating legislation and regulations;
- upgrading existing infrastructure and building new infrastructure (intake structures, wells, dams, dikes, drainage, bridges, culverts, navigable waterways, locks, bank protection and flood protection structures);
- land use planning (flood zone management and land use restriction);
- optimizing water management (deployment of tools, integrated management, modifying infrastructure management).

A combination of these adaptation measures could help to minimize the adverse effects of climate change, and possibly even to profit from new opportunities brought by climate change.

Figure 21: Simulations of the current management plan for the Saint-François and Aylmer reservoirs for climate change impacts on the 2050 time horizon, according to the ECHAM4 A2, HadCM3 A2b and CSIRO A2 models and scenarios. Numbers in the table correspond to days in 30 years (1961-1990) during which management plan requirements (for specific uses) are not met. These requirements are for reservoir water levels or river flows (Fortin *et al.*, 2007).

negative impact
positive impact
no significant change

	Current Management plan				Adapted management ECHAM4 A2			Adapted management CSIRO A2		
	Reference Period	ECHAM4 A2	CSIRO A2	HadCM3 A2b	ECHAM4 A2	CSIRO A2	HadCM3 A2b	ECHAM4 A2	CSIRO A2	HadCM3 A2b
Rupture risk	0	0	0	0	0	0	0	0	0	0
Damage to reservoirs (upstream)	14	0	8	12	8	39	82	0	8	29
Tourism and recreation	481	2634	1137	480	461	192	61	2028	481	213
Water supply	0	310	15	0	0	0	0	272	0	0
Damage to Lake Louise	16	4	17	13	4	16	29	2	12	12
Energy production (downstream)	596	364	523	579	345	482	498	369	526	567

Current compromise (Reference Period)

Unnecessary or negligible adaptation (HadCM3 A2b)

Raise minimum level, Earlier filling period (Adapted management ECHAM4 A2, CSIRO A2)

Earlier filling period (Adapted management CSIRO A2, CSIRO A2)

Usage and exploitation of water resources is often carried out within a context of multiple and even conflicting needs. It is thus advantageous to engage all affected users in a participatory process. The watershed organizations created as part of Quebec's new water policy (Politique nationale de l'eau du Québec) are particularly appropriate for this task. Because watershed management is one of the best strategies for adaptation, a climate change perspective must be systematically integrated into management efforts. Ideally, adaptation solutions would involve integrated and global management adapted for the water cycle of the southern watersheds as well as the Great Lakes–St-Lawrence River system. This must be developed within a context of sustainable regional development, respecting socioeconomic and environmental realities.

Managing dams

This first example of dams management, aiming to meet multiple objectives simultaneously (flood protection, water supply, supporting wildlife and recreational activities, energy production), sheds light on the requirements and challenges involved in adaptation to the impacts of climate change on water resources.

Changing the management practices of dams serving multiple purposes is probably one of the most direct ways to adapt for the impacts of climate change on water resources for several reasons:

- the availability of simulation models (hydrology and management models) required for the application of climate projections;
- explicit, and very often quantified, management objectives in terms of water level or critical discharge – for example, flood protection implies that reservoir levels and outflows remain below known values to serve as constraints to the operations carried out at the dam, while protection of wildlife habitat may depend on precise levels and flow rates on specific dates to encourage spawning, among other things;
- access to round tables such as advisory committees that include representatives from the main stakeholders;
- the possibility that dam management plans can be adjusted.; Figure 21 shows the results of a study of adaptation options for existing management plans for the Haut-Saint-François in the south-central region of Quebec (Turcotte *et al.*, 2005; Fortin *et al.*, 2007). This study rests on a model simulating the daily application of the management plan for the Saint-François and Aylmer reservoirs. The modelling exercise showed that climate change, as simulated by the ECHAM4 and CSIRO models, would lead to a change in the allocation and trade-offs between the various uses of the water in the reservoirs. On the other hand, no major adaptation would be necessary if the climate becomes more humid, as the HadCM3 model simulation predicts. However, for the first two models, filling the reservoirs earlier and raising the minimum levels prove to be the appropriate adaptation measures.

Land use

Land use for example can – for various reasons that may or may not be linked to climate – lead to changes in both the requirements for and availability of water. A study by Quilbé *et al*. (2008b) using the HYDROTEL model and a reconstruction of historic land use, sought to clarify this relationship. The results show that there is a link between the surface area of agricultural land and the water regime. However, the application of two land use scenarios with contrasting characteristics known as "intensified agriculture" and "sustainable development," in combination with different climate change projections for the 2050 time horizon, produce highly variable results. This indicates that it is currently very difficult to select one or another land use scenario as the best way to counteract the negative impacts of climate change, but shows also the importance of considering changes in land use when carrying out impact studies.

Water management in urban environments

Adaptation in the field of potable water supply can be based on measures linked to infrastructure such as rehabilitation, relocation of specific water intakes, reduction in water lost in the network, or increase in the capacity of reservoirs, but also on optimization of current management practices that may result from, for example, a water conservation program.

The expected change in the recurrence of heavy rain events should result in more system overflows, sewer back-ups, and inundations. In the context of aging infrastructure, Mailhot *et al*. (2007a) highlighted the fact that the repercussions of a likely increase in intensities and probabilities of occurrence of heavy rain could be mitigated by:

- reviewing design criteria of buildings and infrastructure;
- new methods in using heavy rains statistics when designing (Duchesne *et al*., 2005);
- improved management of rainwater, particularly by better source control through optimal urban planning and maximizing infiltration.

Commercial navigation on the St. Lawrence

In response to concerns about the impacts for commercial navigation that might result from lower water levels, the Navigation Coordination Committee of the St. Lawrence Plan for a Sustainable Development commissioned a study of the adaptation options that would make it possible to maintain shipping and port activities at current levels (D'Arcy *et al*., 2005). The study shows that if declines in water level remain small, improvements to long-range forecasting would allow optimization of criteria for safety margins that carriers establish for overseas cargoes, thus reducing their vulnerability and serving as a relevant adaptation strategy at the same time. However, if drops in level are more important, adaptations at the organizational level, such as reorganizing maritime transport and related infrastructure, or at a technological level, such as adapting vessel design to minimize draught would be required. The study adds that although such adaptations are possible in theory, they would be difficult to apply given the context of ever growing trade activities and the fact that such changes would require major investment ($260 M to $1,000 M). Finally, adaptations of the physical environment, such as dredging and streamflow regulation structures, can reduce the vulnerabilities for maritime transportation, but not without significant environmental repercussions and necessary offset measures, that are difficult to cost with precision.

Several years ago, the International Joint Commission (IJC) carried out a massive study to evaluate different flow regulation plans. The study included an analysis of discharges under climate change conditions (IJC, 2006) and options for facilitating adaptation since the principle of adaptative management was one of the options being studied. In addition, the governments of Quebec, Ontario and the eight American states bordering the Great Lakes signed the Great Lakes–St. Lawrence River Basin Sustainable Water Resources Agreement in 2005, the goal of which is to control the use of water throughout the watershed, and particularly to forbid diversions of water outside the river basin. The Agreement made explicit reference to climate change and the precautionary principle (Great Lakes – St. Lawrence River Water Resources Regional Body, 2005). In Quebec, the substance of the agreement was framed in an Act to affirm the collective nature of water resources and provide for increased water resource protection.

The forest

Since the last glaciation, Quebec's forests have evolved under a harsh climate coupled with natural disturbance dynamics that are dominated by forest fires and insect infestations. This led to the formation of three major forest ecozones from south to north (see vegetation zones and sub-zones in Figure 22): the maple forest (11-15), the fir forest (7-10) and the spruce forest (4-6). During the last century, the climate warmed significantly, and the impacts of human activity on the forest, especially harvesting, substantially modified the forest landscape. These impacts have already changed the dynamics between the climate and the forest composition.

Climate warming, which is expected due to an increase in greenhouse gas concentrations and which will occur much more rapidly than observed in the past century, is likely to accelerate the disruption of equilibrium between climate and forest. This would lead to modifications in the composition and productivity of forest stands. The natural disturbance dynamic (fires and insects) and the frequency of extreme weather events (droughts and ice storms) are also likely to change. In this context, the decisions taken today with respect to forest management are crucial and must be based on the most up-to-date knowledge on the multiple and subtle effects of climate change on the forest ecosystems.

Growth and Productivity

Changes in temperature and the precipitation regime, as well as increasing concentrations of CO_2 in the air, all have an influence on the growth and productivity of forest ecosystems. A rise in temperature can translate into a longer growing season. Julien and Sobrino (2009) estimated that between 1981 and 2004, the length of the growth season increased on average by 0.8 days per year. Signs of a longer growing season are already noticeable; for example, Raulier and Bernier (2000), used climate models to establish that over a period of one hundred years, sugar maple buds began to open earlier by a few days. In the course of the 21st century, leaves of numerous other species in North America could emerge earlier by 9.2 days (Morin *et al.*, 2009) because of climate warming.

In addition to extending the growing season, a rise in temperatures could act directly on the physiology and the metabolism of trees and ipso facto increase primary productivity of forests, as long as such a rise in temperatures does not affect the availability of water (Price *et al.*, 1999; Kirschbaum, 2000). An increase in soil temperatures could also increase the rate of organic matter decay, increasing nitrogen availability for the root systems of trees (Van Cleve *et al.*, 1990; Kirschbaum, 1995; MacDonald *et al.*, 1995; Rustad *et al.*, 2000 and 2001; Verburg, 2005).

Figure 22: Vegetation zones and sub-zones in Quebec.
Quebec is divided into three vegetation zones: the northern temperate zone, dominated by broad-leaved and mixed stands; the boreal zone, characterized by coniferous forests; and the Arctic zone, with shrubby and herbaceous vegetation (MRNF, 2009b).

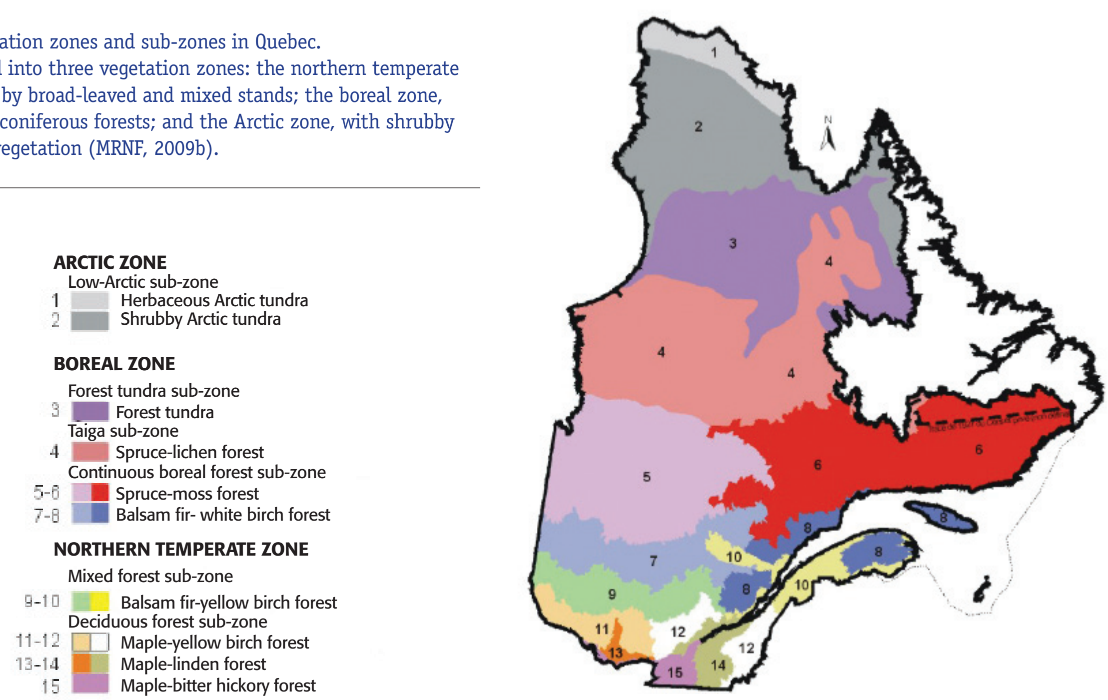


Figure 23 shows the discrepancy between growing degree-days for the 2041-2070 period in comparison to the reference period of 1971-2000 as simulated with the Canadian Regional Climate Model (CRCM). The number of degree-days in a given area is indicative of the quantity of energy available for the growth of vegetation. More specifically, this indicator shows the annual total number of degree-days above 5°C.

Figure 24 shows the median values projected by a set of global climate models as well as the associated standard deviations.

For the forested territory of Quebec, the median value projected for the set of global models shows an increase from approximately 300 to 400 degree-days, with higher augmentations in the south of the territory. Considering a large number of models makes it possible to associate a dispersion value with the median scenario.

In the southern forest, the maple stand region, increases in the order of 400±200 degree-days are predicted, whereas in the northern sector, the spruce region, increases of 300±175 degree-days are predicted. The simulation from the Canadian Regional Climate Model indicates rises in degree-days somewhat higher than the median for the set of global models, but the higher resolution allows for a better appreciation of the spatial gradient of anticipated changes. Overall, the predicted increases in degree-days are quantitatively very high, in the order of 35% to 45%.

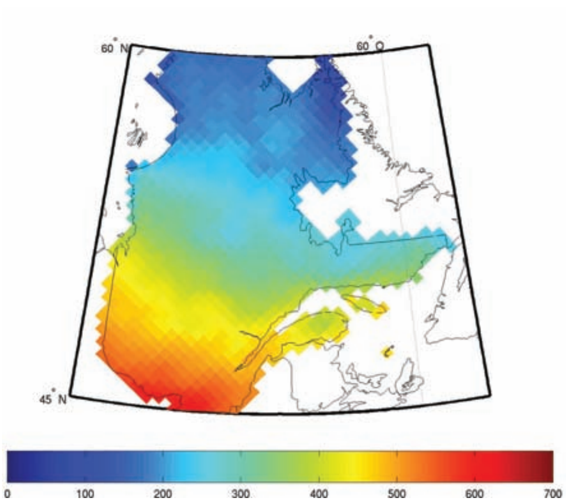


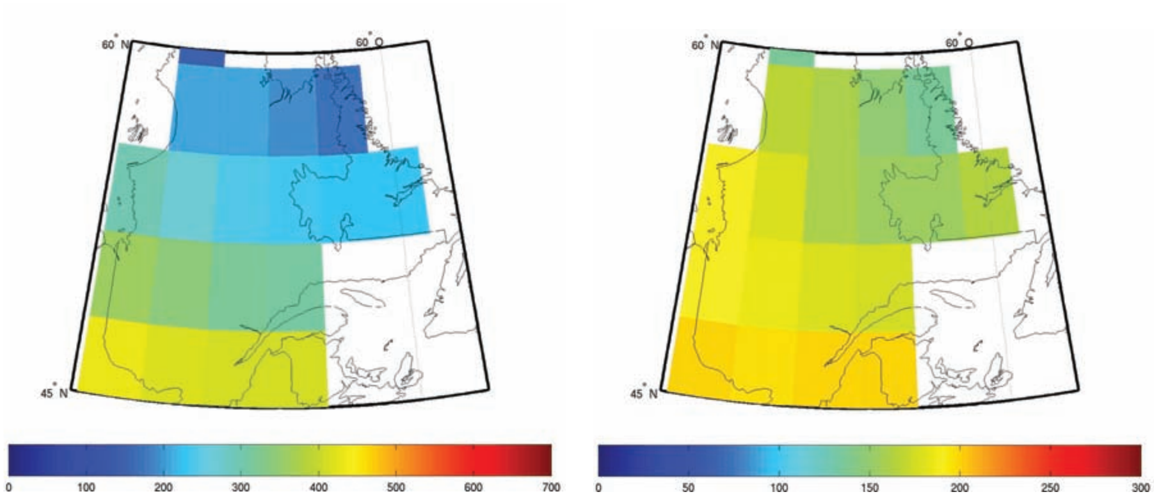
Figure 23: Differences in growing degree-days between the 2041-2070 period and the 1971-2000 period, based on two Canadian Regional Climate Model simulations (CRCM version 4.2.0) and scenario SRES A2 (Music and Caya, 2007).

Another important indicator for the forest is the length of the growing season, a variable defined as the maximal consecutive number of days without frost. For the 2050 time horizon, global model predictions as well as those of the regional model show increases in the order of 25 to 30 days (Logan *et al*., in preparation). Given that the growing season is already rather short, particularly for conifers in the boreal forest, such an increase is quantitatively significant.

The second factor is an increase in atmospheric CO_2 concentrations, which is thought to have a fertilizing effect on forests, increasing the photosynthetic and water uptake efficiency of plants and leading to an increas e in net primary productivity (Drake *et al*., 1997; Ainsworth and Long, 2005; Norby *et al*., 2005). Several studies have already recorded increased forest productivity during the last decades (Gielen and Ceulemans, 2001; Nemani *et al*., 2003; Boisvenue and Running, 2006). In the long term, however, such gains could be offset by the acclimatization of trees to the new CO_2 concentrations (DeLucia *et al*., 1999), or limited by lack of nutrients such as soil available nitrogen (Luxmoore *et al*., 1993a; Luo *et al*., 2004).

Based on the probable evolution of the variables discussed above, it seems that the climate context of 2050 will be more favorable to forest growth. However, the overall forecasts regarding precipitation appear less positive. Even though the CRCM is predicting marked increases in annual precipitation (see Figure 25), principally in winter and in Northern Quebec (Logan *et al*., in preparation), changes will be minimal during the growing season (June, July and August) in most of Quebec's forests, except in Northern Quebec. In general, these results agree with those from the global model simulations presented in Figure 26. Nearly identical precipitation combined with higher temperatures could increase the evapotranspiration of plants and cause soil water content decreases. Such changes could have consequences for both the composition and productivity of forests.

Figure 24: Median growing degree-days differences according to several global models (to the left) and associated standard deviation (to the right), from 70 simulations using the SRES A1B, A2 and B1 scenarios (adapted from Logan *et al.*, in preparation).



Considering these possible effects of climate change on forests, preliminary results of growth prediction models conducted using a scenario with double the concentrations of CO_2 foresee an increase of net primary productivity of forests in Eastern Canada, while those in Western Canada would be inversely affected (Price and Scott, 2006). Most of the models are, however, based on specific climate/growth relationships and do not take into account factors potentially unfavorable to productivity. For example, species genotypes that are present in a given ecosystem are in general highly adapted to the prevailing climate. In this respect, Andalo *et al*. (2005) and Beaulieu and Rainville (2005) demonstrated that when white spruce seeds from Quebec were planted in areas 4°C warmer and with slightly more abundant precipitation than in their area of origin, their productivity dropped significantly. Forests might require several generations to adapt to new conditions resulting from climate change.

The evolution of forest ecosystems in the face of climate change is not solely dependent on their direct response to the factors listed above, and this must be taken into account. The forest is also indirectly affected by the climate through its influence on the regime of natural disturbances, such as insect infestations, droughts and fires.

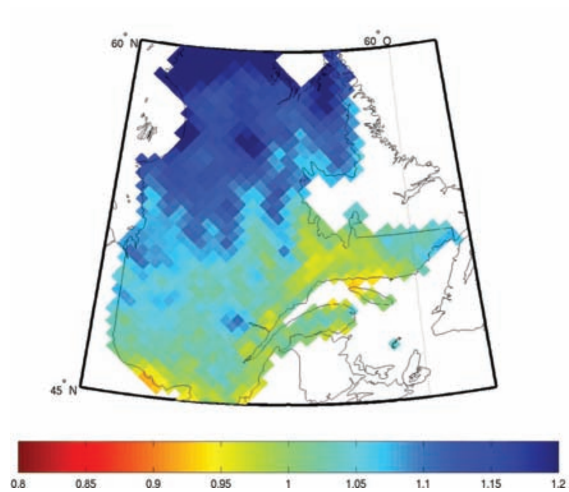


Figure 25: Results of precipitation simulations during the growing season, for the 2041-2070 period in comparison to the 1971-2000 period, based on two CRCM simulations (CRCM version 4.2.0) and the SRES A2 scenario (Music and Caya, 2007).

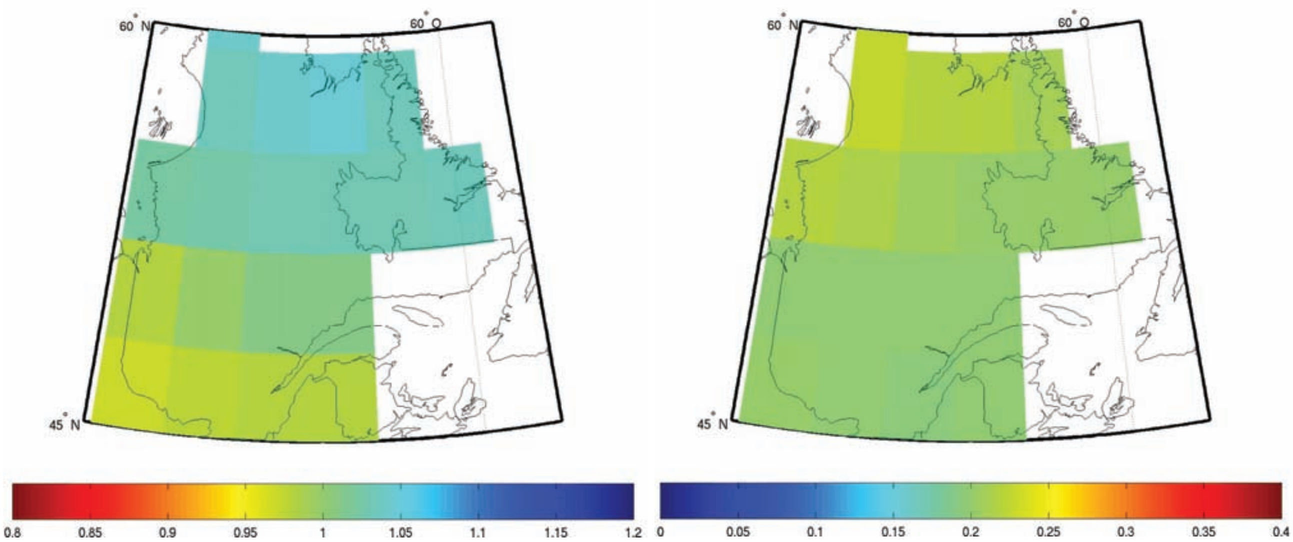


Figure 26: Results of precipitation simulations during the growing season, for the 2041-2070 period compared to the 1971-2000 period (median on the left and standard deviation on the right) based on 127 simulations using several global models and the SRES A1b, A2 and B1 scenarios (adapted from Logan *et al.*, in preparation).

Migration

One of a forest's adaptation and acclimatization strategies is the migration of species and communities. In a scenario with double the concentration of atmospheric CO_2, models predict that different biomes would have the potential to shift over significant geographical areas both in latitude and longitude. The expected 3.2°C increase in the mean annual temperature between now and 2050 in central Quebec would lead to a climate zone shift of 515 km to the north. A forest in equilibrium in such a climate would be much different than that of today. For example, the sugar maple domain could extend as far as Baie-Comeau, whereas the distribution range of black spruce would expand drastically towards the north.

However, for the forest communities to be able to "follow" the speed of climatic changes, they would have to migrate 10 km per year. In reality, the migration velocity of trees is much slower, reaching 10 km to 45 km per century (Davis, 1981; Huntley and Birks, 1983). In addition, several factors are likely to slow down this movement, including the fragmentation of forest ecosystems (Schwartz, 1992). Given the differences in migration speed from one species to another, the shift could also lead to new forest communities, thereby affecting interactions between species (Kirschbaum, 2000; Hansen *et al*., 2001). Finally, soil fertility and water-holding capacity could also limit the shift of trees northward, since the nutrient needs of the forest vary from stand to stand.

For example, maple stands have greater nutrient needs than fir or spruce stands (Houle, 2006). Consequently, the migration of ecosystems, which would occur over many centuries, would clearly be slower than the speed at which habitats are modified as a result of climatic changes (Weber and Flannigan, 1997; Parker *et al*., 2000; Price *et al*., 2001; Malcolm *et al*., 2002; Neilson *et al*., 2005; Aitken *et al*., 2008).

Disturbances

The regime of natural disturbances plays an important role in the shaping of the forest landscape: it has an effect on the composition, the structure and the processes inherent to ecosystems. Such disturbances include insect proliferations, forest fires, diseases and extreme climatic conditions such as droughts, ice storms and high winds. A change in climatic conditions would influence the severity, the frequency and the extent of these disturbances.

Climate change could affect the distribution and abundance of insects, which could adapt quickly given their high mobility and reproduction rates. The metabolic rate of insects could benefit from higher temperature (Ayres and Lombardero, 2000). Thus the frequency, intensity and length of infestations could increase, making forests particularly vulnerable (Logan *et al*., 2003). 2003).

Based on a model at the landscape scale, Régnière *et al.* (2005) demonstrated that the distribution range of the spruce budworm (*Choristoneura fumiferana* [Clem.]) could increase significantly. It would also cause more damage since infestations would last longer and the percentage of defoliation would be higher (Gray, 2008). In addition, due to climate change the Quebec forests could be greatly affected by invading exotic insect species. For example, the distribution of the gypsy moth, (*Lymantria dispar* [L.]) could progress northward to reach the southern part of Quebec, the mountain pine beetle (*Dendroctonus ponderosae* [Hopk.]) could extend ove the entire boreal forest from Western Canada to Quebec and the Maritimes, while the Asian longhorned beetle (*Anoplophora glabripennis* [Motschulsky]) could invade the maples, elms and birches of southeastern Canada (Carroll *et al.*, 2003; Gray, 2004; Peterson and Scachetti-Pereira, 2004).

Climate warming could also increase the frequency of forest fires in several ecosystems, especially because of a longer growing season and an increase in lightning strikes (Wotton and Flannigan, 1993). Several observations have already demonstrated an increase in extreme fire episodes linked to recent climatic changes (Podur *et al.*, 2002; Gillett *et al.*, 2004). In a scenario with triple the concentrations of atmospheric CO_2, Flannigan *et al.* (2005) estimated that by the end of the century, the area of burnt forests could double annually in Canada. In Quebec, the change in fire frequency could be rather variable depending on the geographical region: it could increase in Northern Quebec but stay the same or decrease in the western and southern parts of Quebec (Bergeron *et al.*, 2004).

Current models predict an increase in extreme weather events (intense precipitation, high winds, hurricanes, ice storms) in North America, although some uncertainty persists (Field *et al.*, 2007). An increase in the frequency of such events could modify the dynamics of populations and communities and alter forest ecosystem processes (Williamson *et al.*, 2009).

Finally, climate warming could disturb the frost dynamics of the forest soil. A decrease in the thickness of the snow cover, its discontinuity or early thaw would expose the soil to more frost, potentially resulting in significant damage to roots, which would have an adverse effect on the growth of trees (Boutin and Robitaille, 1995). Less snow cover and a shorter winter could also influence the planning and carrying out of forestry operations, notably by curtailing access to sites in winter, increasing the potential for soil deterioration and increasing seasonal job fluctuations.

Maple syrup production

Quebec is the largest maple syrup producer in the world, and the activity generates gross revenue of more than $200 million for the numerous Quebec producers. It is a well-accepted fact that the quantity of sap produced by each sugar maple during the spring sap run is directly influenced by climatic conditions. The ideal conditions entail a series of days during which the temperature falls below zero during the night and rises above zero during the day; it is therefore relatively easy to link the quantity of daily sap production to the specific climate of a given area.

Until very recently, there were no models to link the total provincial annual production of syrup to the climate. A model now exists that predicts 84% of the variability in annual production (expressed per tapped tree) from four monthly variables. Based on this model, Duchesne *et al.* (2009) have used global climate scenarios to estimate the effect of climate warming on the production of syrup.

The results indicate that average production could be diminished by 15% and 22% in 2050 and 2090 respectively. Increasingly warmer Aprils would account for most of this future decline. The anticipated losses could possibly be less, however, if sugar maples can adapt and the maximum sap production period arrives 12 and 19 days earlier, respectively, in 2050 and 2090. The fact that sap run dates vary significantly from one year to the other suggests that sugar maples have a degree of adaptability, but this variability is currently poorly documented. A better quantification of inter- and intra-annual variability would improve our understanding of the effects of climate change on the production of maple syrup.

Adaptation strategies

Since forest ecosystems will likely be greatly affected by climate change, forestry management practices must be adapted in order to reduce the vulnerability of the forest and maintain the viability of the industry. Adaptation mechanisms will allow us, among other things, to:

1) benefit from new opportunities;
2) reduce the potentially negative impacts of climate change; and
3) reduce the risks associated with climate change (Williamson *et al*., 2009).

Adaptation and acclimatization strategies must include awareness initiatives as well as monitoring and management of forests. Several actions could be envisaged in order to limit the effects of climate change. Taking climate effects into consideration in the strategic planning of forest management could minimize the propagation of fires and the proliferation of insects and diseases. Determination of forest potential should also factor in the impact of climate change on the productivity of the various species harvested.

Another adaptation option could be to facilitate the migration of forests by planting species and genotypes that are better adapted to the new climate conditions and limit habitat fragmentation (Spittlehouse and Stewart, 2004). One more concrete example would be to adapt forestry practices to changing conditions by modifying infrastructure and equipment.

Conclusion

In summary, climate change will affect forest productivity and composition. The current state of knowledge does not identify with certainty the net impact on forest productivity, although it could be positive for the midterm. The frequency and intensity of natural disturbances, the proliferation of pathogens and destructive insects as well as the frequency of extreme climatic events could all increase. Given the sensitivity of Quebec's forests to climatic changes and their socioeconomic significance, it is imperative that adaptation strategies be developed and put into place in order to reduce the negative impacts of climate change.

Agriculture

Agricultural activity in Quebec is concentrated mainly in the South, where climate and fertile soils are favourable for farming, especially in the central regions (Montérégie, Chaudière-Appalaches and Centre-du-Québec); these three regions produce more than 58% of total agricultural earnings (MAPAQ, 2008a). The total area under cultivation in Quebec, which was as high as 2.5 million hectares in 1931, had dropped to 1.6 million hectares by 1991. Since then it has begun to expand again, with 1.9 million hectares under production in 2006 (see Table 6). At the same time (and similar to the case of most developed countries), the number of farms has fallen considerably, meaning an increase in the average size of a farm (Statistics Canada, 2007).

In 2006, the agricultural industry in Quebec had a gross domestic product (GDP) of $2,840 million and employed more than 60,562 people. Animal products and livestock accounted for 68% of agricultural income in Quebec, with dairy products accounting for 30%. Vegetables, grain corn, horticulture and nursery products, maple products, potatoes and soybeans were the main plant production and accounted for more than 74% of income from crops (MAPAQ, 2008b).

Climate and agriculture

Climate, along with the soil type and quality, is a major determining factor for agricultural activities. Climate and soil have a major influence on crops, but also for livestock farming in terms of feed production, among other things.

The length of the crop growing season and the accumulation of heat during this season are the main agro-climatic factors governing crop selection and yield. Growers select hybrids and varieties based on the number of degree-days (a measure of the accumulation of heat during the growing season) that usually occurs in a given region. The higher the number of degree-days in the growing season, the greater the potential yield for hybrids and varieties.

Relatively cool and humid climate conditions in Quebec's agricultural areas are conducive to forage crops and cereals such as wheat, barley, oats and rye, which explains in part the importance of dairy production. Land dedicated to crops that are more reliant on heat, such as corn and soybeans, tends to be concentrated in the southern parts of Quebec. It is worth noting that the productivity of crops that require more heat is usually greater than for crops that are better adapted to cool climates.

According to Yagouti *et al.* (2008), there was a statistically significant increase in the number of growing degree-days above 5°C between 1960 and 2005 at 38 of the 53 weather stations in southern Quebec included in their study, making the season more favourable for most crops. On the other hand, there was no detectable trend in the length of the growing season; the growing season increased in a third of the weather stations studied, and decreased in the others, but in neither case was the change statistically significant.

Interannual climate variability can indicate the sensitivity of the agricultural sector to climate conditions. For example, in the 1987-2001 period (see Figure 27), the greatest drop in grain corn production took place in 2000, a year marked by excessive moisture and insufficient sunlight to promote growth (Environment Canada, 2002). As a consequence, crop insurance compensations for corn reached a record level of $97 million in 2000, compared to $191,000 in 1999 (La Financière agricole du Québec, 2006). During the same period, the sub-regions showed different responses to the impacts of climate variability due to their different biophysical environments: soil type, topography, temperature (Bryant *et al.*, 2005).

Table 6: Surface Area under cultivation and number of farms in Quebec, 1931 to 2006 (Statistics Canada, 2007).

	1931	1951	1971	1981	1991	2001	2006
Surface area (x 1000 ha)	2,485	2,484	1,755	1,756	1,638	1,850	1,933
Farms [1]	135,957	134,336	57,549	42,646	31,160	26,036	23,967
Surface area per farm (ha)[1]	18	17	30	41	53	71	81

[1] Number of farms declaring surface area under cultivation for the 1971-2006 period, all farms for the 1931-1951 period.

Potential climate change impacts

In Quebec, the main limits to agricultural production are the short growing season and relatively low number of degree-days. Climate scenarios for the coming decades indicate that climate conditions may be more favourable for some crops. However, these same conditions could aggravate pressure from crop pests and the risks of soil erosion. In addition, increased concentration of atmospheric CO_2 will have a direct effect on crop growth by increasing net photosynthesis (Long *et al*., 2006) and can also affect the leaf/root ratio of plants (Ziska and McClung, 2008). The net effect may be positive or negative depending on complex and sometimes unpredictable interactions of all these factors, and may result in revenue gains or losses depending on the crop, the intensity and rapidity of climate change, and of course the response of growers.

Temperatures

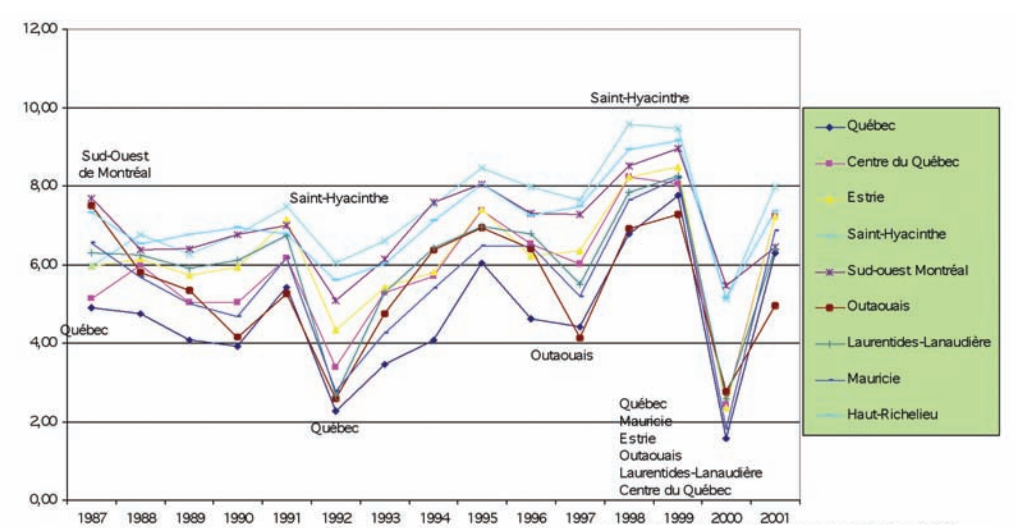
Significant growth in agricultural potential is predicted in coming years for crops such as corn and soybeans that benefit from summer heat and a longer growing season (Bootsma *et al*., 2004, 2005a and 2005b). Their cultivation might extend into new regions with the appropriate soil and topography, such as the Saguenay–Lac-Saint-Jean, Abitibi and the Bas-Saint-Laurent–Gaspésie. According to the same studies, climate change might be less favourable for small grain crops yields. As for forage crops, predictions are that the number of harvests per year might increase (Bélanger, 2002), but nutritional quality might diminish (Gitz *et al*., 2006).

Climate conditions outside the growing season will also have implications for agriculture, especially for perennial plants. For forage crops, which represented about 40% of hectares under cultivation in 2007 (ISQ and MAPAQ, 2009), warmer autumns, reduced snow cover and increased winter rains might increase the risk of winter mortality (Bélanger *et al*., 2002). In current commercial apple producing regions of Quebec, apple trees might be exposed to a lower risk of intense cold in winter, while the risk to buds of spring frost might remain unchanged (Rochette *et al*., 2004; Lease *et al*., 2009)

Precipitation

Given that the majority of climate scenarios for southern Quebec do not show any significant increase in precipitation during the growing season, there is an increased probability of water stress resulting from increased evapotranspiration brought on by higher temperatures. Since water-use efficiency in plants increases in a CO_2-enriched atmosphere (Bunce, 2004), the combined effects of these factors on crop productivity is unknown.

Excessive water is also devastating for agriculture, and climate change could increase the likelihood of events of this nature. Aside from its direct impact on crops, precipitations have a major influence on runoff, soil erosion and water quality. This means that it is important to consider not only the total amount of precipitation, but changes in the rainfall intensity and the rain/snow ratio of precipitation (Nearing *et al*., 2004). The spring snowmelt period is particularly conducive to soil erosion and to the loss of soil nutrients (Beaudet *et al*., 2008).



Date source : La Financière agricole du Québec (2004)

Figure 27: Changes in grain-corn yield as reported by farmers in their compensation claim declarations, 1987-2001, in different agricultural regions of Quebec (Bryant *et al*., 2007)

However, soil's vulnerability to water erosion depends also on agricultural land use. In a historical modelling study of the Chaudière River watershed (Savary *et al*., 2009), we can see that the annual depth of run-off, sediment load and low water discharge at the watershed outlet were heavily influenced by changes in the extent of land under cultivation. In a study by Quilbé *et al*. (2008b) it was noted that uncertainties linked to climate change scenarios did not allow for the evaluation of the impact of different land use scenarios on the various hydrological parameters being studied.

We do know that the land management choices made by agricultural producers can increase the risks for soil erosion in the case where an expansion of the cultivated area leaves the soil exposed to erosion. However, these risks can be reduced with improved soil conservation practices and water resource management.

Other stress factors

There is a risk that climate change will increase the thermal and water stresses that are a constant threat to crops and especially to horticultural production. A simultaneous or successive combination of different climate stress factors causes immediate damage to plants or makes them more susceptible to disease. More accurately, when the temperature changes radically and too rapidly, plants are unable to adjust at the same rate, and we can see problems related to sun exposure such as sunscald and crown canker in carrots, lettuces, radishes and a good number of other vegetable crops. We can also see cases of root asphyxiation in potatoes, corn and soybeans resulting from episodes of heavy rain, which fill low spots with several centimetres of water and create asphyxiating conditions for plant roots. In these circumstances, secondary fungi can attack the plants if the excess water does not drain off in time.

Changes in pathogen and insect populations are inevitable, as they are directly affected by temperature and humidity. However it remains extremely difficult to assess the magnitude of these impacts. This is due to the sometimes large differences between climate change scenarios, to the nonlinear responses of biological systems to environmental parameters and to the unknown capacity of organisms to genetically adapt to new environmental conditions (Scherm, 2004). The effectiveness of weed control treatments can also diminish, partly due to the direct effect of an increased concentration of atmospheric CO_2 on the root growth of weeds (Ziska and Goins, 2006).

Climate change will also have consequences for the livestock production that dominates agriculture in Quebec. The dangers posed by heat waves were amply illustrated in July 2002 when at least 500,000 poultry died, despite modern ventilation systems. On the other hand, milder winter conditions may result in greater weight gains for beef cattle raised outdoors, and a reduction in heating requirements for poultry and pig production facilities.

Socioeconomic factors

Preparing an integrated portrait of the potential impacts of climate change on the agricultural sector has to include consideration of the decision-making context within which farmers operate (Wall *et al*., 2004). The European ACCELERATES project (Assessing climate change effects on land use and ecosystems), an attempt to integrate diverse biophysical and socioeconomic models in order to assess the future sensitivity of European agrosystems (Rounsevell *et al*., 2006), concluded that the main impacts are related to socioeconomic scenarios rather than climate ones. The inherent uncertainly of these scenarios makes it difficult to draw clear conclusions about the future of agriculture.

Many other factors influence agricultural activities, including changes in domestic and international markets resulting from trade agreements, the effects of government support programmes on agricultural revenues, changing technologies, the management capacities of farming enterprises, access to credit, and environmental regulations. It is particularly important to take into account the impacts of climate change on agriculture outside of Quebec, which could potentially cause changes in world markets for agricultural products at least as great as the direct impacts on agricultural production within the territory.

Adaptation strategies

Agricultural producers could substantially reduce the impacts discussed in the preceding paragraphs by adopting technologies and practices already in use in areas that are currently living with conditions like those expected as a result of climate change in Quebec. The capacity of farmers to adapt, with institutional support, will determine the degree to which agricultural production will decrease or increase due to climate change. That said, the agricultural community has repeatedly demonstrated an enormous capacity to adapt to change, especially in terms of climate.

Agricultural enterprises

In the field, agricultural producers believe they have the tools and methods to adapt the management of their farms to climate change, at least in the medium term (André and Bryant, 2001; Bryant *et al*., 2007). Planting and harvest dates can be adapted to changes in the growing season, as shown in a study by Smit *et al*. (1997), who observed that farmers take into account the climate conditions of the previous year when selecting their corn hybrids, farmers will also choose more productive cultivars that are currently grown further south. Although crop diversification is often considered to be a strategy for managing climate change risk, it actually runs counter to a strong current trend towards specialization, as demonstrated by Bradshaw *et al*. (2004), who concluded that despite increased regional crop diversification in the Canadian Prairies after 1994, farms themselves were more specialized.

Certain agricultural practices, such as the establishment of riparian buffers, management of crop residue, and suitable dates and methods of fertilizer application, have been developed to promote production while protecting the environment. If rainfall intensity increases, these practices would need to be reassessed and improved. However, a longer growing season would support sowing cover crops after the main crop has been harvested to protect the soil from the effects of erosion and the leaching of nutrients.


Photo : Marc Lajoie, MAPAQ

Decreased availability of water will make it absolutely essential to improve water management. Already, several micro-irrigation projects are taking place in horticultural crop fields. The method uses water more efficiently, a plus for the environment.

As for livestock production, certain recommendations involving animal density in buildings, feeding, and ventilation and misting of facilities, will help producers to reduce the stress their animals experience in hot weather (Blanchard and Pouliot, 2003). Animals raised outdoors would benefit from more shelters and waterers in summer.

At the institutional level

Many programmes and regulations set standards for agricultural practices. All these rules are in some way connected to the projected climate, including the capacity of manure storage facilities and deadlines for planting, harvesting and manure spreading. When these standards are revised, it would be timely to factor in climate change and encourage producers to adapt their practices to this expected change.

With the help of government resources, certain losses connected to difficult climate conditions can be prevented or reduced. The Réseau d'avertissements phytosanitaires (Quebec's phytosanitary warning network) informs producers about the presence of and changes in crop pests, as well as the most appropriate interventions, based on forecasts from mathematical forecasting models using climate data. Bourgeois *et al*. (2004) emphasized that climate change will make it necessary to revise these models to take into account the nonlinear responses to higher temperatures. The same applies to activities related to the issue of water, where planning and coordination at the regional level will be necessary. A number of initiatives are under way to encourage watershed management practices that promote better water quality and protect biodiversity in rural environments.

The agricultural sector is directly dependent on climate conditions, and will certainly have to adapt to the new climate reality. A good number of these adaptations will be spontaneous, especially within agricultural enterprises. The various institutions in the sector provide important support to producers faced with the vagaries of climate. Integrating the issue of climate change into their services will help them to promote and facilitate the process of adaptation to climate change within the agricultural sector.

Transportation

Transportation is essential to daily life. By ensuring the movements of people and goods that are necessary to cultural, social and economic activities, transportation is also one of the primary means of communication. In Quebec's economy, efficient, reliable and safe transportation systems represent a considerable asset since their efficiency is an important component of productivity and competitiveness for business within Quebec and trade beyond its borders. Even a momentary disruption, particularly in remote areas, can increase risks to human health, diminish the quality of life and cause significant economic losses for producers of goods and services, especially in the agricultural or tourism sectors. Quebec's total transport demand (i.e., the total purchases of goods and services related to transport) accounts for an estimated 12% of the gross domestic product.

Impacts

Changes in the average temperature and precipitation as well as in the frequency and severity of extreme climatic events would affect both the use of modes of transport and the infrastructure required for their operation. Although land transport would be particularly affected, marine and air transportation would also suffer because of the pressure such events would put on the transportation infrastructure.

Land transport

Internally, land transportation is responsible for most of the transport of people and goods. In this respect, the road network plays a primary role, followed by the railways, which carry a significant percentage of goods.

Quebec's road network includes approximately 185,000 km of freeways, national and regional highways, streets and roads, including 20,000 km of main roads that crisscross the vast provincial territory and link the various regions of Quebec. There are also close to 12,000 bridges, tunnels, retaining walls, culverts and other works.

Winter viability

Driving in winter on Quebec's roads is quite a challenge, mostly because of harsh and changing conditions. Cohen and Miller (2001) predicted that in the northern hemisphere, winter storms would be less frequent but more intense.

In their analysis of climate regional simulations and climatic indicators associated with road transportation in southern Quebec, Brown and Chaumont (2009) concluded that, depending on the climatic scenarios, the winter climate for the period 2041-2070 would be warmer and more humid with frost beginning later and ending sooner, which would decrease the frost period by 24 days. The annual number of snowfall events would decrease while winter rain and mild spells would be more frequent. The quantity of precipitation per event would also increase by about 10% and 20% for snowfall and winter rain respectively. The management of winter ma intenance operations, which encompasses all the measures taken to combat or adapt to the deterioration of driving conditions in winter, would become therefore more complex, notably in the presence of several types of precipitation (rain, snow, black ice and ice pellets).

Pavement

In southern Quebec, temperature can fluctuate by 25°C in a few hours. For more than four months, the soil freezes to a depth of 1.2 m to 3.0 m and precipitation can reach up to 1000 mm per year (MTQ, 2006b). In the spring, after being subjected to frost heaving, the roads must support heavy loads while pavement resistance is reduced by 40% (Frigon, 2003). According to scenarios derived from climatic models, an increase in mild spells is to be expected (MDDEP, 2006c). Freeze-thaw cycles, the depth of frost and an increased presence of water on the pavement accentuate certain phenomena of surface degradation; these new weather conditions would have an effect on road conditions and, consequently, on maintenance costs.

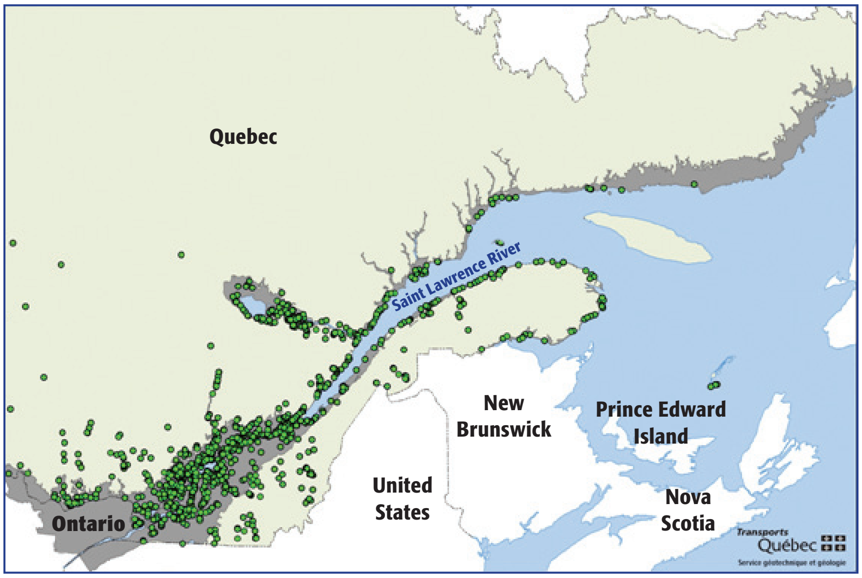


Figure 28: Map inventory of action requests for landslides in Quebec between 1972 and 2005 (map provided by the MTQ, personal communication). The dark grey area shows the limits of postglacial marine transgression that left clay deposits.

Landslides in Quebec

Hundreds of landslides occur each year in Quebec, most of them in clay soils (see Figure 28). Landslides are known to be triggered by two main factors: water infiltration in the soil caused by snowmelt in the spring or by precipitation; and the progressive erosion of shorelines by watercourses or destabilization caused by human intervention. Extreme weather events, as we know, often take the form of heavy rain, frequently causing floods, as evidenced by the numerous landslides that occur in the spring or following exceptional weather events — such as the downpours of 1996 in Saguenay–Lac-Saint-Jean, where more than 1000 landslides occurred in less than 36 hours (MTQ, 2000).

Landslides

Most of the inhabited territory of Quebec is composed of clay soils conducive to landslides [see boxed insert], and any increase in the number of landslides would have significant consequences for the safety of people and goods. Although knowledge is limited on the links between climate and the geology of southern Quebec, it is feared that an increase in intense precipitation attributable to climate change would translate into an even greater increase in the number of landslides and road network disruptions.

Marine transport

Marine transportation plays an essential role in the transport of goods, especially in supplying the coastal communities of the Gulf of St. Lawrence and of Nunavik, as well as in international trade.

With respect to conditions in the Gulf and Nunavik coastal communities, a significant extension of the navigation season can reasonably be expected, which would make supplying these communities easier and less costly. However, a diminution in the ice cover could make marine facilities more vulnerable, which would require modifying their design.

One of the main concerns arising from climatic changes in the field of transportation is linked to the expected lower water levels in the St. Lawrence River corresponding to lower levels in the Great Lakes. D'Arcy *et al*. (2005) demonstrated that by 2050 the water level of the St. Lawrence in Montreal could be as low as 1m below the chart datum. This drop would diminish further downstream and would be insignificant at Bécancour. Given the rather thin margin between the river shipping channel bottom and the hull of ships, lower levels could require in the short term the reduction of cargo ship tonnage. Such a reduction would have significant economic impacts, affecting the competitiveness of marine traffic on the St. Lawrence River in favour of other marine transportation routes.

In contrast, the open water or ice-free navigation season in the St. Lawrence River and Gulf could be lengthened, which would lessen ice damage to ships and reduce the risks of accidents and the use of the Canadian Coast Guard icebreakers. Similarly, the part of the St. Lawrence Seaway upstream from Montreal could have a longer navigation season and reduced icebreaker costs (Millerd, 2005).

Air transportation

With respect to air transportation, the potential impacts would basically affect airport infrastructure that is built partly on permafrost. In some Nunavik communities, airport facilities are already degrading faster due to the thawing of permafrost. This issue is examined in greater details in the section of this document on the North.

Adaptation

Much of the transportation infrastructure has a lifespan that will coincide with the years in which the impact of climatic changes will begin to be clearly felt. Consequently, the safe operation of such infrastructure requires that climate change be taken into account in order to ensure their viability in the mid- and long term. This is particularly true of infrastructure components that have a very long lifespan, such as bridges, tunnels, pipelines and railroads as well as airport and marine facilities. In this regard, the rapid evolution of methods and knowledge with respect to the design of pavement and the emergence of new technologies and new products have encouraged the MTQ to adapt various technologies to the Quebec reality and to design and develop new diagnostic equipment.

These activities are being carried out in collaboration with university researchers, and include meetings, technical exchanges and joint research projects with several countries, including France (Doré and Savard, 2006) and the United States.

As for winter viability, several measures have already been initiated to improve the maintenance of Quebec's road network and better manage weather events induced by climate change. For example, in 1999 the MTQ put into place (Tanguay and Roussel, 2000) a winter maintenance decision support system (DVH-6024) based on data collected by weather stations equipped with meteorological and road sensors.

In addition, the development and purchase of technologies linked to road conditions forecasting are ongoing, notably with respect to fixed and mobile instrumentation deployed throughout the entire territory.

As for the significant impacts of a lower mean water level in the St. Lawrence River, as mentioned in the section on water resources, several adaptation measures are possible for the channel between Montreal and the upper estuary downstream (D'Arcy *et al*., 2005). In order to adequately inform the marine transportation industry of foreseeable depths in the navigation channel, increased efforts could be made to monitor and forecast water levels along the length of the river. The International Joint Commission for the Great-Lakes and St. Lawrence System could also intervene by allowing the discharge of outflows from Lake Ontario to be modulated to respond to the needs of commercial navigation.

Adaptation measures for shallower depths include reducing tonnage, using more ships with shallower draughts, and reducing the speed of ships to minimize the squat effect. Additionally, some portions of the navigation channel could be deepened to maintain prescribed keel clearances. More dramatic drops in water level could require more costly work in order to rebuild existing infrastructure such as the overflow weirs of the Sorel delta, to re-design port facilities, and possibly to artificially narrow sections of the watercourse, or use mobile structures to this end, in order to raise its depth for navigation.

Tourism and Recreation

In terms of the economy and of employment, tourism and recreational activities will undoubtedly be one of the economic sectors to feel the greatest impacts from climate change -- tourism income amounts to more than $10 billion annually. Indeed, climate is a determining factor for tourism, especially for sports and outdoor activities, either directly (sunshine, good weather, snow and ice) or indirectly (landscapes and vegetation). For example, climate determines the nature and duration of activities related to snow and cold weather (skiing, snowmobiling), to water (swimming, boating activities), and even to the colour of autumn leaves (hiking), just as it influences the life conditions for game (hunting) or fish (fishing). Climate can even influence the number and duration of cultural trips or stays. However, despite the importance of climate to tourism and recreation, little is known about its impacts on this sector or its capacity to adapt (Scott and Jones, 2006).

Anticipated Impacts

Among tourism activities, only the skiing and golf industries have been the subjects of studies to date, and skiing has received by far the most attention. It should be pointed out that Quebec represents the largest regional skiing destination in Canada, with 80 ski hills, 37% of the national market and almost 7 million visitors annually. Of these, about 80% are from Quebec, 11% from Ontario, 6% from the United States, 2% from overseas and 1% from the Maritimes (Archambault, 2008).

The total annual economic impact of the ski industry in Quebec is evaluated at some $600 million including, among other things, expenditures on equipment and clothing, transportation, lodging, restaurants and the cost of ski passes. In Quebec, the industry supplies a total of 32,500 jobs (Archambault, 2008).

According to Singh *et al*. (2006) and Scott *et al*. (2007), the Quebec ski industry will have to adapt to more difficult climatic conditions in the decades to come. Ski regions in southern Quebec (Montreal, Estrie) will undergo increasingly mild and rainy conditions, resulting in a shorter ski season. Certain profitable periods (Christmas, Easter, spring break) could also be affected. However, warming (less cold and wind) could also increase the number of skiable days and traffic on the trails, especially in January and February.

A more recent study (Scott and McBoyle, 2007) focussed on three ski regions (Quebec City, Sherbrooke and the Laurentides). The study incorporated artificial snow-making capacities and modelling of adaptation decisions by ski hill owners. According to this study, and as shown in Table 7, it is estimated that under an optimistic climate scenario, the ski season would be only very slightly shortened by the year 2020, while under a warmer or more pessimistic scenario it would be shortened by 13% to 15%.

Table 7: Percentage changes in the length of the ski season in three ski regions by 2020 and 2050 under two climate scenarios (taken from Scott *et al.*, 2007).

Region	Reference average of skiable days from the 1970s	Climate scenario	Change (%) compared to the reference average from the 1970s	
			2020	2050
Quebec City	160	NCARPCM-B2	-1	-5
		CCSRNIES-A1	-13	-34
Sherbrooke	152	NCARPCM-B2	-2	-7
		CCSRNIES-A1	-15	-39
Sainte-Agathe-des-Monts	163	NCARPCM-B2	0	-4
		CCSRNIES-A1	-13	-32

By 2050, however, although under an optimistic scenario the changes in the three regions would remain minor, the results under the pessimistic scenario indicate the season would be reduced by more than 30% in all three regions. However, the impact on revenues would be significantly lower than these percentages, since it would be mainly ski days at the beginning and end of the season that would be lost, and not those operating days essential to ski hill profitability (end-of-year, mid-season and spring break holidays).

These relatively reassuring results presume however, – under a pessimistic scenario – that by 2020, snow-making will increase by 8% to 24% in the Quebec City region and 25% to 59% in the Sherbrooke region, and that by 2050 it will more than double for all three regions. This means that the cost of artificial snow-making, despite the fact that the required equipment is already in place, is likely to increase and consequently hurt ski hill profitability. There are also concerns with regard to the availability of the water needed for snow-making. This could become a critical issue in locations where increased water usage combined with a potential drop in water levels could generate or aggravate usage conflicts (Singh *et al*, 2006).

From the demand side, Quebec, which will retain a large proportion of its natural snow, could benefit from the attraction this constitutes and the quality of skiing that it ensures, particularly for ski hills able to attract a clientele from outside. In addition, competing regions further south would be more affected by climate change. And finally, It seems that climate may have a negative impact on the demand for winter sports due to problems of perception (rain in the city while it snows on the ski hills) or even by facilitating substitute activities (Hamilton *et al*., 2007).

Other winter activities such as snowmobiling, cross-country skiing and snowshoeing may also suffer serious repercussions, and for these, possible adaptation measures are less effective. Under a pessimistic scenario, it is estimated (Scott *et al*., 2002a; Scott and Jones, 2006) that the reduction in snow cover will mean that the snowmobiling season will be cut by up to 50% in many regions of Canada. This is another tourist activity with major economic impacts, especially in resource regions. Here again, the negative impacts of climate change could be offset by an increased competitive edge over regions further south.

Ice-fishing is also very vulnerable to increasing temperatures, which would increase the risk to the safety of anglers. Finally, events such as winter festivals would also be affected.

In summer, 75% of golf course use occurs from July to September. Climate change could, according to estimates, prolong the golf season by two to three weeks (Singh *et al*., 2006), mainly at the beginning of the season. However, the frequency of days unfavourable to golf will increase due to an increased frequency of heat waves and of rainy days if the precipitation predictions bear out.

The main challenge for golf courses will be the increased irrigation requirements resulting from higher temperatures, which could be problematic to the extent that they become a source of usage conflict in a context of decreasing water levels. The current grass varieties used on courses will deteriorate more rapidly during the summer. Meanwhile, winter warm spells and future climate conditions could promote bacteria and other pathogenic organisms. The quality of drainage on golf courses could also be affected by the intensity and frequency of precipitation, and course maintenance could become more costly as increased evapotranspiration results in soil exsiccation. These new climatic constraints will be critical for operators, who must also comply with environmental standards on the application of course maintenance products (Singh *et al*., 2006).

With regard to other summer tourism activities, despite the lack of studies, we can presume an increase in activities such as hiking, park usage, recreational boating and sailing (Jones and Scott, 2005; Scott *et al*., 2002b). Several tourism regions in colder areas will benefit from warming temperatures and, generally speaking, Quebec will benefit compared to regions further south, leading to higher tourism revenues. The negative impacts will come from increased precipitation, heat waves and degraded water quality, especially due to the proliferation of cyanobacteria and other harmful species (MDDEP, 2009a). Fishing would be affected, since fish are sensitive to even small variations in temperature.

Adaptation Strategies

Adaptation of the tourism industry to climate change will occur both through changes in tourism demand and through modifications to what tourism facilities offer. On the demand side, we can expect that customers will shift in time and in space in search of the desired climate conditions (Wietze and Tol, 2002). On the supply side, several strategies are possible, depending on the industry sector (Scott, 2005).

Faced with increased market competitiveness, regular replacement of infrastructure costs and increased costs for artificial snow-making, electricity, property taxes etc., many ski hill operators believe that the best adaptation strategy consists of better understanding future climate phenomena in order to better plan their investments and satisfy an increasingly demanding and selective clientele. The ski industry benefits from constant technical progress and has displayed a strong capacity for adapting to new consumption habits, increasing competition, demographic changes, and even access to instantaneous information on weather, which plays an expanding role in the choice of activities.

Technological solutions include increasing snow-making capacity in addition to the construction of water reservoirs, opening new and better-located trails, creating trails on gentler slopes with forest cover, or even indoor skiing.

Among the business strategies available to operators are: creating new or offering a broader range of activities at a site, creating inter-regional conglomerates, increasing marketing efforts, purchasing climate insurance and also, for governments and the media, improved weather forecasts and better information dissemination on snow conditions (Scott and McBoyle, 2007; Singh *et al*., 2006). For the ski industry, adaptation on the demand side may mean that skiers will move to new destinations while peak traffic at ski hills increases and almost certainly a drop in the overall number of ski hill visitors will be observed.

For the golf industry, adaptation strategies will revolve mainly around water management, both in terms of natural input and drainage. The turf quality, a major consideration on the part of clients, will need to be better monitored in order to avoid increased die-back. A longer season will generate increased revenues, and even more so if there is an expansion of other services such as restaurants and lodging.

With regard to other summer activities, the impacts can be reduced by measures such as establishing plant cover on shorelines for sport fishing, or increasing the monitoring of water quality at designated swimming sites. With regard to the consumers or users of tourism infrastructure, it would be useful to determine their reactions to different climate thresholds for various activities, and how their preferences for these activities may change under new climate conditions.

HEALTH OF POPULATIONS

Climate change poses a challenge to human health. The impacts are either direct (for example, mortality due to heatstroke) or indirect (for example, recrudescence of pathogenic insects). The following paragraphs describe what we currently know about the main impacts of climate change on human health, and especially of average warming, heat waves and urban heat islands, air pollution, forest fires and wildfires, summer and winter storms, and exposure to ultraviolet rays (UV). Following that the more indirect impacts in the quantity and quality of the water resource, zoonotic diseases and vector transmission, and various other impacts will be discussed.

The second part of this section is devoted to possible adaptations for handling each of these vulnerabilities. In this latter regard, different populations show different degrees of vulnerability to climate change, which makes it more complicated to initiate adaptation measures.

Impacts and sensitivities

Average warming

In Quebec, warmer temperatures could, without adaptation measures, result in higher annual mortality (see Figure 29). A study by Doyon *et al*. (2006, 2008) on the impacts of climate change on mortality in three cities -- Montreal, Quebec and Saguenay – predicted that the summer mortality rate (from non-traumatic causes) would increase by about 2% by the year 2020 and by 10% by 2080, according to the A2 scenario (IPCC, 2001a). This increase would not be offset by a drop in autumn and winter mortality. Thus, on an annual basis, the mortality would increase by about 0.5% by the year 2020 and by 3% by 2080; this corresponds to an annual increase of about 150 deaths by 2020 and 1,400 deaths by 2080 for Quebec south of the 50th parallel; this increase does not include additional deaths during heat waves. However, the 95% confidence interval of these figures shows that there is a wide range of possible values, which also vary depending on the climate scenarios. This increase will affect most regions of Quebec, with the exception of the Côte-Nord and the Gaspésie, and with increasing intensity from east to west.

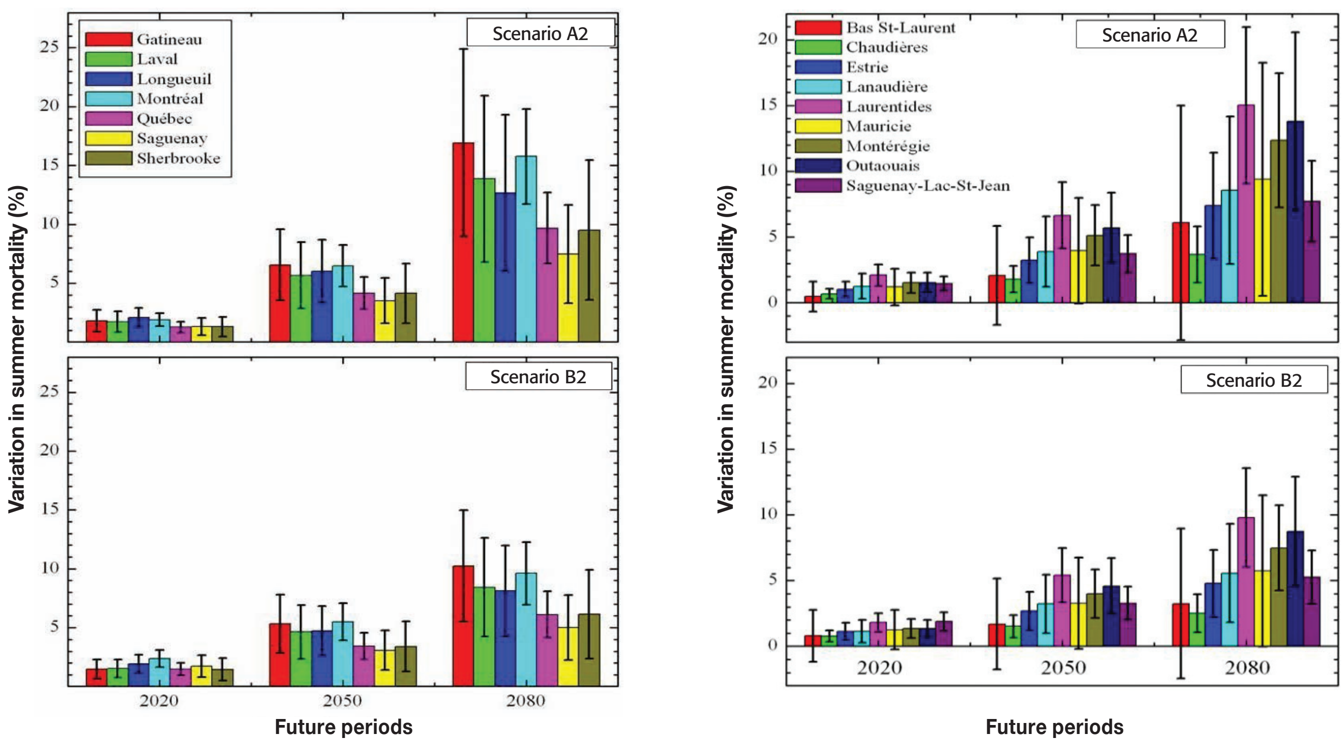


Figure 29: Variations in summer mortality in Quebec (cities and regions) according to different scenarios (Doyon *et al*., 2006.

These conclusions are similar to those that Kalkstein and Green (1997) arrived at for several U.S. cities. They estimated that there are three times as many deaths on hot days as on cold days. However, they contradict the results of Keatinge *et al*. (2000), who predicted a net annual decline in mortality in the United Kingdom resulting from a decline in winter mortality, probably due to cold adaptation (affordable heating, home insulation).

These simulations do not factor in either the aging population or the increase in air pollution that could increase the mortality rate substantially, or adaptation measures that could reduce it. In this connection, it is worth noting that Quebec will have an increasing number of people aged 65 and older; the proportion is expected to grow from 12% in 2001 to about 24% in 2025 (ISQ, 2009), and the mortality rate for this group is two to three times higher than it is for individuals aged 15 to 64 (Doyon *et al*., 2006). Other methodological explanations can also be put forward to explain these discrepancies (Gosselin *et al*., 2008).

Heat waves and the urban heat island effect

Higher temperatures, a daily humidex that has been rising for the last four decades in Montreal and Quebec City, and heat waves that are more frequent and intense, all present significant risks to human health (Environment Canada, 2004a and 2004b). To these we must add the urban heat island effect (UHIE), which is generated by asphalt surfaces and various infrastructure materials that absorb heat, raising the ambient air temperature by 0.5°C to 5.6 ºC in urban areas (Oke, 1982). Heat can cause discomfort ranging from light-headedness to impairment of consciousness, but can also lead to syncope and heat stroke that can prove fatal (Besancenot, 2004). Indirectly, heat can aggravate chronic conditions such as diabetes, respiratory failure and kidney failure.

Populations in the South are more sensitive to increasingly frequent episodes of muggy heat, while those in the North will suffer more from higher temperatures, to which they are not acclimatized (Health Canada, 2005). Several scientific studies (Commission de la santé et de la sécurité du travail, 2004; Direction de la santé publique de Montréal, 2004) have mentioned individuals at increased risk related to environmental (for example, housing, work, access to fresh sites) or individual characteristics (for example, illness, disability, age).

Studies by Bélanger *et al*. (2006, 2007, 2008) shed new light on the vulnerability to heat of certain groups. They highlighted some known risk factors and documented some new associations that may aggravate the impacts of heat waves, notably:

1) the fact of living alone as an elderly individual;
2) economic insecurity;
3) restricted mobility;
4) chronic neurological problems (epilepsy, multiple sclerosis);
5) inadequate social support;
6) type of housing (such as certain apartment buildings);
7) limited access to recreational activities during heat waves (such as places to swim).

A relationship between apartment buildings with several storeys and increased mortality rate during periods of intense heat has been established by several researchers (Klinenberg, 2002; Dixsaut, 2005) and this vulnerability has also been documented in the perceptions of the Quebec population at large (Bélanger *et al*., 2006). A study carried out in Montreal (Smargiassi *et al*., 2009) also suggests that summer mortality occurring at home or in a long-term care facility increases when the building is located in an urban heat island (as determined by satellite maps); the increase is about 20% when one compares the deaths occurring on days with an average temperature of 20°C and those when the average temperature is 26°C, although this varied depending on other factors.

Exploratory research carried out in the Estrie region on the subject of medication usage during periods of intense heat highlighted the importance of pharmacist prescription warnings (Albert *et al*., 2006). The study indicated that a high percentage (30.2%) of individuals aged 65 and older were taking medications the effectiveness of which could be compromised by dehydration, or that could impede heat reduction or adversely affect kidney function.

Nearly 5% of the elderly had three or more prescription medications of this type to take simultaneously. Knowledge in this area is still rather limited, which makes it difficult to interpret the possible implications related to climate change.

Air pollution

A second group of climate change impacts on human health is connected to the effect of increased temperatures on air pollution, particularly pollens, ozone and suspended particulates. Urban populations (80.4% of Quebeckers) are especially vulnerable to air quality problems, particulary in the Montreal region (ISQ, 2005a and 2005b). The current estimates of mortality and morbidity linked to air pollution in Quebec are appreciable (Bouchard and Smargiassi, 2008): annually, there would be some 2,000 premature deaths and some 250,000 person-days with asthma symptoms linked to pollution for a population of 3.6 million. Thus, in the context of climate change, the total health burden associated with air pollution could grow substantially.

Pollens

The World Health Organization (WHO) expressed the hypothesis that a warmer and more humid climate will increase the atmospheric concentration of certain pollens that will in turn give rise to a recrudescence of allergy problems, such as allergic rhinitis and asthma (McMichael *et al*., 2003). Allergic rhinitis constitutes a serious problem for public health in industrial countries, altering the quality of life of populations, creating absenteeism and productivity losses, and resulting in significant costs in hospitalizations, prescriptions, and medical visits (Breton *et al*., 2006; Garneau *et al*., 2006). Allergic rhinitis is ranked number 5 (9.4%) of reported health problems (ISQ, 2009) and affects mainly children and young adults. It seems to have increased in prevalence by 6% since 1987 (Garneau *et al*., 2006), although many external factors other than climate may have contributed to this. In the Quebec City and Montreal regions, there has been a documented increase in both pollen concentrations and the frequency of medical visits for rhinitis for the 1994-2002 period.

Ozone

In urban areas, sunlight contributes to the formation of tropospheric ozone (O_3), a gas that is harmful to human health and the main component in summer smog in Quebec. Modelling of climate change data for Canada supports the hypothesis that rising temperatures will lead to increased concentrations of ambient O_3 and an increase in the length of time that the standards are exceeded (Lamy and Bouchet, 2008). Tropospheric ozone is responsible for acute and chronic damage to the respiratory system; acute reactions are particularly concerning for asthmatics.

Ozone can cause irritation to the eyes and the respiratory tract, reduce respiratory function, aggravate diseases of the respiratory tract and cardiovascular system and even cause premature death (Health Canada, 2009).

Particulates

As for particulates, the same simulations indicate that they will remain stable or decline slightly. However the authors of these Canadian simulations stress that the relationship between climate change and particulates is still the subject of numerous studies and more research is required. It must be noted that these simulations deal only with summer data and do not include winter smog, which in Quebec is linked mainly to fine particulates that come from heating with wood (47% of the total) (MDDEP, 2002). Thus, these results on particulates deserve to be regarded as preliminary, especially if we look at some studies that were recently done in the United States. According to Pye *et al*. (2009), climate change alone (with the GEOS-Chem model, under scenario A1B) would by the year 2050 bring about an increase in aerosols (sulphates and ammoniums) in the American Midwest and Northeast, while levels would decline elsewhere in the U.S., resulting in an overall increase on the national scale with significant seasonal variations.

An analysis of health effects done by historical modelling of the climate combined with atmospheric pollution (Jacobson, 2008) concluded that ozone and particulate concentrations have been rising simultaneously with CO_2 concentrations since the preindustrial era, with mortality increasing by 1.1% for each degree Celsius; 60% of that mortality is attributable to the effect of particulates, and 40% to ozone.

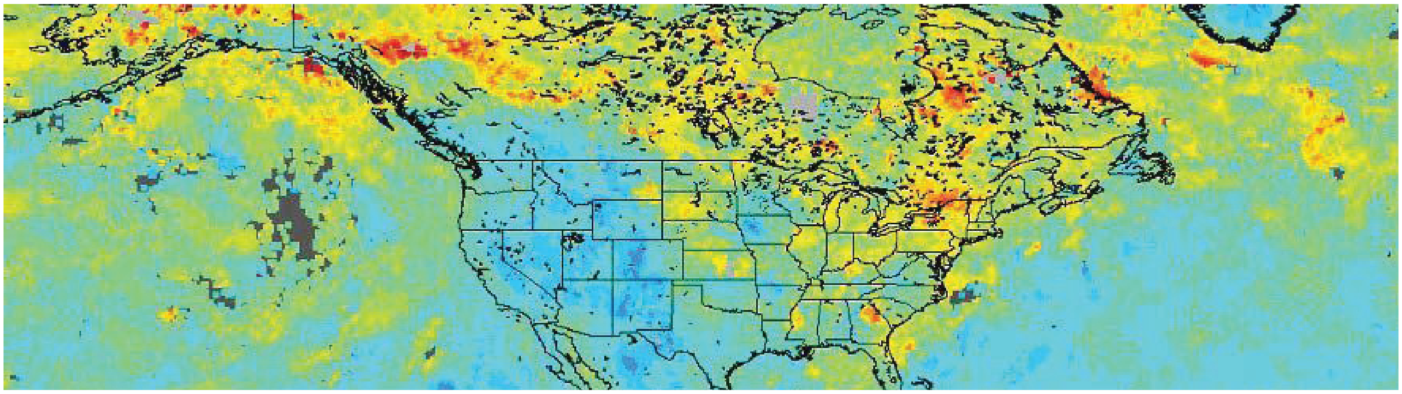


Figure 30: Satellite imagery of carbon monoxide particulate pollution emitted by forest fires and wildfires in the American Midwest and the Canadian Prairies in July 2004. The pollution level increases from blue to green to yellow to red. (*National Center for Atmospheric Research/ NASA*)

As indicated by a U.S. assessment of health and climate change (Ebi *et al*., 2008), most studies carried out to date only involve ozone, and additional research on particulates is necessary before any conclusions can be drawn. One aspect that is very well understood, however, is the fact that the presence of fine particulates (smaller than 2.5 μm – PM2.5) is associated with hospitalizations and an increase in cardiorespiratory morbidity, and particularly aggravates asthma (Dominici *et al*., 2006; Goldberg *et al*., 2001), and that the harmful effect of heat waves is amplified by air pollution, as much from ozone as from suspended particulates (WHO, 2008).

These particulates are released by various combustion processes, and one of these – heating with wood – is increasingly popular (Bélanger *et al*., 2008). For instance, Montreal experienced its worst smog season (linked to particulates) in history in the winter of 2008-2009, with 68 days of smog compared to the preceding record of 19 days in 2005, with wood heating contributing most of this. Although Natural Resources Canada recommends this type of heating to increase household resilience and independence in case of electricity outages, in actual fact it is a poor adaptation solution due to it significant health impacts (Bélanger *et al*., 2008). For that matter, the city of Montreal recently instituted stricter regulations for wood heating.

Forest fires and wildfires

Another major concern is the impact of forest fires on health. In addition to their serious economic impact on the forestry industry, forest fires emit a variety of chemical compounds into the atmosphere, including particulates, nitrogen oxides, carbon monoxide and organic compounds. For humans, these emissions can irritate the respiratory tract, aggravate certain chronic diseases, and cause smoke inhalation poisoning. Acute symptoms can occur in forest-fire fighters and forest workers with long-term smoke exposure (Dost, 1991). As well as these direct impacts, there are indirect health impacts for workers and the general population linked to post-traumatic stress, often with severe consequences.

Current scenarios for Quebec's boreal forests do not predict any significant changes in the rainfall or forest fire regimes, but uncertainty persists (Ouranos, 2004) because the scenarios for the U.S. Northeast and Ontario indicate an increase in fires (Lemmen *et al*., 2008; Ebi *et al*., 2008), which would expose Quebec's population due to the transborder atmospheric transport of pollutants.

For Canada in total, it is expected that the number of forest fires will increase, except perhaps in certain parts of Quebec where the numbers would remain stable (Lemmen *et al*., 2008). Likewise, a marked increase in forest fires is expected for the entire west of the American continent (Ebi *et al*., 2008). The fact that particulates can be transported long distances by prevailing west-to-east winds increases the risks of exposure to particulates from forest fires. Figure 30 illustrates an episode of long-distance transport of pollutants from forest fires and wildfires in the American Midwest and Canadian Prairies towards Quebec in July 2004 (polluted areas in yellow and red).

Summer and winter storms

Storms also produce significant health impacts. Summer storms with violent rains cause inundations that can lead to injuries, cardiac problems and deaths by drowning. Indirect effects take the form of infectious diseases (conjunctivitis and dermatitis) caused by contaminants carried in flood water, gastroenteritis due to microbial contamination of drinking water sources, and respiratory problems triggered by molds and mildew. Because these events sometimes cause significant material and emotional losses (home loss, job loss) injured parties and emergency responders can suffer from post-traumatic stress syndrome that can lead to depression, anxiety, psychosocial problems and even suicide (WHO, 2005).

Winter storms can result in injuries, frostbite, hypothermia and sometimes death (100 Canadians each year) (Institute for Catastrophic Loss Reduction, 2005).

The January 1998 ice storm lasted five consecutive days and left more than 3 million people without electricity; hundreds of thousands of them remained without electricity for close to 40 days. The episode led to 21 deaths and 200 cases of carbon monoxide poisoning (Roy, 1998), mainly in the Montérégie and the Island of Montréal (Tremblay *et al*., 1998). Laplante *et al*. (2004) conducted a study of 224 women who were either pregnant during or became pregnant in the three months following the storm. The study assessed their "objective" stress (number of days without electricity) and "subjective" reactions (post-traumatic stress syndrome). The results showed a link between significant maternal prenatal stress and increased perinatal mortality, differences in psychomotor development in children aged 2 to 5.5 and behavioural problems in children aged 4 to 5.5.

The North of Quebec

In the North of Quebec, recent climate trends should not be dismissed as a cause of the avalanche that occurred in 1999 in Kangiqsualujjuaq, when 9 people were killed and 25 injured (Public Safety Canada, 2006). Other incidents, less tragic, took place in other communities during the same period. Not only were human lives endangered, the events created a great deal of insecurity among the population.

The effects of climate change on the quantity and quality of the water resource

In the South, climate change could lead to a drop in the levels and flow rates of rivers, alter the rainfall regime and cause the salinity of the St. Lawrence to increase (Bourgault, 2001). These projections are problematic because more than 70% of the population gets its potable water from surface water (MDDEP, 2004). The risks of microbial, chemical and biotoxic contamination will be higher. The population in general will be affected both physically and psychologically by water shortages; families already facing a precarious economic existence will suffer even more food insecurity as they will have to add purchased water to their grocery budget (Direction de la santé publique de la Montérégie, 2004). In addition, water shortages caused by a reduced capacity of the aqueducts will present an increased risk in terms of fires, accompanied by injuries, deaths and significant psychological issues for families that experience the destruction of their personal belongings (Enright, 2001).

Water-borne illnesses may make an appearance if pathogenic microorganisms move into the groundwater or surface water supplies of potable water (Canadian Council of Ministers of the Environment, 2005a and 2005b). Phosphorus, sunlight and temperature are the principal factors responsible for the proliferation of algae or algal blooms of cyanobacteria (MDDEP, 2009a). In Quebec, this phenomenon has already affected some 156 lakes and waterways between 2004 and 2008 (MDDEP, 2009b), some of them for several summer seasons, and led to bans on water consumption and swimming, although no resulting human diseases have been reported.

The cyanotoxins produced by cyanobacteria can cause skin irritation and serious liver or nervous system damage, both from skin contact and ingestion (American Water Works Association, 1999; Agriculture and Agri-Food Canada, 2003). Young children, the elderly and the chronically ill are at greater risk of developing severe symptoms resulting from contaminated water. Fans of aquatic activities are particularly vulnerable to contamination from natural biotoxins (MSSS, 2008).

On the other hand, in terms of the capacity of Quebec treatment facilities to handle cyanobacteria, it seems that the current capabilities combined with improvements that are in progress are fully sufficient to protect against the risks associated with the biotoxins produced by these algae (Barbeau *et al*., 2008).

A recent study led to the finding that current climate change projections trend towards a change in the intra-monthly distribution of rainfall events during the summer as well as a probable increase in the intensity of each rainfall event (Mailhot *et al*., 2008a), producing a context that is likely to create an upsurge in infectious diseases resulting from water. Several studies suggest a direct relationship between the emergence of episodes of water-borne illness and extreme climate events (MacKenzie *et al*., 1994; Rose *et al*., 2000; Thomas *et al*., 2006). Curriero *et al*. (2001) also demonstrated, based on data gathered in the United States in the 1984-1994 period, that 68% of outbreaks of water-borne infections were preceded by an intense rain event (80th percentile and more). A recent study carried out in several rural areas of Quebec arrived at the same conclusion (Febriani *et al*., 2008). This strongly suggests that rain events – although they are not the sole cause -- play a preponderant role (Watson *et al*., 2005).

Right now, it is still difficult to determine with any precision the effect that a modification, for example of extreme rain-fall events, could have on the frequency and amplitude of outbreaks of waterborne illnesses (Patz *et al*., 2000; Benson *et al*., 2000; Huntingford *et al*., 2007). Other factors responsible for these outbreaks are varied and not well studied. Significant variations in the quality of the water supply that are associated with inadequate treatment equipment in drinking water treatment plants, or with suboptimal operating conditions in these plants, are also possible contributing factors (Rizak and Hrudey, 2008).

Waterborne illnesses (transmitted by protozoa, bacteria and viruses) are present in Nunavik, and in the period from 1990 to 1992 a proportionally higher number of cases than in the rest of Quebec were recorded for some of them (for example, giardasis, salmonellosis), whereas for other types of infectious disease it was inferior in number (Furgal *et al*., 2002). Climate change could have an effect on water supplies (both household and community systems), cause the degradation of the permafrost and contribute to saltwater infiltrating the aquifers. In several communities, garbage buried in thawing permafrost would pollute the groundwater table, streams and neighbouring land (Furgal and Seguin, 2005).

In Nunavik, one in five people is below the age of five; this group is at risk for gastrointestinal illnesses because the immune systems of children are not as strong (Martin *et al*., 2005a and 2005b). Expected climate change highlight the urgency of improving the environmental monitoring and health screening systems in order to rapidly detect and treat health problems related to water quality (Owens *et al*., 2006).

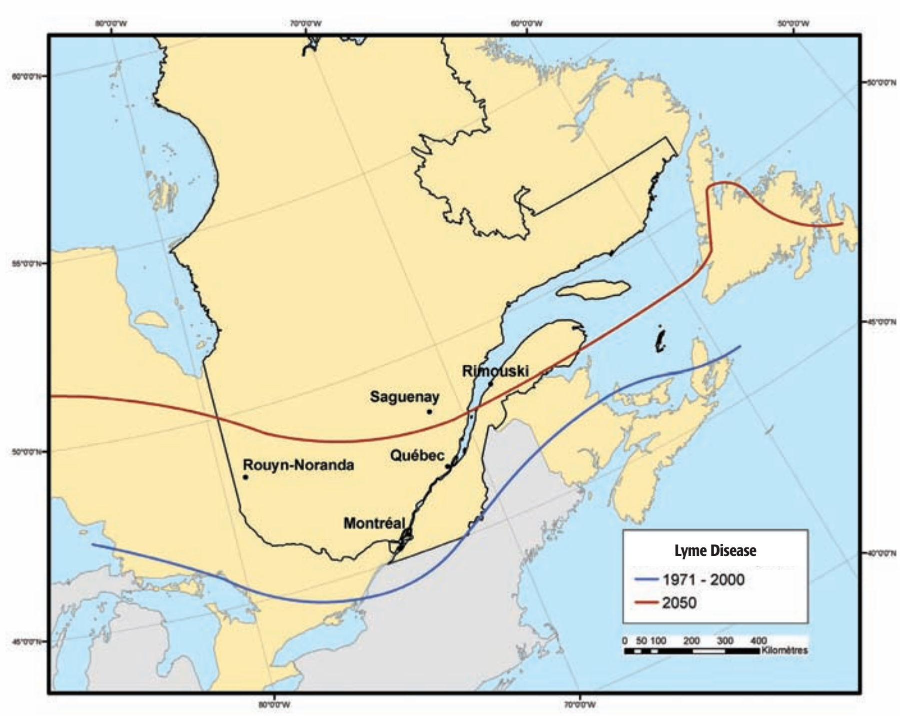


Figure 31: Simulation of the change in the spread of Lyme disease in Quebec by the year 2050 (Ogden, 2006).

Emergence and spread of vector-borne and zoonotic diseases

Climate change may modify the range of parasites and of illnesses transmitted by animals, insects and ticks, leading to an increase in existing infectious diseases or the arrival of diseases that currently are not found in Quebec. Among the zoonotic diseases transmissible to humans is hantavirus pulmonary syndrome (HPS) which is caused by a virus that can infect some rodents. A warmer climate may lead to the spread of rodents to new geographic areas. Several indigenous rodents can serve as vectors for this disease; the first case was reported in Quebec in 2005 (Direction de la santé publique, 2005).

Rabies is another disease that can be transmitted to humans by a bite or scratch from an infected animal. Climate change could cause modifications to habitat, the length of the hibernation period, and the reproductive cycles in the animal reservoirs, with the result that this disease could spread to Northern Quebec (Ontario Forest Research Institute, 2003).

Currently in Quebec, there are only a few species of mosquitoes that carry vector-borne diseases that are transmissible to humans. However, some species found in the South serve as vectors for the West Nile virus, St. Louis encephalitis, La Crosse encephalitis, and eastern equine encephalitis (INSPQ, 2003a and 2003b).

Milder winters and longer summers could prolong the lifespan of these mosquitoes, as well as the season for transmission of the virus that causes St. Louis encephalitis, which is native to the U.S. but could spread to Quebec. La Crosse encephalitis, meanwhile, is endemic in the U.S. and the Snowshoe Hare variety (which attacks hares) is already present in Quebec. Likewise, eastern equine encephalitis has already been identified in Quebec, but to date, no case of human infection has been reported (INSPQ, 2005a and 2005b); still, there is the risk that it will be reintroduced each year by migratory birds (Ontario Forest Research Institute, 2003), as was the case with an episode of equine virus in September 2008. Lyme disease is an emerging zoonosis in Canada. The bacteria can be transmitted to humans by the bite of an infected tick. According to researchers at the Université de Montréal (and as shown in Figure 31), in 10 or 20 years the ticks responsible for spreading this disease will become rife in several parts of eastern Canada, including Quebec, as the climate warms up (Ogden *et al*., 2006; Charron *et al*., 2008).

There are also several zoonotic diseases in Arctic animal species, notably: tularaemia in hares, muskrats and beavers; rabies in foxes (Dietrich, 1981); brucellosis in hoofed animals, foxes and bears; echinococcus in canine species (Chin, 2000). The Inuit show elevated levels of several zoonotic parasites, especially toxoplasmosis (Tanner *et al*., 1987; Anctil and Rochette, 2008). It is likely that climate change will increase transmission, either from consumption of animal flesh or water contamination. Likewise, the winter survival rate and distribution range of certain insects increase as a result of rising temperatures, which could lead to the appearance of new pathogens in arctic regions or increase the risk of infection from endemic agents (Parkinson and Butler, 2005).

Other impacts in the Arctic

The Inuit are hunters and fishers, and continue to procure a large part of their diet traditionally, which benefits them in ways that foods imported from the South do not (MSSS, 2004). The Qanuippitaa health survey (Anctil and Rochette, 2008) of 2004 showed that 24% of Quebec Inuit reported that they had been short of food during the month before the survey was conducted. Consumption of traditional foods, which are basically foods obtained from hunting and fishing activities, were still important in 2004 (16% of caloric intake), although lower than in 1992 (21%). If, as a result of climate warming, animals are more affected by disease, parasites, a greater number of biting insects, starvation or changes to or loss of habitat, the food resources of the Inuit could be displaced and their quality altered. This will mean a reduction in the amount of high quality animal protein, a situation that will be all the more problematic as the population increases and hunting and fishing skills diminish (Furgal *et al*., 2002).

The replacement of traditional foods with imported products, which are higher in sugars and carbohydrates, will give rise to more cardiovascular problems, diabetes, vitamin deficiencies, anemia, dental problems and obesity, as well as reduced resistance to infections. The Inuit already suffer from much higher mortality and morbidity rates than other Quebeckers, for the most part connected to diet (INSPQ, 2006), and a reduced life expectancy mostly due to death from trauma, cancers, and to a lesser extent, cardiovascular diseases.

Although there has been a significant reduction in blood concentrations of heavy metals among the Inuit over the past decade, a substantial proportion continues to post concentrations above the acceptable levels, according to Health Canada. As a result, it is important to monitor the potential sources of exposure that could be affected by climate change.

Finally, the direct and indirect impacts of climate conditions on the natural and built environment will probably increase the risks to health, safety and wellbeing of these isolated populations. As an example, the substantial increase in the quantity and intensity of precipitation could lead to more landslides and avalanches.

Exposure to ultraviolet rays (UV)

In northern regions such as Quebec, behavioural changes connected to climate change will be the most important factor in future exposure to ultraviolet rays (UV), as opposed to thinning of the ozone layer (Diffey, 2004). Basically, it is expected that the lengthening of the warm season will mean that the population will be that much more exposed to UV (Hill *et al*., 1992). Increased exposure means that overall, there will be more cases of sunburn, skin cancers (an annual increase of 4% to 6%), cataracts and diseases associated with the immunosuppressive effects of UV rays (WHO, 2003). Diffey (2004) demonstrated that warmer summer temperatures in our latitudes could encourage the population to spend more time outdoors, and that future warming would lead to about a 20% increase in UV exposure and skin cancers compared to current levels. This increase is twice as great as the effect of the thinning ozone layer on cancers (increase of about 10%), which should be eliminated by 2050 as a result of the Montreal Protocol.

Health problems associated with UV could thus continue to grow at a rate even greater than in recent decades. The impacts on public health are serious, with an estimated 80,000 new cases of skin cancer in Canada each year. Skin cancer is the most frequent form of cancer (Canadian Cancer Society, 2009); some 400 cases of melanoma (the most serious form, and often deadly) are diagnosed each year in Quebec. This said, there is very little research on this issue in Quebec, and the UV protectio component is seldom considered in the process of planning adaptation measures, even though this topic is a Canadian priority (Warren *et al*., 2004).

Adaptation strategies

Average warming

Work is ongoing within the Ouranos health research program to characterize the links that may exist between weather averages and extremes, on the one hand, and the rates of mortality, hospitalization, or visits to the emergency room on the other. This work will be carried out within the framework of the health section of the Plan d'action 2006-2012 en changements climatiques (MDDEP, 2006b), referred to below as PACC-santé.

Heat waves and the urban heat island effect

According to Bélanger *et al*. (2006), adaptation strategies for heat waves need to revolve around the activities of monitoring, research, information dissemination and assistance programmes. The main purpose of the research component would be to determine which services vulnerable individuals need access to in order to ensure their safety during periods of extreme heat. A project to this effect, scheduled for 2009-2012 and targeted at public housing, is part of the PACC-santé initiative. The results will be shared with community organizations and front-line workers in emergency preparedness.

In 2006, seven out of eight regions already had in place an emergency plan for responding to heat waves (MSSS, 2006a). These emergency plans, involving alerts and mobilization, are based on a threshold established through the analysis of medical and weather data from the last 20 years, and some plans include monitoring deaths in alarm situations.

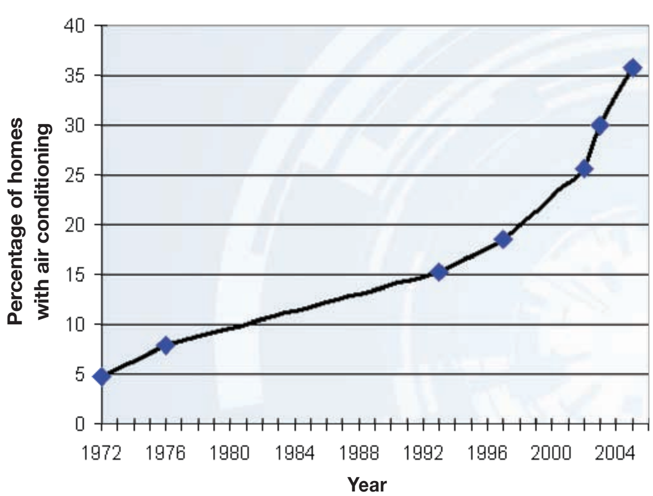


Figure 32 : Prevalence of air conditioning in Quebec, 1972 to 2005 (INSPQ, 2005b; Bélanger *et al.*, 2006).

Regional and town-specific intervention thresholds for heat waves will soon be established, and could be modified from time to time depending on changes in temperature as well as fatalities and illness. Other initiatives with regards to the risks of extreme heat have been put in place to inform the population and the most vulnerable groups (MSSS, 2006c), along with emergency response and health personnel.

Meanwhile, Ouranos has already carried out research projects on heat waves and the urban heat island effect (UHIE) (2006). A study by Vescovi *et al*. (2005) made it possible to map the zones that present risks stemming from climate warming, and a web-based atlas covering some vulnerabilities to human health on the provincial scale, based on earlier projects, is in development as part of the PACC-santé projects (Gosselin, 2005; Kosatsky *et al*., 2005). There has also been growing interest in various measures than can combat UHIE, including tree planting and the installation of green roofs or roofs constructed with higher albedo materials, as well as public transportation in certain regions (Ducas, 2004; Ville de Montréal, 2005).

Some regional public health administrations are beginning to promote these kinds of approaches for urban environments. Several additional initiatives could be taken, as well, including training health professionals, creating public education projects on personal safety and the fight against UHIE, or providing economic incentives to encourage the mitigation of oppressive heat (Giguère and Gosselin, 2006d). The Quebec government's 2006-2012 Action Plan (MDDEP, 2006b) foresees the promotion of cool islands and the training of personnel in climate change adaptation practices over the coming years, under the supervision of the MSSS.

At the same time, and as shown in Figure 32, the use of home air conditioning in Quebec has been growing significantly and at an accelerating rate, especially in the last decade (Gosselin *et al*., 2008).

Air pollution

According to Garneau *et al*. (2006), critical thresholds for pollen need to be established, and warnings issued when these thresholds are exceeded, as is done for heat waves. It is also important to pursue control methods for Ambrosia spp. (ragweed), as the pollen of this plant is associated with the greatest percentage of allergy symptoms, and to encourage the main stakeholders to strengthen their interventions. Since 1999, Quebec has had a public body (the Table québécoise sur l'herbe à poux) to support the efforts on the ground of municipal, private and nongovernmental partners trying to control ragweed (Agence de la santé et des services sociaux de la Montérégie, 2007).

A bona fide network for monitoring bio-aerosols in Quebec still needs to be established following the example of some European countries and especially France, which has a national network called Réseau national de surveillance aérobiologique (see http://www.pollens.fr/accueil.php), that can direct and assess corrective measures and safeguards. In recent decades, various public health notices have been released aimed at reducing urban sprawl and vehicle traffic (Direction de la santé publique de Québec, 2004; King *et al*., 2005), but so far without measurable results. The Info-smog programme is now available throughout southern Quebec, and all year long (MSSS, 2006b), but to date, the impacts on behaviour appear to be limited (Bélanger *et al*., 2006, 2008 and 2009; Tardif *et al*., 2006). In recent years, the Quebec government has introduced various measures to reduce air emissions, especially by passing regulations to limit emissions by light and heavy vehicles (MDDEP 2010). Because a large proportion of atmospheric contaminants affecting Quebec in fact comes from across the borders, the province is participating in various intergovernmental initiatives.

Recent governmental and municipal actions regarding idling engines and the operation of wood-burning stoves are steps in the right direction, especially in combination with larger measures aimed at reducing emissions (Bélanger *et al*., 2008, 2009) such as regulating vehicle emissions, regulating industrial emissions, and promoting the purchase of more-fuel-efficient vehicles, by foot or bicycle travels, or public transportation. Besides, public transportation and walking and biking all have a direct impact on people's quality of life and on public health. By reducing automobile use, public transport cuts down on pollutants created by the combustion of gasoline (MTQ 2006c). There is a direct relationship between the rate of automobile use and the episodes of smog in large urban centres.

Winter and summer storms

Quebec already has in place good systems for responding to emergencies, and most adaptation initiatives related to health now focus on surveillance and monitoring, training and education, and modifications of laws and policies. With respect to surveillance and monitoring, it still appears to be necessary – according to various observers (Giguère and Gosselin, 2006a) – to expand and strengthen the role of Geographic Information Systems (GIS) and new technologies for risk management, currently being done as part of PACC-santé. Different Quebec departments (MSP, MSSS), Public Safety Canada and organizations such as the Red Cross are preparing guides for the public on the measures to take in case of various kinds of extreme events. The creation of Ouranos and of its health component (in collaboration with Health Canada, the MSSS and INSPQ) is part of Quebec's strategy for adapting to climate change (INSPQ, 2005a and 2005b).

Management by watershed areas, which is currently under way, will make it possible to take an ecosystemic approach to water management that will include stakeholders from public health (MDDEP, 2004). However, it would be desirable to see vastly expanded efforts to develop and promote numerous other adaptation initiatives in regards to extreme weather events (Giguère and Gosselin, 2006a), notably:

- upgrading of preventive planning;
- risk modelling and communication for different types of events;
- research on short- and long-term health impacts;
- research on possible improvements to emergency measures in the heath realm.

The MSSS (MDDEP, 2006b) has announced its intention to have in place by 2012 an epidemiological monitoring system and follow-up of the consequences of extreme weather events, and this work is already in progress.

The quantity and quality of the water resource

In the context of climate change, several major adaptation initiatives aimed at preserving the quantity and the quality of Quebec's water resources have already been launched, or soon will be (Giguère and Gosselin, 2006c).

Programs to monitor the quality of surface water on parts of sites make it possible to enjoy water activities safely. Quebec's water quality regulations (MDDEP, 2005a) require rigorous monitoring and oblige supervisory personnel or those in charge of controlling drinking water quality, as well as those responsible for maintenance of water treatment infrastructure, to be adequately trained. However, even though Quebec's standards are among the highest in North America, none of them apply to cyanotoxins, which are toxic to humans and which are likely to proliferate in the context of climate warming. A pan-Canadian recommendation on microcystins is now available, which means that it should be possible to adopt new standards for this issue. In addition, all the new treatments for water taken from lakes and rivers that might potentially be at risk are designed to protect against the later degradation of this water. Finally, research and development programmes on treatment methods for drinking water have been underway for a few years at several Quebec universities.

Research on the links between climate, health, and water quality are also in progress. According to Charron *et al*. (2005), water- and food-borne diseases represent by far the greatest health problem on the planet (IPCC, 2008). The Centre for Infectious Disease Prevention and Control at the Public Health Agency of Canada is currently collaborating with INSPQ on a study of the determinants of gastroenteritis, particularly in ecosystems, the population, communities and individuals, in order to define the vulnerability to water- and food-borne diseases resulting from climate change in rural areas. Quebec's 2006-2012 action plan includes a plan to improve the methods for detecting epidemics and infectious diseases as a function of climate variables (MDDEP, 2006b).

Zoonoses and vector-borne diseases

In Quebec, it seems that the greatest number of adaptation initiatives in the face of climate change have been taken in the fields of zoonoses and vector-borne diseases, even though the actual risks appear to be relatively low. The INSPQ coordinates activities in terms of early detection, real-time monitoring (see Figure 33) and research on the West Nile virus (Bouden *et al*., 2005; Gosselin *et al*., 2005; INSPQ, 2005a and 2005b).

In addition, information sheets on zoonotic and vector-borne diseases, and ways to protect against them, have been made available to the public. Certain experts have proposed various initiatives (Giguère and Gosselin, 2006b), such as integrating climate change impact indicators into the surveillance of zoonotic and vector-borne diseases, as well as intensified research on ways to control these diseases. An in-depth revision of monitoring systems in this field is underway as part of PACC-santé. Meanwhile Quebec's department of agriculture, fisheries and food (MAPAQ, 2006) has invested significant sums into researching better ways to monitor and block zoonotic diseases.

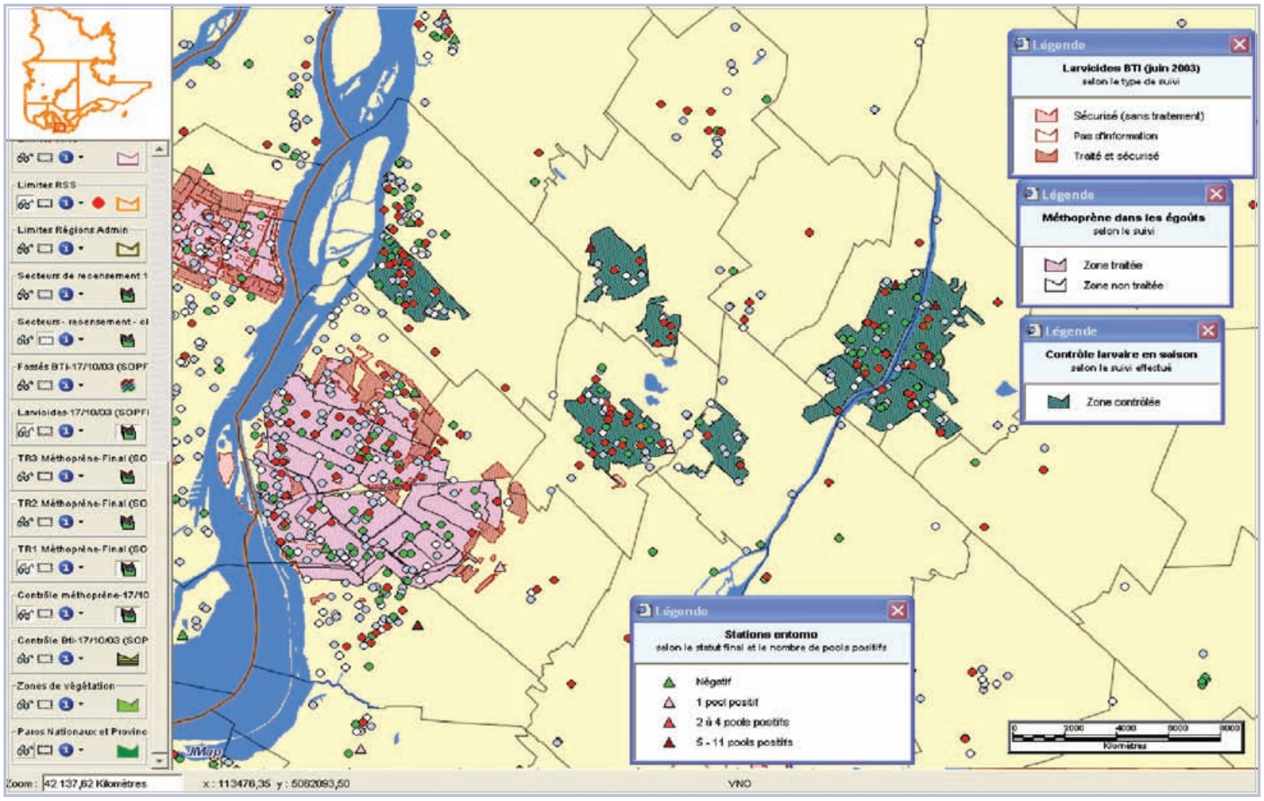


Figure 33: Example of a thematic map from the real-time monitoring system for West Nile virus of the Institut national de la santé publique du Québec (Système intégré des données de vigie sanitaire-Virus du Nil occidental [SIDVS-VNO]). The darkened areas indicate where various preventative treatments (insecticides) were applied on the South Shore of Montreal in 2003 against larvae of the mosquitoes that serve as vectors for transmission of West Nile virus (see Gosselin *et al.*, 2005).

Ultraviolet rays (UV)

The health impacts associated with UV can be avoided by changing individual behaviours regarding protection, and by encouraging certain environmental changes to create shade. On an individual basis, most people have access to Environment Canada's UV index, as well as to the Canadian recommendations for appropriate clothing and the effective use of sunscreen products (Waller *et al*., 2008). The effects of climate change with regard to this topic have yet to be documented in Quebec (Canadian Institutes of Health Research, 2002), but it is already accepted that preventative measures to create shade against the sun would be useful (MDDEP, 2006b), as is proposed in a recent update (MSSS, 2008) of Quebec's public health programme (Programme national de santé publique du Québec, 2003-2012).

It has been shown that the health impacts associated with UV are in large part avoidable (Mills *et al*., 1997), in part by creating shade zones in places that are frequented by the young (and not so young). Recent studies (Thieden *et al*., 2004a and 2004b) indicate that UV exposure accumulates throughout an individual's life, and not mostly in their early years, as was previously thought. The example of interventions applied in New Zealand is interesting (Stoneham *et al*., 2001; Greenwood *et al*., 2000); it involved assessing, through audits, the development of shade zones in outdoor spaces frequented by young people aged 0-18 (and their families and friends) as an adaptation measure for reducing exposure to UV and intense heat at the same time. In addition, programmes to sensitize the public to the risks of UV are affordable and effective. For example, in Australia, the prevention of the negative impacts of UV costs $0.08 US per capita, whereas the cost of treating skin cancers is US $5 per capita (WHO, 2003).

ECOSYSTEMS AND BIODIVERSITY

Climate is the main factor governing plant structure and productivity as well as the distribution of plant and animal species around the world (IPCC, 2002). It is clear that the climate change foreseen for Quebec will have impacts that will be felt by sensitive populations and ecosystems at the local scale. In some cases, the impacts of climate change will result in the decrease or the total disappearance of certain populations; in other cases, it will stimulate a demographic growth and will expand the distribution range of populations. Climate change will alter the ecological dynamic of ecosystems and, in the mid to long term, the landscape (McCarty, 2001; Root and Schneider, 2002; Scott *et al*., 2002b; Walther *et al*., 2002, Rodenhouse *et al*., 2009).

A dynamic biodiversity

These transformations are not deterministic; living organisms are subjected to multiple pressures and climate change is only one element in the equation. In essence, each ecosystem has its own structure and functions that it maintains over time in a dynamic relationship with the environmental parameters (Di Castri and Younes, 1990). It is this dynamic and this evolution which have maintained the biological diversity (or biodiversity) with which we are familiar. Biodiversity declines on three levels: genetic diversity, species diversity, and ecosystems diversity (United Nations, 1993; Di Castri and Younes, 1996).

It is at the population level that the issues surrounding biodiversity can be grasped most clearly. A population is a group of individuals of the same species that attempts to maintain its demography from one generation to the next; this is the unit at which adaptation pressures are exerted. The individuals in each new generation must adapt to a whole range of ecological factors and produce fertile progeny to maintain the species features. Ecosystems supply a multitude of goods and services that are essential to human survival, as can be seen especially in certain native and rural communities that are particularly dependent on these resources (IPCC, 2002).

Living organisms react directly to ecological factors and survive depending on their tolerance. They can also be affected indirectly by climate variations that, for example, alter the availability of food. This means that the number of individuals in a population within a particular ecosystem is an indicator of their adaptation to biophysical and climatic factors (Dajoz, 2000). The higher their tolerance, the better their adaptation, as Albanese *et al*. (2004) demonstrated with fish. For example, an invasive species rapidly expands its range in a new ecosystem, either because it is not constrained by an ecological factor that existed in the past, or because it benefits from new conditions created by a disruption affecting the dominant species with which the invasive species is competing either for food or habitat in the same ecosystem (Bagon *et al*., 1996).

Several phenological modifications were observed in the 20th century, and this trend – triggered by changes in temperature, precipitation, photoperiod or a combination of these factors – should accelerate (IPCC, 2002). Phenological changes have already been detected in small northern mammals, such as squirrels (Réale *et al*., 2003; Berteaux *et al*., 2004). Observations are that birds are arriving in Quebec earlier in the spring, which seems to confirm a clear trend observed elsewhere in the world (Berteaux, personal communication).

Visser and Both (2005) demonstrated that the majority of species are unable to optimally coordinate changes to their phenology with changes to their food. For example, a migration date triggered by a specific photoperiod will not change due to an increase in temperature, but the latter may influence the behaviour of a species or the behaviour of its food species. The risk of this lack of coordination is a reduction of migratory predators in particular (Jones *et al*., 2003; Strode, 2003).

Regional issues

The impacts of climate change on Quebec's species and ecosystems will be quite different in each region, and in general, we can expect that species will move from south to north in reaction to warming temperatures and the shift of isotherms northward (Berteaux, 2008). At the level of species diversity, the effect of climate warming will not necessarily be negative, because some currently threatened species may find better refuge by migrating to certain regions at the rate of climate change (Berteaux, 2009). For other species, however, climate change will be synonymous with decline. Changes in precipitation as well as the earlier arrival of seasonal flood and minimum flow will also have varied impacts, depending on the species. This is especially the case with insects, which will see changes to their geographic ranges, causing local modifications to biodiversity (Rodenhouse *et al*., 2009).

The impact of climate change on the distribution of species within Quebec and the potential displacement of ecological niches to new biogeographical regions are the object of a major research study (from 2007 to 2010) involving researchers from several universities and expertise in regional climatology at Ouranos (See http://cc-bio.uqar.ca). The study should shed new light on the current state of biodiversity in Quebec and the foreseeable impacts of climate change.

The southern region

The South, which is home to the majority of Quebec's threatened or sensitive species and ecosystems (Institut québécois d'aménagement de la forêt feuillue, 2003), will be affected by the rise in average temperatures, changes in the flood regime and the winter warming trend, among other things (Kling *et al*., 2003).

As a result mainly of climate change impacts on the Great Lakes, changes to the mean levels and the flood and discharge regimes of the St. Lawrence River will cause a geomorphological adjustment at the mouths of its tributaries. This means that the river beds and banks will be cut into and destabilized, affecting numerous species of fauna and flora, both in and outside of wetlands; these species being already impacted by human activities (Mortsch *et al*., 2000; Morin *et al*., 2005).

Studies on the two deltas in Lake Saint-Pierre show that rapid adjustment processes are accompanied by the progradation of these deltas into the St. Lawrence (Boyer *et al*., 2004). Species that are dependent on the flood regime of the St. Lawrence, such as northern pike (*Esox lucius*) and yellow perch (*Perca flavescens*), will be affected (Casselman, 2002; Chu *et al*., 2005; Brodeur *et al*., 2006).

An approach that combines multivariate models of habitat and bidimensional physical modelling (Morin *et al*., 2003; Mingelbier *et al*., 2004 and 2005) makes it possible to measure the impacts of climate change on the area of the habitat that is available to several species of fish during the critical periods of their life cycle. Water temperature, current velocity and water level are all key variables for understanding the impacts that climate change will have on fish. Already, there is data showing that the water in certain locations is warming up (Hudon, 2004), and the atypical temperatures of the summer of 2001 led to a massive die-off of carp (*Cyprinus carpio*) in the St. Lawrence and its tributaries (Mingelbier *et al*., 2001, Monette *et al*., 2006).

Amphibians, meanwhile, are very dependent on the temporary puddles that result from snowmelt and spring floods, and they are likely to be affected by reduced snowfall and by periods of drought that will diminish their reproductive success (Brooks and Hayashi, 2002). On the other side, warmer temperatures may allow certain species of amphibians to extend their distribution range further north (Araujo *et al*., 2006).

Projected changes to spring floods will lead to lower reproduction such as has been observed in palustrine birds and waterfowl of the St. Lawrence wetlands, including some species at risk (Giguère *et al*., 2005; Lehoux *et al*., 2005; Desgranges *et al*., 2006). In the flood plain of the St. Lawrence, muskrats (*Ondrata zibethica*) are particularly sensitive to winter fluctuations in water levels, and changes will affect them dramatically (Ouellet *et al*., 2005).

In the extreme south of Quebec, small mammal species that hibernate, such as bats, seek out a stable winter temperature. Fluctuations upwards, such as occur in winter warm spells, cause the animals to wake up, which results in a high energy cost.

An increased frequency of winter mild spells could lead to deaths in colonies of little brown bats (*Myotis lucifugus*) (Rodenhouse *et al*., 2009). Meanwhile, changes in the flood regime and periods of drought could reduce the abundance of insects on which the bats feed, which could limit the capacity of several bat species to find adequate food.

In the South, the populations of cold water fish will be affected by accelerated eutrophication and by unexpected or sudden floods, potentially more frequent, which will lead to watershed erosion and the transport of sediment into lakes, a pattern that is already intensified by human activities such as agriculture, urbanization and forest exploitation (Shuter *et al*., 1998). Increasing temperatures of the lakes in southern Quebec will cause longer periods of thermal stratification, creating anoxic conditions in the lowermost water layer for part of the year. The lake trout (*Salvelinus namaycush*), for example, is sensitive to these last two stresses (Hesslein *et al*., 2001).

Changes in the discharge regime of the St. Lawrence River will also modify the spatiotemporal pattern of water masses and their physicochemical properties (Frenette *et al*., 2003 and 2006). These changes pose a threat to the nutritive quality of algae (Huggins *et al*., 2004) and the structure of algal communities (micro- and macrophytes). Lower water depths could mean an increase in light near the bottom and therefore, a concomitant increase in the quantity of submerged plants, as well as modifications in the properties of dissolved organic matter and particles (Martin *et al*., 2005a).

Wetlands in all areas are sensitive to climate changes due to the increased variation of annual or interannual floods and low water periods associated with extreme precipitation or drought. Turgeon *et al*. (2005) demonstrated that there are fundamental links between hydrology and the spatial distribution of the main classes of wetlands. Several species of fauna that use these wetlands would be affected, which represents a significant issue for the St. Lawrence ecosystem as well as marshes of Lake Saint-Pierre (Hudon *et al*., 2005). In addition, other pressures, especially from agriculture and industrial and urban development, will be exerted (Bernier *et al*., 1998; Robichaud and Drolet, 1998; Jean *et al*., 2002; Ouranos, 2004) and will cause harmful fragmentation of habitats (Root and Schneider, 2002; Villeneuve, 2008).

The central region

Plant and animal species in Quebec's central region are very resilient, and communities are ecologically young, dating from the postglacial retreat of less than 10,000 years ago. These species – adapted to significant annual climatic variation and recurring disasters, and comprised of large numbers of individuals spread over an immense territory – will be affected mostly in transition zones, which is to say, mountain and riparian zones. Changes may also occur within closed forest. In fact, between now and the end of the century, it is expected that an expanded area of forest will be affected by the two largest disruptive natural agents in boreal forests – fires, and outbreaks of spruce budworm (*Choristoneura fumiferana*) (Flannigan *et al*., 2005; Kurz *et al*., 2008). It is likely that the concurrence of these two disruptions will make certain boreal ecosystems even more sensitive, especially black spruce-moss woodlands (Jasinsky and Payette, 2005; Girard *et al*., 2008), the most frequently occurring of continuous boreal forest ecosystems, and creating a positive feedback loop to climate warming (Kurz *et al*., 2008). However, boreal ecosystems should not experience significant changes to their specific composition, although the frequency of forest fires and human activity could favour certain plant communities at the local scale, accelerating the process of opening the forest ecosystem (Payette, 1992; Jasinski and Payette, 2005; Girard *et al*., 2008).

The moose (*Alces alces*) is a large mammal that is well-adapted to cold, but cannot easily tolerate high temperatures in summer and winter. For example, its metabolic costs for thermoregulation needs increase when temperatures exceed 14°C in summer and -5.1°C in winter (Renecker and Hudson, 1986). Rodenhouse *et al*. (2009) estimated that the moose could disappear from the most southern zones of its distribution range in eastern North America. Moose can also be affected indirectly by milder winters and reduced snow cover as a result of parasites transmitted by the white-tailed deer (*Odocoileus virginianus*). In this regard, Rodenhouse mentions the meningeal worm (*Parelaphostrongylus tenuis*), which can be fatal for the moose although it is harmless to white-tail deer, and the winter or moose tick (*Dermacentor albipictus*), which could reach levels of infestation that could weaken moose.

The maritime region

Shorelines are generally fragile environments that play a key role in ecological processes because they supply the connection at the interface of the marine and terrestrial environments. The shores of the Gulf of St. Lawrence, and the ecosystems and populations that they harbour, are particularly sensitive to climate changes (Savard *et al*., 2008).

Coastal erosion is occurring throughout the Gulf, and is correlated with several climate change variables such as the frequency of winter storms and the retreat of sea ice (Bernatchez *et al*., 2008). Rising sea levels in the Gulf of St. Lawrence, which is following a trend observed world-wide (Forbes *et al*., 2004), is also having a direct impact on the most sensitive coastal and estuary ecosystems, leading to a reduction in breeding grounds and feeding areas for numerous resident and migratory species (Harvell *et al*., 2002; Jackson and Mandrak, 2002; Kennedy *et al*., 2002).

The hydrographic network and lakes in this region are especially sensitive as they could act as a barrier in fish migration (Hauer *et al*., 1997). This means that species such as Atlantic salmon (*Salmo salar*) will be affected by an increase in water temperatures which could reach the thresholds at which this species can survive (Swansberg and El-Jabi, 2001). New temperature conditions will favour species that are more tolerant of higher temperatures. In addition, it is possible that species will undergo phenological changes and that the distribution range of species limited by average or minimum temperatures will expand (Edwards and Richardson, 2004; Rodenhouse *et al*., 2009).

The Arctic region

The Arctic region will possibly be the most affected by the magnitude of climate changes (Flanagan *et al*., 2003). Ecological changes will be to the detriment of species that are adapted to the extreme conditions occurring in this region (Rizzo and Wilken, 1992; Payette *et al*., 2001). The northern expansion of plant species typical of the boreal forest will start with individuals already in situ, which will more easily produce viable seeds. Some adaptation in the black spruce (*Picea mariana*) has already been observed (Gamache and Payette, 2004 and 2005). However, the speed of isotherm migration will be much more rapid than that of plants.

In Arctic regions, two species will be especially threatened by climate changes: the polar bear (*Ursus maritimus*) because it is dependent on sea ice and the Arctic fox (*Alopex lagopus*), which is suffering from the northern extension of the red fox (*Vulpes vulpes*) in search of the same food resources (Hersteinssonand MacDonald, 1992; Stirling, 1999; Walther *et al*., 2002; Derocher *et al*., 2004; Berteaux, 2008).

Marine species of the Arctic also inhabit a particularly demanding physical and climatic environment. In general, in terms of number of species the biodiversity is lower in the Arctic than in more southern areas. In addition, a relatively small number of marine species with large distribution ranges dominate most of the Arctic marine ecosystem and the few dominant species, highly adapted to those extreme conditions — such as the Atlantic cod (*Gadus morhua*), Arctic cod (*Arctogadus glacialis*), beluga (*Delphinapterus leucas*), narwhal (*Monodon monoceros*), walrus (*Odobenus rosmarus*), and Atlantic puffin (*Fratercula arctica*) — show a great variability within the same species (Siron *et al*., 2008). The pattern of biodiversity that seems to characterize the Arctic marine environment could be a key factor in adaptation to climate change if there is a change to the environmental conditions in which these dominant species developed.

Adaptation strategies

In order to adapt to climate change and reduce the impacts on biodiversity, several essential actions need to be taken in terms of planning the measures necessary to conservation of ecosystems and biodiversity.

• *Reduce the fragmentation of ecosystems*

Of all the actions that appear to be effective for maintaining genetic diversity, the foremost option involves reducing the fragmentation between ecosystems. As an example, the reforestation of clear-cut boreal land, which is usually aimed at reducing greenhouse gas emissions (Gaboury *et al*., 2009), also turns out to be an option for increasing the adaptivity of boreal forest ecosystems to climate change (Boucher *et al*., 2008).

The current trend shows progressive fragmentation of the boreal forest caused by the regression of black spruce-moss woodland to the benefit of black spruce-lichen woodland (Payette, 1992; Gagnon and Morin, 2001; Jasinsky and Payette, 2005). In addition, the increase in the expanse of burnt forest or forest attacked by insect infestations, both related to climate change (Flannigan *et al*., 2005; Kurz *et al*., 2008) could result in increased fragmentation of the continuous boreal forest, as has been observed over recent decades (Girard *et al*., 2008). In these circumstances, reforestation of denuded boreal lands could constitute a defence against the loss of closed crown forest ecosystems.

Because climate change could trigger the migration of fauna towards the north (Berteaux, 2008 and 2009), forestation of open woodlands could lead to the restoration of part of the closed forest and maintain more hospitable habitat for more southern species. In addition, closed forest cover generally provides a better buffering action than sparse cover against the more intense weather events that are expected (Buckley *et al*., 1998; Noss, 2001).

It is worth mentioning here that the resilience of ecosystems also ensures the resilience of human populations that live in these ecosystems and depend upon them for their survival. This resilience, both human and of the natural environment, is now regarded as an essential factor for ensuring the adaptation of these populations to climate change (The Secretariat of CBD and Nature Conservancy, 2008; Nature Conservancy, 2009).

• *Monitor sensitive species*

Quebec's strategy regarding biodiversity (Stratégie québécoise sur la diversité biologique 2004-2007) engaged each government ministry to determine a set of actions and make regular reports of headway on these to the department of sustainable development, environment and parks (Ministère du Développement durable, de l'Environnement et des Parcs du Québec - MDDEP, 2008b). However, as noted by Gérardin *et al*. (2002), there are still gaps in the existing information on flora and fauna, especially as concerns non-forestry areas (for example, regions of non-productive forest, wetlands, subarctic and alpine flora), which could adversely affect the capacity of government authorities to monitor species that are sensitive to climate change.

An atlas on northern biodiversity called the *Atlas de la biodiversité du Québec nordique*, a pilot project of the MDDEP in collaboration with the Prince Albert II of Monaco Foundation and Ouranos, should serve to fill part of this gap. This new study combines data on biodiversity (databases on the occurrence and distribution of species in zones representative of certain ecoregions of Northern Quebec) and data on projected climate changes based on climate scenarios. The objective of this project is to improve knowledge on biodiversity in order to help select the location of future protected areas and to improve the tools for biodiversity conservation in the context of climate change. Eventually, this project will lead to additions to documents such as the *Atlas de la biodiversité du Québec* which focused on threatened and sensitive species, but did not take climate evolution into consideration (MDDEP, 2005b).

• *Continue the establishment of protected areas*

Protected areas and zones where certain, or even all, human activities are not allowed, serve to ensure the conservation of rare or representative natural ecosystems (see Figure 34). Protected areas, combined into networks that improve the connectivity between ecosystems, represent one of the most effective conservation tools available to governments to maintain the biodiversity and integrity of the ecosystems for which they are responsible (Jaffreux, 2008).

In this respect, and as part of its biodiversity strategy, the *Strategie québécoise sur la diversité biologique 2004-2007*, the Quebec government describes the consolidation of a network of protected areas as a priority intervention, along with the protection of threatened and sensitive species, as a contribution to the implementation of the international Convention on Biological Diversity (Ministère de l'Environnement du Québec, 2004).

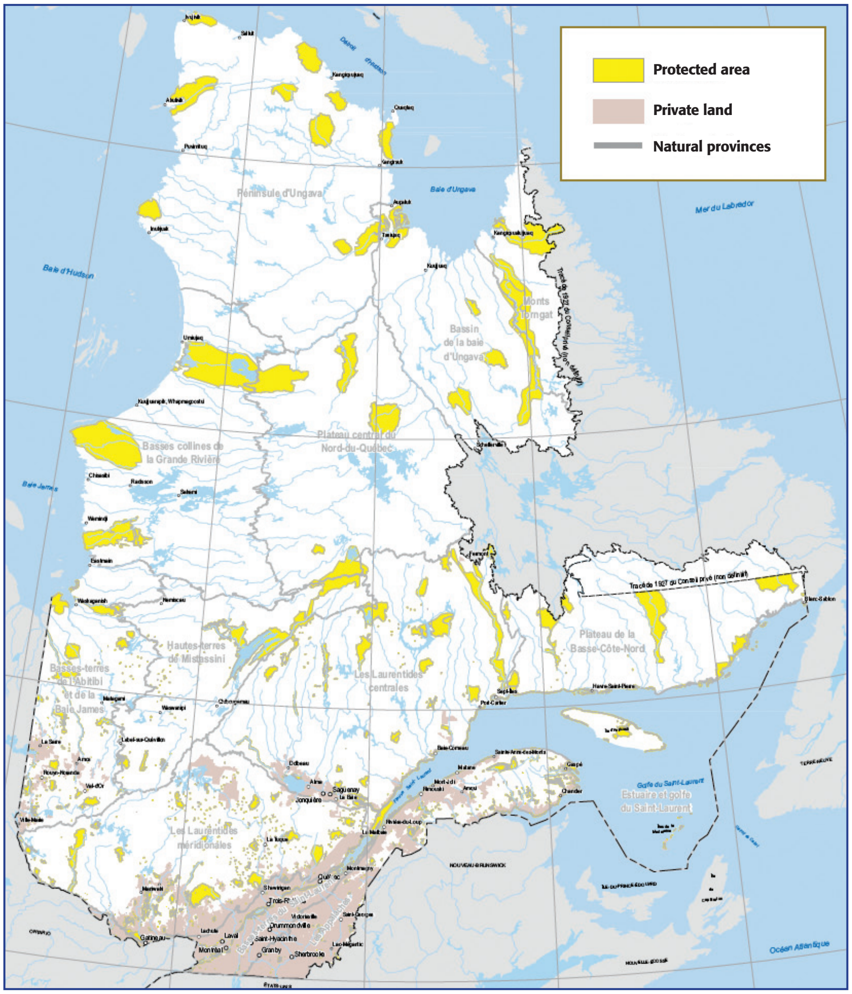


Figure 34: Map of protected areas in Quebec. These include areas under federal, provincial and municipal jurisdiction as well as privately-owned protected areas. The network of protected areas covers about 8% of the territory. (MDDEP, 2009c).

The current approach to selecting new protected areas (the Stratégie des aires protégées) underlies "a holistic vision of the territory in which the ecosystem is considered as a spatial entity and which includes the coarse-filter concept" (Gérardin *et al*., 2002). However this method, which accords preponderant value to the physical elements of an ecosystem (climate, geology, topography, hydrology and soil), is likely to destabilize the future network of protected areas and its role in protecting species and ecosystems, because the hydrological conditions and the climate will change in the midterm. Thus, it would be more fitting to take these variables into account in future conservation plans.

For its part, Parks Canada has developed a strategy that takes climate change into account in its approach to managing the biodiversity of existing parks (Wrona *et al*., 2005). Likewise, the coordination and establishment of a vast network of marine protected areas by Fisheries and Oceans Canada (Landry *et al*., 2008) in collaboration with all the levels of government concerned, is an effort to protect biodiversity and the productivity of marine ecosystems, essential to ensuring their resilience in the face of the combined impacts of climate change and human activities (Siron *et al*., 2008).

At the municipal and private levels, there do not yet seem to be these kinds of concerted mechanisms for establishing protected areas. Whatever the scope and scale of conservation strategies that are adopted, it would be relevant to consider protected areas as control sites for natural regions and their evolution, and to locate them and manage them with concern for coming climate changes.

This means that to promote adaptation, it would make sense to complete the network of terrestrial and marine protected areas as soon as possible in order to conserve representative parts of each of these natural regions. It would also be necessary to encourage the scientific management of protected areas, making use of any programmes for stocktaking, research, monitoring and comparison points with adjacent areas in order to be able to monitor the evolution of species and ecosystems in the context of climate change.

Considering ecological goods and services

Ecosystems supply a host of goods and services to society, from supplying drinkable water to purifying water and air, pollinating crops, among others (Limoges, 2009). Like the ecosystems that supply them, ecological services will be disrupted by climate change and we have reason to fear significant consequences for human well-being. Ecosystems sustain our life on Earth through the goods and services they supply. With the emergence of what is now known as the economics of ecosystems and biodiversity, which consists of putting a monetary value on the different elements of biodiversity and the natural environment (Chevassus-au-Louis *et al*., 2009; Jones-Walters and Mulder, 2009), these concepts will no doubt play a fundamental role in the way we perceive biodiversity and evaluate more precisely the impacts of human activities – including climate change – on the natural environment.

- ***Modify the rules regarding the exploitation of living resources***

The expected changes in the communities of some wildlife populations that are of interest to hunters and commercial and sports-fishermen will require more diligent monitoring in order to avoid additional pressures on fragile species or to slow the expansion of certain species towards zones where they were historically absent, and where they could compete to the detriment of other species.

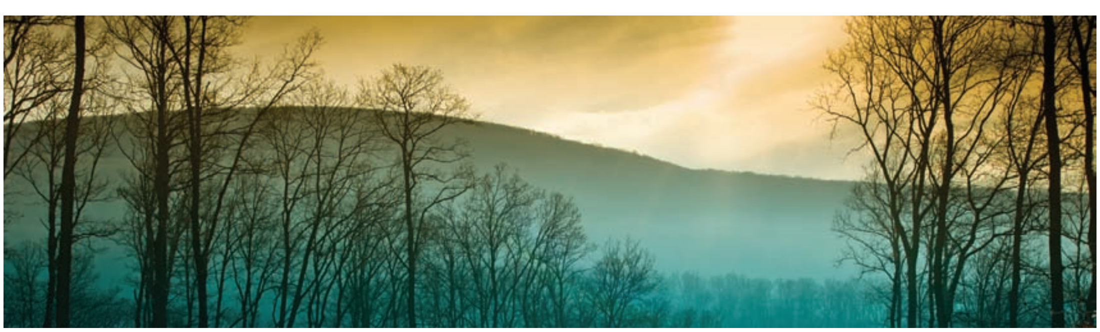
- ***Integrate consideration of climate change in territorial management activities***

This consists of involving managers at the territorial level in responsibility for overseeing biodiversity management; they would better understand the issues and better adapt their practices in ways that would promote species adaptation to new conditions (Génot and Barbault, 2005). The measures taken by Ouranos to enrich current knowledge on biodiversity, described earlier, would facilitate this linkup.

Act as quickly as possible to help the environment adapt to climate change

For millions of years, ecosystems and biodiversity have been adapting to natural climate variations. However, we do not understand all the mechanisms that living organisms, even the most highly evolved, use to adapt to climate variations (Berteaux and Stenseth, 2006). Climate change pose an additional challenge now because the rate at which the climate is changing is beyond its historic variability. In this context, it is hard to know whether ecosystems, habitats and species are capable of moving at the same rate, or how they will reconstruct themselves and what they will be like in 30, 50 or 100 years.

As we proceed towards the deadline, it is becoming more and more clear that the target date of 2010 for maintaining biological diversity will not be fully met (Secretariat of the Convention on Biological Diversity, 2006). Climate change will add to the other pressures on ecosystems and biodiversity that are created by human activity. Consequently, we need to begin immediately to take a census of the most sensitive elements of the natural environment, and to develop adaptation measures that will minimize this pressure on ecosystems in order to optimize their conditions for adapting to climate change. Not only will this safeguard the natural wealth of the planet, it will save ecological services that are essential to the survival and wellbeing of humanity.



SUMMARY AND CONCLUSION

Climate conditions have always had a determinant influence on ecosystems and on human societies. For the first, climate is one of the main factors controlling the nature and size of the communities of plant and animal species that make up any given ecosystem. For human societies, despite technological progress, the characteristics of the climate often serve as the foundation for local or regional economic activities and underlie numerous aspects of culture as well as the particularities of the built environment in a region.

The magnitude of the climate changes expected as a result of increased concentrations of greenhouse gases will disrupt the equilibrium that was established over time in the natural environment, and for humans, these changes will have impacts on the built environment, economic activities and health.

Recent and foreseeable climate changes

Already, we have seen a number of climate changes. For instance, in recent decades the average daily temperature in southern Quebec has increased by 0.2°C to 0.4°C per decade, with warming being greater for minimum than for maximum temperatures. These temperature increases also resulted in a shortened frost season, an increase in the number of growing degree-days, and a reduction in the number of heating degree-days. In terms of precipitation, we have also experienced an increase in the number of days with low-intensity rains and a reduction of precipitation in the form of snow in the South, while snowfall in the North has increased.

In the coming decades, it is expected that the climate will become warmer throughout the Quebec territory, and much more markedly in the winter than in the summer. This means that by the year 2050, temperatures will increase by 2.5°C to 3.8°C in southern Quebec and by 4.5°C to 6.5°C in the North. In summer, the temperature increases will be between 1.9°C to 3.0°C in the South and between 1.6°C and 2.8°C in the North.

Increases in precipitation — of between 16.8% and 29.4% in the North and between 8.6% and 18.1% in the South — are anticipated by the winter of 2050. Increased winter precipitation would lead to a greater accumulation of snow on the ground in the North. In the South, on the other hand, a reduced accumulation of snow on the ground is projected as a result of increased temperatures and a shortened frost season. In the summer, projections call for a 3.0% to 12.1% increase in precipitation in the North, while in the South, no significant change is expected.

The vulnerability of ecosystems

Already, in the North, terrestrial and aquatic ecosystems have begun to change with the degradation of the permafrost, which is leading to the creation of thermokarst basins and lakes as well as the expansion of shrub populations. It is quite possible that the Arctic region will the most affected by climate change where species adapted to the extreme conditions in this region will find themselves in competition with species from the South.

In the South, milder winters and the "tropicalization" of summers will mean the increased evaporation of surface water, causing the fragmentation of wetlands that rely on flood regimes. Several threatened species, with fragmented habitats, poor migratory capacity and already suffering from various stresses, will also be at great risk.

Climate changes will alter the ecological dynamics of ecosystems, as well as the range and relative abundance of species of flora and fauna. In some cases, this will result in a reduction of communities or the disappearance of certain populations, while for other species, their communities and ranges may expand. Beyond the simple displacement of ecosystems northward, it is feared that several threatened species and rare habitats will disappear, especially in areas where human activity is intense. Climate changes will add to the other pressures on ecosystems and biodiversity that result from human activities.

Determining the most vulnerable elements in the natural environment and taking adaptation measures to minimize the pressures on ecosystems caused by human activities will help to preserve the natural wealth of the planet and at the same time, preserve the ecological services essential to human survival and well-being.

Climate change will have a direct impact on infrastructure in all regions of Quebec.

In Quebec's Arctic, the very rapid and marked rise in temperatures will result in the accelerated melting of the permafrost, which will expose buildings and infrastructure to greater risk of subsidence and distortion. In particular, the airport runways in several communities, vital for communications and supplies, could suffer severe damage and require more frequent maintenance.

In the Gulf of St. Lawrence and estuary, a number of private and public buildings and several infrastructures will be exposed to increased shoreline erosion. It appears that rising sea levels, a reduction in freeze-up, the geology of certain coasts and changes in the storm regimes will be combined, resulting in an intensification of the natural processes of erosion.

In the South, the increasing frequency, intensity or duration of extreme climate events such as precipitations represent an increased risk to aging infrastructure, resulting in reduced effectiveness, accelerated wear, and even total loss. In addition, as recent weather events have shown, communities both urban and rural are highly dependent on infrastructure for transportation and water and power supply that are exposed to the vagaries of climate.

Giving priority to adaptation strategies for critical infrastructure is essential if we want to limit the magnitude of the expected impacts, especially in Quebec's Arctic and coastal areas. More generally, it will be crucial to invest in the refurbishment and renewal of existing infrastructure, as well as new construction, in order to prevent risk rather than react to events after they happen. In this connection, the renewal of aging infrastructure offers a unique opportunity to adapt it for future climate conditions. In this context it would appear suitable to review design criteria, which at present are usually based on historic data. The current approach, based on the assumption of a historically stable climate, needs to be reviewed to take into account the expected changes in climate data.

Various economic activities will be directly affected.

Because the time horizons for the most dramatic climate changes are relatively far off, it is especially difficult to assess their impacts on socioeconomic activities. These will depend in part on biophysical impacts that are still poorly understood or quantified, and in part on business and technological changes that will be at least as great, if not greater, than climate changes. All things being equal, moderate and gradual climate change could be beneficial for several economic sectors and perhaps the Quebec economy as a whole; however, larger and more rapid changes and an increase in the number of extreme climatic events could be distinctly unfavourable.

Forestry, hydroelectricity generation, agriculture, tourism and several other activities will be directly affected by changes in temperature and precipitation. In many cases, these climate changes and their indirect effects will have negative impacts for activities that are at the very heart of the existence of many Quebec communities. Conversely, some climate modifications will have positive aspects from which the Quebec economy could benefit.

For hydroelectricity generation, the projections, despite some uncertainties, tend to show that Quebec actually has nothing to fear in terms of the impacts of climate change on the annual hydroelectric production. Overall, it is expected that climate changes will result in increased rainfall and snowfall in all watersheds, although perhaps with some significant differences between regions and in seasonal distribution. In terms of energy demand, although there will be a substantial increase in demand for air conditioning, rising temperatures will reduce heating requirements even more, and this will reduce annual consumption.

Likewise, although right now research does not allow us to determine this with absolute certainly, the net impact of climate change on forest productivity could be positive over the mid-term due to rising temperatures and precipitation combined with increased concentrations of atmospheric CO_2. However, the frequency and intensity of natural disturbances such as the proliferation of pathogens and insect pests will increase, as will the frequency of extreme climatic events, which could mean that overall, the impacts will be negative.

Climate conditions might also turn out to be more favourable for agricultural production, which at present is limited in Quebec due to a short growing season and a limited accumulation of heat. This might be the case with crops like corn and soybeans, which may be able to grow in new regions. Likewise, increased atmospheric CO_2 could benefit agriculture. However, other factors influenced by climate, including the proliferation of crop pests and the increased vulnerability of the soil to erosion, could be more problematic in future. Moreover, there will be an increased probability of water stress resulting from increased evapotranspiration brought on by higher temperatures. The net effect could be positive or negative, depending on the complex and sometimes unanticipated interactions of all these factors.

Tourism is another important industry where climate plays a determinant role, whether we are talking about skiing, snowmobiling, swimming, recreational boating or nature hiking, or indirectly, hunting and fishing. The studies available so far indicate that in some locations further south in Quebec, the season for skiing and other winter sports will be shortened by several days. Accelerated coastal erosion, meanwhile, could also harm some tourism regions. Here again, technology-based adaptation measures or diversification could make it possible for the industry to reduce climate change impacts.

For Quebec in total, then, climate change could have a slight positive effect. However, in some regions and communities, the impacts could be major. For example, in Quebec's Arctic, which could experience the most dramatic changes by absolute measures, access to resources obtained by hunting and fishing would be seriously compromised. This would add to the complexity of cultural and demographic issues that already exist in the region, as communities are severely exposed to natural risks and are dependent on a range of critical infrastructures. On the other hand, development opportunities related to navigation, energy production and the mining sector due to milder winter conditions are possible, along with a diversification of fauna and flora. Elsewhere in Quebec, the lives of some communities where the economy relies heavily on tourism, forestry or hunting and fishing could be changed dramatically.

Climate change represent a challenge to human health.

The expected impacts of climate change on human health are many and diverse. They range from the direct effects of average warming, heat waves and thermal heat islands, atmospheric pollution, forest fires and wildfires, summer and winter storms and UV exposure to the indirect effects of changes in the quantity and quality of water resources and zoonotic diseases.

In particular, higher temperatures associated with a higher humidity level and more frequent and intense heat waves represent significant threats to human health. A second group of significant impacts is connected to the incidence of increasing temperatures on atmospheric pollution, especially pollens, ozone, and suspended particulates.

The indirect impacts resulting from the reactions of the natural and built environment will also mean increased risks in the areas of health, safety and well-being. Meanwhile, the expected changes in the water cycle and the impacts on the numerous uses of the water resource raise concerns about the quality and the quantity of available water, as well as the safety of populations at risk for flooding.

The extent of these negative impacts can be minimized by applying adaptation measures, especially preventive measures, giving priority to populations that are now or will be at risk. These measures can include efforts aimed at modifying behaviours that increase risk, assistance to vulnerable populations, and land use decisions that reduce climate risk.

Climate change adaptation means considering a variety of solutions that could mitigate the negative impacts substantially.

For generations, human societies have shown a great capacity for adapting to different climates, ranging from the hot humid atmosphere of the tropics to the cold, dry barrens of the Arctic. For centuries, human systems have shown a tendency to react to the impacts of natural climatic variability in ways that diminish their exposure to climate hazards and increase their resilience and adaptive capacity. Likewise, the components of the natural environment have shown themselves able to adapt to climate variability.

Still, these adaptations will not be without difficulty and will often be accompanied by significant losses and costs. The goal of preparing and implementing adaptation strategies is to reduce these losses and costs, and if possible, to take advantage of new conditions. Planned adaptation depends on the following elements:

- determining and understanding the priority issues;
- being mindful of uncertainties when making decisions;
- developing and implementing the optimal techniques and technologies;
- acquiring and sharing data and information that all levels of decision-makers require for adaptation;
- Changing or adapting policies and standards as well as organizational structures.

The array of adaptation issues and the great number of decision-makers means that we will be able to use a vast assortment of tools, ranging from raising awareness and disseminating information to integrating considerations related to changes in climate variability into our regulations, construction standards and organizational policies.

To meet the challenges, we will need to develop or make available a full range of tools and skills, including:

- adding relevant and high-quality data for understanding the issues;
- increasing the interdisciplinarity between the climate sciences and the sciences that focus on the biophysical, economic, social and health impacts, to create an integrated body of knowledge;
- improving the monitoring and warning systems, for preparedness;
- enhancing the interaction between researchers and the political and operational players;
- promoting leadership and open-mindedness at all levels of society in order to determine and prioritize the problems.

Table 8 summarizes a variety of adaptation strategies under study or already available and that are being used or could be applied for communities, socioeconomic activities and the natural environment. One can see that clearly, numerous players are involved — individuals, communities, industries, provincial, federal and international agencies —, understand also that there are many possible moments for intervention — short-term decisions and long-range planning — and that these are mutiple issues that must be targeted for adaptation measures. It is obvious that perceptions and behaviours, the processes and factors involved in decision-making, and the aspirations and convictions of individuals and communities are all fundamental elements in the adaptation of human systems.

Quebec, which is facing the same sorts of challenges as the rest of the world's inhabitants, is fortunate to possess a great adaptive capacity, particularly due to its diversified economy and many research institutions. In this regard, Ouranos can play a crucial role as a catalyst for putting our existing research capacities at the service of society.

In closing, we need to remember that even though we cannot ignore adaptation as an option, it is still imperative to accompany it with reductions in greenhouse gas emissions so that we can attack the source of the problem. Basically, even though it may be possible to reduce the negative impacts of climate change over the mid-term through careful adaptation measures, only a reduction in greenhouse gas emissions will limit the ever-growing and potentially disastrous costs in the long-term. The purpose of adaptation solutions is to build upon the efforts already invested in reducing greenhouse gas emissions, so that we can avoid some of the challenges posed by climate change for current and future generations.

Table 8 : Examples of climate change adaptation measures. Numbers in parentheses refer to the references on pages 117 to 119.

	Develop and understand Acquire information and develop expertise	**Communicate and raise awareness** Increase awareness and modify behaviour	**Respond and legislate** Amend laws, regulations and standards	**Apply technologies** Use techniques, products, materials	**Apply/recommend guidelines or ways of doing things** Adjust practices and policies
COMMUNITIES					
Isolated	Map sensitive zones for the development of infrastructure (1)	Disseminate information on transportation system conditions (2)	Establish land-use standards based on sensitive zones (2-3)	Apply techniques to reduce thawing of permafrost (4)	Produce a best practices guide for building on permafrost (5)
Dependent on natural resources	Identify the best sources of seeds/genotypes (6)	Inform communities on fire risk using forest fire-weather index (7)	Regulate fishing (opening/closing dates, locations, etc.) (8)	Manage fishing by habitat to ensure resource sustainability (8)	Establish a plan for economic diversification of communities at risk (9)
Coastal	Create an integrated scientific project in coordination with other agencies to meet needs of coastal regions (10)	Use simulation exercises to prepare citizens, municipalities, governments and others involved (11)	Regulate construction in flood zones, zoning and temporary control regulations (12)	Monitor protection structures (13)	Establish integrated management of coastal zones (14)
Rural	Identify cultivars used further south (analogs) and appropriate for the region (15)	Increase public awareness about saving water during droughts (16)	Establish a program of income stabilization, private insurance and incentives to take climate change into consideration (17)	Expand drip irrigation and combined technologies of surface drainage and runoff (18)	Install efficient ventilation systems or sprinklers to cool livestock (19)
Urban	Identify land favourable to allergenic species and map sources of allergen emissions (20)	Announce municipal emergency measures (21-22)	Regulate construction resistance standards (23), and the Building Code regarding energy (24)	Extend the use of reflective surfaces and coverings (roofs, facade paints, etc.) (25)	Set up local alert systems for heat waves (26)
SECTORS					
Health	Analyse the link between morbidity-mortality and climate (27-28)	Increase public awareness about smog and heat waves and give advice (29)	Take preventive measures to limit polluting emissions (at the start of high-pressure periods) (30)	Launch campaigns to pull up ragweed and plant competing species (20)	Use green roofs or high-albedo materials (12-25). Establish care guides adapted for home care clientele during extreme events
Infrastructure	Analyze aerial photos of coastlines over time and calculate the erosion rate (12)	Set up forecast and early warning systems and public education systems (23)	*Provincial Civil Protection Act* adopted in 2001 following the ice storm crisis of 1998 (31)	Design more resistant buildings (12) or better adapted with new methods (32)	Add 1 m to the Confederation Bridge due to the anticipated rise in sea level (38)
Primary sector of the economy	Develop biological methods to control propagation (6)	Increase awareness about harvest and field management adapted to present and anticipated climate conditions (15)	Amend the Forest Act to remove the outdated concept of sustained volume yield (34)	Use species and varieties adapted to different climate conditions (15)	Anticipate by building up financial reserves(35)
Tertiary sector of the economy	Use economic assessment tools (39-36)	Diversify recreational tourism choices to minimize climate risk (37)	Insure against losses due to bad weather and climate impacts (22)	Establish emergency, response and evacuation plans (22)	Raise the design criteria for bridges and culverts by 10% (civil engineering, MTQ) (38)
Water	Update IDF curves (40-41)	Communicate practices to manage rainwater recovery (24)	Implement international agreement on the Great Lakes basin water resources (48)	Rehabilitate degraded resources (22)	Test and review management rules based on various possible climate scenarios (42)
Ecosystems	Map ecological niches and assess changes (43)	Symposia at popular science events (44)	Maintain representative regional plants and wildlife (protected areas) (45)	Restore and protect wetlands (46)	Protect species and habitats (47)

REFERENCES

Agence canadienne d'évaluation environnementale. Examen des facteurs de changement climatique dans des évaluations environnementales antérieures choisies. Annexe D. Pont de la Confédération, Agence canadienne d'évaluation environnementale, 2000, <http://www.ceaa-acee.gc.ca/015/001/005/index_f.htm> [accessed : august 14, 2009].

Agence de la santé et des services sociaux de la Montérégie. (2007) Table québécoise sur l'herbe à poux, Agence de la santé et des services sociaux de la Montérégie, <http://www.santemonteregie.qc.ca/agence/santepublique/directiondesantepublique/herbeapoux.fr.html> [accessed June 11, 2009].

Agriculture and Agri-Food Canada. (2003) Les algues, les cyanobactéries et la qualité de l'eau, Agriculture and Agri-Food Canada, <http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1189714026543&lang=fra> [accessed June 11, 2009].

Ainsworth, E.A. and Long, S.P. (2005) What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2, New Phytologist, 165(2):337-653.

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, 1:95-111.

Albanese, B., Andermeier, P.L. and Dorai-Raj, S. (2004) Ecological correlates of fish movement in a network of Virginia streams, Canadian Journal of Fisheries and Aquatic Sciences, 61:857-869.

Albert, C., Roulx, R. and Richard, P. (2006) Chaleur accablante et usage de médicaments: étude exploratoire en Estrie, Institut national de santé publique du Québec, Bulletin d'information en santé onnementale, 17(3):5-8, <http://www.inspq.qc.ca/pdf/bulletins/bise/BISE-17-3.pdf> [accessed June 11, 2009].

Allard, M. and Seguin, M.K. (1987) Le pergélisol au Québec nordique: bilan et perspectives, Géographie physique et Quaternaire, 41(1):141-152.

Allard, M., Fortier, R., Duguay, C. and Barrette, N. (2002a) A new trend of fast climate warming in Northern Quebec since 1993. Impacts on permafrost and man-made infrastructures, meeting of the American Geophysical Union, Moscone Center, San Francisco, autumn 2002.

Allard, M., Fortier R. and Gagnon, O. (2002b) Problématique du développement du village de Salluit, Nunavik, Québec, Centre d'études nordiques, Université Laval, Québec, 121 p.

Allard, M., Fortier, R. Gagnon, O. and Michaud, Y. (2004) Problématique du développement du village de Salluit, Nunavik. Une communauté en croissance sur un terrain sensible au changement climatique, final report, Centre d'études nordiques, Université Laval, Quebec, 101 p. <http://www.assnat.qc.ca/fra/37legislature2/commissions/Cte/depot-rechauffement.html> [accessed September 17, 2009].

Allard, M., Fortier, R., Sarrazin, D., Calmels, F., Fortier, D., Chaumont, D., Savard, J.-P. and Tarussov, A. (2007a) L'impact du réchauffement climatique sur les aéroports du Nunavik: caractéristiques du pergélisol et caractérisation des processus de dégradation des pistes, Centre d'études nordiques, Université Laval, report prepared for Ouranos, Natural Resources Canada and Transports Québec, 184 p., <http://www.ouranos.ca/media/publication/13_Rapport_Allard2_nord_2007.pdf> [accessed September 17, 2009].

Allard, M., Calmels, F., Fortier, D., Laurent, C., L'Hérault, E. and Vinet, F. (2007b) Cartographie des conditions de pergélisol dans les communautés du Nunavik en vue de l'adaptation au réchauffement climatique, Centre d'études nordiques, Université Laval, report prepared for Ouranos and Natural Resources Canada, 42 p., <http://www.ouranos.ca/media/publication/14_Rapport_Allard_nord_2007.pdf> [accessed September 17, 2009].

Allard, M., Sarrazin, D. and Marchildon, C. (2008) Evidences of impacts of climate warming on permafrost in Nunavik (Northern Quebec), proceedings of symposium on the environment and mining, November 2-5, 2008, Rouyn-Noranda (Québec), 16 p.

American Water Works Association. (1999) Manual of Water Supply Practices — M48: Waterborne Pathogens, 1st edition, Denver, Colorado, 285 p.

Anctil, M. and Rochette, L. (2008) Enquête de santé auprès des Inuits du Nunavik 2004, Qanuippitaa ? Comment allons-nous ? Les faits saillants de l'enquête, Institut national de santé publique du Québec (INSPQ) and Régie régionale de la santé et des services sociaux du Nunavik (RRSSSN), 7 p.

Andalo, C., Beaulieu, J. and Bousquet, J. (2005) The impact of climate change on growth of local white spruce populations in Quebec, Canada, Forest Ecology and Management, 205:169-182.

André, P. and Bryant, C.R. (May 2001) Évaluation environnementale des stratégies d'investissement des producteurs agricoles de la région de Montréal en regard des changements climatiques, report prepared for the Climate Change Action Fund, Natural Resources Canada.

Araujo, M.B., Thuillier, W., and Pearson, R.G. (2006) Climate warming and the decline of Amphibians and Reptiles in Europe, Journal of Bio-Geography, 33:1712-1728.

Archambault, M. (2008) Étude économique et financière des stations de ski du Québec. Le portrait de la saison 2007-2008 des stations de ski alpin du Québec, Chaire de tourisme Transat, Université du Québec à Montréal, Montréal, <http://www.chairedetourisme.uqam.ca/pdf/sommaire%20ex%e9cutif%20ski%2007-08.pdf> [accessed June 18, 2009].

Ashmore, P. and Church, M. (2001) The Impact of Climate Change on Rivers and River Processes in Canada, Geological Survey of Canada, Bulletin 555.

Auld, H. and MacIver, D. (2004) Cities and communities: the changing climate and increasing vulnerability of infrastructure, *in* Climate Change: Building the Adaptive Capacity, A. Fenech, D. MacIver, H. Auld, B. Rong et Y.Y. Yin (ed.), Meteorological Service of Canada, Environment Canada, Toronto, p. 289-305.

Ayres, M.P. and Lombardero, M.J. (2000) Assessing the consequences of global change for forest disturbance from herbivores and pathogens, Science of the Total Environment, 262(3):263-286.

Bagon, M., Harper, J.L. and Townsend, C.R. (1996) Ecology: Individuals, Populations and Communities, 3rd edition, Blackwell Science, Oxford, UK, 1068 p.

Barbeau, B., Carrière, A., Prévost, M., Zamyadi, A. and Chevalier, P. (2008) Changements climatiques au Québec méridional — Analyse de la vulnérabilité des installations québécoises de production d'eau potable aux cyanobactéries toxiques — Résumé, Institut national de santé publique du Québec, 2008, 16 p., <http://www.inspq.qc.ca/publications/notice.asp?E=p&NumPublication=867> [accessed June 11, 2009].

Beaudet, P., Beaudin, I., Michaud, A., and Giroux, M. (2008) Le transport du phosphore, Fiche technique #3, Centre de référence en agriculture et agroalimentaire du Québec, 11 p., <http://www.craaq.qc.ca/Publications?p=32&l=fr&IdDoc=1997> [accessed April 24, 2008].

Beaulac, I. and Doré, G. (2005) Impacts du dégel du pergélisol sur les infrastructures de transport aérien et routier au Nunavik et adaptations — état des connaissances, Faculté des Sciences et de Génie, Université Laval, Québec, 141 p.

Beaulieu, J. and Rainville, A. (2005) Adaptation to climate change: Genetic variation is both a short- and a long-term solution, The Forestry Chronicle, 81:704-709.

Bégin, Y. (2006) Le changement climatique en cours dans le nord du Québec, submission by the Centre d'études nordiques to the Commission parlementaire sur les transports et l'environnement, <www.cen.ulaval.ca/documents/Memoire2006CommissionParlementaire.pdf> [accessed September 17, 2009].

Bélanger, D., Gosselin, P., Valois, P. and Abdous, B. (2006) Vagues de chaleur au Québec méridional: adaptations actuelles et suggestions d'adaptations futures, Institut national de santé publique du Québec, <http://www.inspq.qc.ca/publications/default.asp?E=p&NumPublication=538> [accessed June 11, 2009].

Bélanger, D. and Gosselin, P. (2007) Changements climatiques au Québec méridional: perceptions de la population générale et suggestions d'adaptations futures, Institut national de santé publique du Québec, 49 p., <http://www.inspq.qc.ca/publications/notice.asp?E=p&NumPublication=618> [accessed June 11, 2009].

Bélanger, D., Gosselin, P., Valois, P. and Abdous, B. (2008) Use of residential wood heating in a context of climate change: a population survey in Quebec (Canada), BMC Public Health, 8(184), <http://www.biomedcentral.com/1471-2458/8/184/abstract> [accessed June 11, 2009].

Bélanger, D., Gosselin, P., Valois, P., Germain, S. and Abdous, B. (2009) Use of a remote car starter in relation to smog and climate change perceptions: A population survey in Québec (Canada), International Journal of Environmental Research and Public Health, 6(2):694-709.

Bélanger, G., Rochette, P., Castonguay, Y., Bootsma, A., Mongrain, D. and Ryan, D.A.J. (2002) Climate change and winter survival of perennial forage crops in Eastern Canada, Agronomy Journal, 94:1120-1130.

Benson, K., Kocagil, P. and Shortle, J. (2000) Climate change and health in the Mid-Atlantic Region, Climate Research, 14:245-253.

Bergeron, Y., Flannigan, M., Gauthier, S., Leduc, A. and Lefort, P. (2004) Past, current and future fire frequency in the Canadian boreal forest: Implications for sustainable forest management, Ambio, 33(6):356-360.

Bernatchez, P. and Dubois, J.-M. M. (2004) Bilan des connaissances de la dynamique de l'érosion des côtes du Québec maritime laurentien, Géographie physique et Quaternaire, 58(1):45-71.

Bernatchez, P. and Dubois, J.-M. M. (2008) Seasonal quantification of coastal processes and cliff erosion on fine sediments shoreline in a cold temperate climate, North Shore of the St. Lawrence Estuary, Québec, Journal of Coastal Research, 24(1A):169-180.

Bernatchez, P., Fraser, C., Friesinger, S., Jolivet, Y., Dugas, S., Drejza, S. and Morisette, A. (2008) Sensibilité des côtes et vulnérabilité des communautés du golfe du Saint-Laurent aux impacts des changements climatiques, rapport sectoriel, Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski, Rimouski, 256 p., <http://www.ouranos.ca/media/publication/145_Bernatchezetal2008.pdf> [accessed July 28, 2009].

Bernier, L., Lachance, P., Quilliam, L. and Gingras, D. (1998) Rapport sur l'état du Saint-Laurent — La contribution des activités urbaines à la détérioration du Saint-Laurent, Joint team report, with representatives from Environment Canada, Fisheries and Oceans Canada, and the Ministère de l'Environnement et de la Faune du Québec, Sainte-Foy (Québec), technical report.

Berteaux, D. (2008) Le renard arctique: un exemple concret de la modification de l'écosystème nordique, Francvert, 5(1) <http://www.francvert.org/pages/51dossierlerenardarctique.asp> [accessed September 4, 2009].

Berteaux, D. (2009) Les effets des changements climatiques sur la biodiversité du Québec, In Vivo, in press, 29(2):8 -10.

Berteaux, D., Réale, D., McAdam, A.G. and Boutin, S. (2004) Keeping pace with fast climate change: Can arctic life count on evolution? Integrative and Comparative Biology, 44:140 -151.

Berteaux, D. and Stenseth, N.C. (2006) Measuring, understanding and projecting the effects of large-scale climatic variability on mammals, Climate Research, 32:95-97.

Besancenot, J.-P. (2004) Vagues de chaleur et mortalité dans les grandes agglomérations urbaines, Environnement, Risques et Santé, 1(4):229-240.

Blanchard, D. and Pouliot, F. (2003) Comment diminuer l'impact des températures chaudes durant l'été, Porc Québec,. 14(1):75-76.

Boisvenue, C. and Running, S. (2006) Impact of climate change on natural forest productivity — Evidence since the middle of the 20th century, Global Change Biology, 12:862–882. boréale », Liaison Énergie-Francophonie, 2008, n° spécial septembre 2008, 148 p.

Bootsma, A., Anderson, D. and Gameda, S. (2004) Indices potentiels du changement climatique sur les indices agroclimatiques dans les régions du sud de l'Ontario et du Québec, Centre de recherches de l'Est sur les céréales et les oléagineux, Agriculture and Agri-Foods Canada, Technical bulletin 03-284.

Bootsma, A., Gameda, S. and McKenny, D.W. (2005a) Impacts of potential climate change on selected agroclimatic indices in Atlantic Canada, Canadian Journal of Soil Science, 85:329-343.

Bootsma, A., Gameda, S. and McKenney, D.W. (2005b) Potential impacts of climate change on corn, soybeans and barley yields in Atlantic Canada, Canadian Journal of Soil Science, 85:345-357.

Bouchard, M. and Smargiassi, A. (2008) Estimation des impacts sanitaires de la pollution atmosphérique au Québec: essai d'utilisation du Air Quality Benefits Assessment Tool (AQBAT), Institut de santé publique du Québec, 30 p., <http://www.inspq.qc.ca/publications/notice.asp?E=p&NumPublication=817> [accessed June 11, 2009].

Boucher, J.-F., Gaboury, S., Lord, D. and Villeneuve, C. (2008) Potentiel et enjeux à propos de la création de puits de carbone en forêt boréale, Liaison Énergie-Francophonie, special issue, September 2008, 148 p.

Bouden, M., Moulin, B. Gosselin, P., Back, C., Doyon, B., Gingras, D. and Lebel, G. (2005) La géo-simulation de l'infection au virus du Nil occidental en fonction du climat: un outil de gestion du risque en santé publique, *in* Adapting to Climate Change in Canada 2005: Understanding Risks and Building Capacity, Canadian Climate Impacts and Adaptation Research Network (C-CIARN) Conference, May 4-7, 2005 in Montreal, <http://www.adaptation2005.ca/posters/bouden_f.html> [accessed June 11, 2009].

Bourgault, D. (2001) Circulation and mixing in the St. Lawrence estuary, Doctoral thesis, Department of.atmospheric and oceanic sciences and Center for climate and global change research, McGill University, Montreal, 127 p.

Bourgeois, G., Bourque, A. and Deaudelin, G. (2004) Modelling the impact of climate change on disease incidence: a bioclimatic challenge, Canadian Journal of Plant Pathology, 26:284-290.

Bourque, A. And Simonet, G. (2008) Québec *in* D.S. Lemmen, F.J. Warren, J. Lacroix and E. Busg (ed.), Vivre avec les changements climatiques au Canada: edition 2007, Government of Canada, Ottawa, 171-226 p.

Boutin, R. and Robitaille, G. (1995) Increased soil nitrate losses under mature sugar maple trees affected by experimentally induced deep frost, Canadian Journal of Forest Research, 25:588-602.

Boyer C., V. Bondue, P. Biron, M. Lamothe, A.G. Roy and J. Morin. (2004) Modélisation des effets des fluctuations du niveau d'eau du fleuve St-Laurent sur les ajustements des tributaires et le transport des sédiments, *in* Eau et Changements Climatiques: comprendre pour mieux s'adapter / Water and Climate Change: Knowledge For Better Adaptation, 57th annual congress of the Canadian Water Association, programme and abstracts on paper, proceedings on CD-rom.

Bradshaw, B., Dolan, H. and Smit, B. (2004) Farm-level adaptation to climatic variability and change: Crop diversification in the Canadian Prairies, Climatic Change, 67:119-141.

Breton, M.-C., Garneau, M., Fortier, I., Guay, F. and Louise, J. (2006) Relationship between climate, pollen concentrations of Ambrosia and medical consultations for allergic rhinitis in Montreal, 1994–2002, Science of the Total Environment, 370(1):39-50.

Brissette, F., Leconte, R., Marche, C. and Rousselle, J. (2003) Historical evolution of flooding damage on a USA/Quebec river basin, Journal of the American Water Resources Association, 39(6):1385-1396.

Brodeur, P., Mingelbier, M. and Morin, J. (2006) Impact de la régularisation du débit des Grands Lacs sur l'habitat de reproduction des poissons dans la plaine inondable du fleuve Saint-Laurent, Naturaliste canadien, 130(1):60-68.

Brooks, R.T. and Hayashi, M. (2002) Depth-area-volume and hydroperiod relationships in ephemeral (vernal) forest pools in Southern New England, Wetlands, 22:247-255.

Brown, R.D. (2010) Analysis of snow cover variability and change in Quebec, 1948-2005, Hydrological Processes, in press.

Brown, R.D. and Chaumont, D. (2010) Analyse de simulations régionales du climat et d'indices climatiques associés au transport routier dans le sud du Québec, 2009, XIII Annual Winter Road Congress, Quebec City, February 8-11, 2010.

Bruce, J., Burton, I. and Egener, I. (1999) Mesures d'atténuation des catastrophes et protection civile dans un monde au climat changeant, Emergency Preparedness Canada, Environment Canada and Insurance Bureau of Canada, 43 p.

Bryant, C.R., Singh, B., DesRoches, S., Thomassin, P., Baker, L., Madramootoo, C., Delusca, K. and Savoie, M. (2005) Climate Variability and Quebec: Lessons for Farm Adaptation from an Analysis of the Temporal and Spatial patterns of Crop Insurance Claims in Quebec, presentation at the Congrès national sur l'adaptation aux changements climatiques, Montreal, May 2005.

Bryant, C., Singh, B., Thomassin P. and Baker, L. (2007) Vulnérabilités et adaptation aux changements climatiques au Québec au niveau de la ferme: leçons tirées de la gestion du risque et de l'adaptation à la variabilité climatique par les agriculteurs, Ouranos, 49 p., <http://www.ouranos.ca/media/publication/149_Bryant1.pdf> [accessed April 24, 2009].

Buckley, D.S., Sharik, T.L. and Isebrands, J.G. (1998) Regeneration of northern red oak: positive and negative effects of competitor removal, Ecology, 79:65-78.

Budyko, M.I. (1974) Climate and life, in International Geographic Series, D.H. Miller (ed.), Academic Press, New York, 508 p.

Bunce, J.A. (2004) Carbon dioxide effects on stomatal responses to the environment and water use by crops under field conditions, Oecologia, 140:1-10.

Canadian Cancer Society. (2009) Statistiques canadiennes sur le cancer 2009, Canadian Cancer Society, 132 p., <http://www.cancer.ca/Canada-wide/About%20cancer/Cancer%20statistics/Canadian%20Cancer%20Statistics.aspx?sc_lang=fr-CA> [accessed June 11, 2009].

Canadian Council of Ministers of the Environment. (2005a) De la source au robinet: guide d'application de l'approche à barrières multiples pour une eau saine, Canadian Council of Ministers of the Environment, <http://www.ccme.ca/sourcetotap/mba.fr.html> [accessed June 11, 2009].

Canadian Council of Ministers of the Environment. (2005b) Fiches d'information sur les contaminants, Canadian Council of Ministers of the Environment, <http://www.ccme.ca/sourcetotap/infosheets.fr.html> [accessed June 11, 2009].

Canadian Environmental Assessment Agency. (2000) Examen des facteurs de changement climatique dans des évaluations environnementales antérieures choisies. Annexe D. Pont de la Confédération, Agence canadienne d'évaluation environnementale, <http://www.ceaa-acee.gc.ca/015/001/005/index_f.htm> [accessed August 14, 2009].

Canadian Federation of Municipalities. (2002) Final report on Federation of Canadian Municipalities Municipal Infrastructure Risk Project: Adapting to Climate Change, report prepared for the Climate Change Action, Natural Resources Canada, 29 p.

Canadian Institutes of Health Research. (2002) Déterminer les priorités de recherche nationales sur les influences de l'environnement sur la santé. Contexte et options, Canadian Institute of Health Research, <http://www.cihr-irsc.gc.ca/f/pdf_14818.htm> [accessed June 11, 2009].

Canadian Institute of Planners. (2007) Promotion de l'adaptation aux changements climatiques auprès des urbanistes, Institut canadien des urbanistes, <http://www.cip-icu.ca/web/la/en/fi/8F1018CE46964FB0844AB79CA10546F8/get_file.asp> [accessed August 11, 2009].

Carroll, A.L., Taylor, S.W., Régnière, J., and Safranyik, L. (2003) Effects of climate change on range expansion by the Mountain Pine Beetle in British Columbia, Mountain Pine Beetle Symposium: Challenges and Solution, Kelowna B.C , October 30-31 2003..

Caron, A. (2005) Calibration et validation d'un générateur de climat dans le contexte des changements climatiques, Master's thesis, École de technologie supérieure, Montréal, 135 p.

Case, T. (2008) Climate change and infrastructure issues, Drinking Water Research, special issue, , Awwa Research Foundation, 18(2):15-17.

Casselman, J.M. (2002) Effects of temperature, global extremes, and climate change on year-class production of warm water, coolwater, and coldwater fishes in the Great Lakes Basin, American Fisheries Society Symposium, 32:39-60.

Caya, D. and Laprise, R. (1999) A semi-implicit semi-lagrangian regional climate model: the Canadian RCM, The Monthly Weather Review, 127(3):341-362.

Chang, S.E., McDaniels, T.L., Mikawoz, J. and Peterson, K. (2007) Infrastructure failure interdependencies in extreme events: Power outage consequences in the 1998 ice storm, Natural Hazards, 41:337-358.

Charron, D., C. Schuster-Wallace, C. and Noble, D. (2005) La vulnérabilité des Canadiens aux maladies d'origine hydrique et alimentaire, <http://adaptation2005.ca/abstracts/charron_f.html> [accessed June 11, 2009].

Charron D., Fleury, M., Linday, L.R., Ogden, N.H. and Shuster, C.J.. , (2008) Répercussions des changements climatiques sur les maladies transmises par l'eau, les aliments, les vecteurs et les rongeurs, chap. 5 in J. Séguin (ed.), Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity, Health Canada, Ottawa, 558 p.

Chaumont, D. and Chartier, I. (2005) Développement de scénarios hydrologiques à des fins de modélisation de la dynamique sédimentaire des tributaires du Saint-Laurent dans un contexte de changements climatiques, technical report, Ouranos, 37 p.

Chevassus-au-Louis, B., Salles, J.-M., Bielsa, S., Richard, D., Martin G. and Pujol, J.-L. (2009) Approche économique de la biodiversité et des services liés aux écosystèmes, contribution to public decision-making, Centre d'analyse stratégique, France, 376 p.

Chin, J. (2000) Control of Communicable Diseases in Man, American Public Health Association, Washington, DC.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, S., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T. , Laprise, R., Magana Rueda, V., Mearns, L., Menendez, 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, S. Salomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignot and H.L. Miller (ed.), Cambridge University Press, Cambridge and New York, pp.847-940.

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 & Distributions, 11(4):299-310.

Cohen, S. and Miller, K. (2001) North America, *in* Climate Change 2001: Impacts, Adaptation and Vulnerability, contribution by Working Group I I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (ed.), Cambridge University Press, Cambridge and New York, pp. 735-800.

Commission de la santé et de la sécurité du travail. (2004) Travailler à la chaleur — attention !, Commission de la santé et de la sécurité du travail, <http://www.csst.qc.ca/NR/rdonlyres/1615AED8-EC4E-4AC3-AA95-02246E91EE19/4431/DC 200 16184 5.pdf> [accessed June 11, 2009].

Conseil régional des ressources en eau des Grands Lacs et du fleuve Saint-Laurent. (2005) Entente sur les ressources en eaux durables du bassin des Grands Lacs et du fleuve Saint-Laurent, Conseil régional des ressources en eau des Grands Lacs et du fleuve Saint-Laurent, <http://www.mddep.gouv.qc.ca/eau/grandslacs/2005/Entente.pdf> [accessed May 11, 2009].

Côté, M., Lachance, J., Lamontagne, C., Nastev, M., Plamondon, R. and Roy, N. (2006) Atlas du bassin versant de la rivière Châteauguay, ministère du Développement durable, de l'Environnement et des Parcs du Québec, in close collaboration with the Geological Survey of Canada and the Institut national de la recherche scientifique, Eau, Terre et Environnement, 64 p.

Croley, T.E. (2003) Great Lakes Climate Change Hydrologic Assessment, I.J.C. Lake Ontario — St-Lawrence River Regulation Study, National Oceanic and Atmospheric Administration, Technical Memorandum GLERL-126.

Curriero, F.C., Patz, J.A., Rose, J.B. and Lele, S. (2001) The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994, American Journal of Public Health, 91(8):1194-1199.

Daigle, R., Forbes, D., Vasseur, L., Nichols, S., Bérubé, D., Thompson, K., Ritchie, H., Hanson, A., Tremblay, É., Parkes, G., Murphy, K. and Webster, T. (2005) Impacts de l'élévation du niveau de la mer et des changements climatiques sur la zone côtière du sud-est du Nouveau-Brunswick, *in* Adapting to Climate Change in Canada 2005: Understanding Risks and Building Capacity, conference held May 4-7, 2005 *in* Montreal and sponsored by the Climate Change Impacts and Adaptation Program of Natural Resources Canada and the Canadian Climate Impacts and Adaptation Research Network (C-CIARN), 2005, <http://www.adaptation2005.ca/abstracts/daigle_e.html> [accessed July 28, 2009].

Dajoz, R. (2000) Précis d'écologie, 7th edition, Dunod, Paris.

D'Arcy, P., Bibeault, J.-F. and Raffa, R. (2005) Changements climatiques et transport maritime sur le Saint-Laurent. Étude exploratoire d'options d'adaptation, rapport prepared for the Comité de concertation navigation of the Plan d'action Saint-Laurent, 140 p., <http://www.ouranos.ca/media/publication/21_Rapport_Darcy_eau_2005.pdf> [accessed May 11, 2009].

Davis, M.B. (1981) Quaternary history and stability of forest communities, *in* D.C. West and H.H. Shugart (ed.), Forest Succession, Springer-Verlag, New York, pp. 132-153.

De Elía, R. And Côté, H. (2009) Sensitivity study of CRCM-simulated climate change projections over North America, 2nd Lund Regional-scale Climate Modelling Workshop: 21st century Challenges in Regional-scale Climate Modelling, May 4-8, 2009 in Lund, Sweden, <http://www.baltex-research.eu/RCM2009/Material/RCM2009_Proceedings_print.pdf> [accessed November 6, 2009].http://www.baltex-research.eu/RCM2009/Material/RCM2009_Proceedings_print.pdf

DeLucia, E.H., Hamilton, J.G., Naidu, S.L., Thomas, R.B., Andrews, J.A., Finzi, A., Lavine, M., Matamala, R., Mohan, J.E., Hendrey G.R. and Schlesinger, W.H. (1999) Net primary production of a forest ecosystem with experimental CO_2 enrichment, Science, 284:1177-1179.

Derocher, A.F., Lunn, N.J and Stirling, I. (2004) Polar bear in a changing climate, Integrative Comparative Biology, 44:163-176

Desgranges, J.-L., Ingram, J., Drolet, B., Morin, J., Savage, C. and Borcard, D. (2006) Modeling the bird response to water level changes in the Lake Ontario — St. Lawrence River hydrosystem, Environmental Monitoring and Assessment, 113:329-365.

Desrochers, G.É., Pacher, G., Guay, F., Roy, L., Roy, R., Tapsoba, D. And Chartier, I. (2008) Impacts des changements climatiques sur les apports en eau des bassins versants du Québec, presented at the 3rd Ouranos Scientific Symposium, Montreal, November 19-20, 2008.

Diaconesco, R., Gachon, P. and St-Hilaire, A. (2007) Analyse de la variabilité des vents dans le golfe du Saint Laurent: tendances climatiques et de nature non climatique, Ouranos, Research report.

Di Castri, F. and Younes, T. (ed.) (1990) Ecosystem function of Biological diversity, Biology International, special issue, # 22, International Union of Biological Sciences, Paris.

Di Castri, F. and Younes, T. (1996) Biodiversity, the emergence of a new scientific field — Its perspectives and constraints, *in* F. Di Castri and T. Younes (ed.), Biodiversity, Science and Development, Towards a New Partnership, International Union of Biological Sciences CAB International, Wallingford, U.K. pp. 1-11.

Dietrich, R.A. (1981) Alaskan Wildlife Diseases, Institute of Arctic Biology, University of Alaska, Fairbanks, USA.

Diffey, B. (2004) Climate change, ozone depletion and the impact on ultraviolet exposure of human skin, Physics in Medecine and Biology, 49(1):R1-11.

Direction de la santé publique de la Montérégie. (2004) Plan d'urgence spécifique: mesures accablantes, 2004 edition, Direction de la santé publique de la Montérégie, preliminary version.

Direction de la santé publique de Montréal. (2004) Plan de mesures d'urgence: épisode de chaleur accablante 2004, Unité Santé au travail et environnementale, document summary.

Direction de la santé publique de Québec. (2004) Mémoire déposé au Bureau d'audiences publiques sur l'environnement sur le Projet de prolongement de l'axe du Vallon (ville de Québec), Direction de la santé publique de Québec, June 1, 2004, 29 p., <http://www.bape.gouv.qc.ca/sections/mandats/du_vallon/documents/DM65.pdf> [accessed June 11, 2009].

Direction de la santé publique du Québec. (2005) Les souris sylvestres dans les chalets: un risque sérieux pour la santé, Agence de développement de réseaux locaux de services de santé et de services sociaux de la Mauricie et du Centre-du-Québec, <http://www.bibliotheque.assnat.qc.ca/01/PER/830397/2005/Vol_14_no_2_(juil_2005).pdf> [accessed June 11, 2009].

Dixsaut, G. (2005) Vague de chaleur et climatisation: revue bibliographique, Bise, 16(4):1-6.

Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermott, A. and Zeger, S.L. (2006) Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases, The Journal of the American Medical Association, 295(10):1127-1134.

Doré, G. and Savard, Y. (2006) Vérification des méthodes de dimensionnement des chaussées au gel-dégel (coopération Québec-France): suivi des comportements des planches d'essais après trois ans et cinq ans, *in* Répertoire des projets de recherche et développement, Ministère des Transports du Québec.

Dost, F.N. (1991) Acute toxicology of components of vegetation smoke, Reviews of Environmental Contamination and Toxicology, 119:1-46.

Doyon, B., Bélanger, D. and Gosselin, P. (2006) Effets du climat sur la mortalité au Québec méridional de 1981 à 1999 et simulations pour des scénarios climatiques futurs, Institut national de santé publique du Québec, 75 p. <http://www.inspq.qc.ca/publications/default.asp?E=p&NumPublication=538> [accessed June 11, 2009].

Doyon, B., Bélanger, D. and Gosselin, P. (2008) The potential impact of climate change on annual and seasonal mortality for three cities in Quebec, Canada, International Journal of Health Geographics, 7(23) <http://www.ij-healthgeographics.com/content/7/1/23> [accessed June 11, 2009].

Drake, B.G., Gonzalez-Meler, M.A. and Long, S.P. (1997) More efficient plants: A consequence of rising atmospheric CO_2?, Annual Review of Plant Physiology and Plant Molecular Biology, 48:609-639.

Drejza, S., Bernatchez, P. and Dugas, C. (2009) Coastal hazard zoning plan in a climate change context, Percé, Canada, Ancient Landscapes — Modern Perspectives, 7th International Conference on Geomorphology, July 6-11, Melbourne, Australia, <http://cgrg.geog.uvic.ca//abstracts/DrejzaCoastalBecause.html> [accessed November 9, 2009].

Dubois, J.-M. M. (1999) Dynamique de l'érosion littorale sur la Côte-Nord du Saint-Laurent, report of the Colloque régional sur l'érosion des berges: vers une gestion intégrée des interventions en milieu marin, Comité de la zone d'intervention prioritaire de la rive nord de l'estuaire, MRC of Manicouagan (ed.), Baie-Comeau.

Dubois, J.-M. M., Bernatchez, P., Bouchard, J.-D., Daigneault, B., Cayer, D. and Dugas, S. (2006) Évaluation du risque d'érosion du littoral de la Côte-Nord du St-Laurent pour la période de 1996 à 2003, Conférence régionale des élus de la Côte-Nord, report presented to the Comité interministériel sur l'érosion des berges de la Côte-Nord, 291 p. <http://www.crecotenord.qc.ca/index.php?option=com_docman&task=cat_view&gid=97&Itemid=278> [accessed July 28, 2009].

Ducas, S. (2004) Conférence sur le plan d'urbanisme de la Ville de Montréal, *in* 8[es] Journées annuelles de la santé publique, November 30, 2004.

Duchesne, L., Houle, D., Côté, M.-A. and Logan, T. (2009) Modelling the effect of climate on maple syrup production in Quebec, Canada, Forest Ecology and Management, 258(12):2683-2689.

Duchesne, S., Mailhot, A. and Levesque, E. (2005) Impacts et adaptations liés aux changements climatiques en matière de drainage urbain au Québec: évaluation de la performance historique des réseaux, *in* Adapting to Climate Change in Canada 2005: Understanding Risks and Building Capacity, Conference May 4-7, in Montreal and sponsored by the Climate Change Impacts and Adaptation Program at Natural Resources Canada and the Canadian Climate Impacts and Adaptation Research Network (C-CIARN).

Edwards, M. and Richardson, A. (2004) Impact of climate change on marine pelagic phenology and trophic mismatch, Nature, 430:881-884.

Ebi, K.L., Balbus, J., Kinney, P.L., Lipp, E., Mills, D., O'Neill, M.S. and Wilson, M. (2008) Effects of global change on human health, Chap. 2 *in* Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems, report of the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, J.L. Gamble eéd.), U.S. Environmental Protection Agency, Washington, DC,, p. 2-1 to 2-78.

Engineers Canada. (2008) Adaptation aux changements climatiques. Première évaluation nationale de la vulnérabilité de l'ingénierie des infrastructures publiques au Canada, Engineers Canada, 76 p.

Enright, W. (2001) Changement d'habitudes, changement climatique: analyse de base, Canadian Institute of Child Health, 129 p.

Environment Canada. (2002) Les dix principaux événements météorologiques canadiens de 2000, Environment Canada, <http://www.msc.ec.gc.ca/media/top10/2000_f.html> [accessed April 24, 2009].

Environment Canada. (2004a) Avertissements météo publics pour le Canada, Environment Canada, <http://www.weatheroffice.ec.gc.ca/warnings/warnings_f.html> [accessed June 11, 2009].

Environment Canada. (2004b) Fiche d'information sur le smog, Environment Canada, <http://www.msc.ec.gc.ca/cd/factsheets/smog/index_f.cfm> [accessed June 11, 2009].

Environment Canada, (2007a) Atlas des vents, Environment Canada, <http://www.atlaseolien.ca/fr/maps.php> [accessed September 17, 2009].

Environment Canada. (2007b) Atlas des glaces, Environment Canada, <http://ice-glaces.ec.gc.ca/> [accessed July 28, 2009].

Fagherazzi, L., Guay, R. and Sassi, T. (2005) Climate Change Analysis of the Ottawa River System, report submitted to the International Joint Commission — Lake Ontario-St. Lawrence River study on discharge regulation, 72 p.

Febriani, Y., Levallois, P., Gingras, S., Gosselin, P. and Majowicz, S. E. (2008) The Prevalence of Acute Gastrointestinal Illness in Quebec Farming Municipalities and Its Association with Farming Activities and Climate Factors, presented at 3rd Ouranos Scientific Symposium, at l'École de technologie supérieure, Montreal, November 19-20, 2008.

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 by Working Group I I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (ed.), Cambridge University Press, Cambridge, p. 617-652.

Flanagan, K., E. McCauley, E., Wrona, F. and Prowse, T. (2003) Climate change: The potential for latitudinal effects on algal biomass in aquatic ecosystems, Canadian Journal of Fisheries and Aquatic Sciences, 60:635-639.

Flannigan, M., Logan, K., Amiro, B., Skinner, W. and Stocks, B. (2005) Future area burned in Canada, Climatic Change, 72(1&2)1-16.

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, 210:169-204.

Fortier, R. and Allard, M. (2003a) Problématique du développement du village de Salluit, Nunavik. Rapport d'étape 2, Conditions du pergélisol et mollisol, report on fieldwork, summer 2002 and winter 2003, Centre d'études nordiques, Laval University, Quebec.

Fortier, R. and Allard, M. (2003b) Les impacts d'un réchauffement récent sur le pergélisol au Nunavik, presentation in December 2003 to the 24th Colloque annuel du Centre d'études nordiques, Université Laval, Québec.

Fortin, L.G., Turcotte, R., Pugin, S., Cyr, J.-F. And Picard, F. (2007) Impact des changements climatiques sur les plans de gestion des réservoirs Saint-François et Aylmer au Sud du Québec, Canadian Journal of Civil Engineering, 34(8):934-945.

Frenette, J.-J., Arts, M. and Morin, J. (2003) Spectral gradient of downwelling light in a fluvial lake (Lake Saint-Pierre, St. Lawrence River), Aquatic Ecology, 37:77-85.

Frenette, J.-J., Arts, M., Morin, J., Gratton, D. and Martin, C. (2006) Hydrodynamic control of the underwater light climate in fluvial Lac Saint-Pierre, Limnology and Oceanography, 51:2632-2645.

Frigon, M. (2003) L'entretien du réseau routier québécois: une industrie comprenant plusieurs acteurs, Magazine Circuit industriel, June 2003 <http://www.magazinemci.com/articles/dossiers/2003/06/quebec7.htm> [accessed October 10 2009].

Furgal, C.M., Martin, D., Gosseli, P. And Viau, A. (2002) Climate Change and Health in Nunavik and Labrador: What We Know from Science and Inuit Knowledge, Nunavik Regional Board of Health and Social Services/Nunavik Nutrition and Health Committee, Labrador Inuit Association, Labrador Inuit Health Commission, final scientific report of a project financed by the Climate Change Action Fund, 139 p.

Furgal, C.M. and Seguin, J. (2005) Climate change health impacts, vulnerabilities and the capacity to respond in Canadian Northern Aboriginal communities, *in* Adapting to Climate Change in Canada 2005: Understanding Risks and Building Capacity, Conferece May 4-7 in Montreal, sponsored by the Climate Change Impacts and Adaptation Program at Natural Resources Canada and the Canadian Climate Impacts and Adaptation Research Network (C-CIARN).

Gaboury, S., Boucher, J.-F., Villeneuve, C., Lord, D. and Gagnon, R. (2009) Estimating the net carbon balance of boreal open woodland afforestation: A case-study in Quebec's closed-crown boreal forest, Forest Ecology and Management, 257: 483-494.

Gagnon, R. And Morin, H. (2001) Les forêts d'épinettes noires du Québec: dynamique, perturbations et biodiversité, Le Naturaliste canadien, 125(3):26-35.

Gamache, I. and Payette, S. (2004) Height growth response of tree line black spruce to recent climate warming across the forest-tundra of eastern Canada, Journal of Ecology, 92:835-845.

Gamache, I. and Payette, S. (2005) Latitudinal response of subarctic tree lines to recent climate change in Eastern Canada, Journal of Biogeography, 32:849-862.

Garneau, M., Breton, M.C., Guay, F., Fortier, I., Sottile, M.F. and Chaumont, D. (2006) Hausse des concentrations des particules organiques (pollens) causée par le changement climatique et ses conséquences sur les maladies respiratoires des populations vulnérables en milieu urbain, Climate Change Action Fund – sub-component of Impacts and Adaptation, project A571, <http://www.ouranos.ca/media/publication/34_Rapport_Garneau_sante_2006.pdf> [accessed June 11, 2009].

Génot, J.C. and Barbault, R. (2005) Quelle politique de conservation ?, *in* R. Barbault and B. Chavassus-au-Louis, Biodiversité et changements globaux enjeux de société et défis pour la recherche, Association pour la diffusion de la pensée française, p. 162-191.

Gerardin, V., Dubruc, J.-P. and Beauchesne, P. (2002) Planification du réseau d'aires protégées du Québec: principes et méthodes de l'analyse écologique du territoire, Ministère de l'Environnement, Direction du patrimoine écologique et du développement durable, Vertigo, 3, (1), 10 p.

Gielen, B. and Ceulemans, R. (2001) The likely impact of rising atmospheric CO_2 on natural and managed Populus: A literature review, Environmental Pollution, 115:335-358.

Giguère, M. and Gosselin, P. (2006a) Impacts des événements climatiques extrêmes sur la santé: examen des initiatives d'adaptation actuelles au Québec, Institut national de santé publique, 27 p., <www.ouranos.ca/media/publication/41_Feuillet_INSPQ_Evenements20Extremes_Adapations_Oct_2006.pdf> [accessed June 11, 2009].

Giguère, M. and Gosselin, P. (2006b) Les impacts du changement climatique sur l'émergence et l'intensification des maladies zoonotiques et des maladies transmission vectorielle au Québec: examen des initiatives d'adaptation actuelles, Institut national de santé publique, 27 p., <http://www.inspq.qc.ca/publications/notice.asp?E=p&NumPublication=519> [accessed June 11, 2009].

Giguère, M. and Gosselin, P. (2006c) Les impacts du changement climatique sur les ressources hydriques et ses conséquences sur la santé, examen des initiatives d'adaptation actuelles au Québec, Institut national de santé publique, <http://www.inspq.qc.ca/publications/notice.asp?E=p&NumPublication=516> [accessed June 11, 2009].

Giguère, M. and Gosselin, P. (2006d) Les impacts des vagues de chaleur et de l'effet d'îlot thermique urbain sur la santé: examen des initiatives d'adaptation actuelles au Québec, Institut national de santé publique, <http://www.inspq.qc.ca/publications/notice.asp?E=p&NumPublication=515> [accessed June 11, 2009].

Giguère, S., Morin, J., Laporte, P. And Mingelbier, M. (2005) Évaluation des impacts des fluctuations hydrologiques sur les espèces en péril, tronçon fluvial du Saint-Laurent (Cornwall à Trois-Rivières), *in* International Lake Ontario–St. Lawrence River Study, final report prepared for the International Joint Commission, Environment Canada, Canada Wildlife Service and Meteorological Service of Canada and the Ministère des Ressources naturelles et de la Faune, Direction de la recherche sur la faune, Québec, 71 p.

Gillett, N.P., Weaver, A.J., Zwier, F.W. and Flannigan, M.D. (2004) Detecting the effect of climate change on Canadian forest fires, Geophysical Research Letters, 31.

Girard, F., Payette, S. and Gagnon, R. (2008) Rapid expansion of lichen woodlands within the closed-crown boreal forest zone over the last 50 years caused by stand disturbances in Eastern Canada, Journal of Biogeography, 35:529-537.

Gitz, D.C., Ritchie, J.C., Krizek, D.T., Springer, T.L., Reeves, J.B. III, and Reddy, V. (2006) Effect of temperature and CO_2 on forage nutritive value of 'pete' eastern gamagrass, *in* Proceedings of the Fifth Eastern Native Grass Symposium, October 10-13, 2006 Harrisburg, Pennsylvania, Sanderson, M.A., P. Adler, S. Goslee, J.C. Ritchie, H. Skinner and K. Soder (ed.), p. 107-114.

Godbout, L., Fortin, P., Arseneau, M., and St-Cerny, S. (2007) Oser choisir maintenant. Des pistes de solutions pour protéger les services publics et assurer l'équité entre les générations, Presses de l'Université Laval, Québec, 150 p.

Goldberg, M.S., Burnett, R.T., Bailar, J.C. III, Tamblyn, R., Ernst, P., Flegel, K., Brook, J., Bonvalot, Y., Singh, R., Valois, M.F., and Vincent, R. (2001) Identification of persons with cardiorespiratory conditions who are at risk of dying from the acute effects of ambient air particles, Environmental Health Perspectives, 109(supp. 4):487-494.

Gosselin, P. (2005) Développement d'un outil Web interactif pour mieux comprendre les impacts des changements climatiques sur la santé publique, Projet GEOIDE Initiative stratégique, <http://www.geoide.ulaval.ca/files/41_F.jpg> [accessed June 11, 2009].

Gosselin, P., Furgal, C. and Owen, S. (2005) Surveillance and management of climate change impacts in the North: Implications for Northern public health policy and infrastructure, annual scientific report, ArcticNet.

Gosselin, P., Lebel, G., Rivest, S. and Douville-Fradet, M. (2005) The Integrated System for Public Health Monitoring of West Nile Virus (ISPHM-WNV): a real-time GIS for surveillance and decision-making, International Journal of Health Geographics, 4(21) <http://www.ij-healthgeographics.com/content/4/1/21> [accessed June 11, 2009].

Gosselin, P., Bélanger, D. and Doyon, B. (2008) Les impacts santé des changements climatiques au Québec, Chap. 6 *in* J. Séguin (ed.), Santé et changements climatiques: évaluation des vulnérabilités et de la capacité d'adaptation au Canada, Health Canada, Ottawa, 558 p., <http://www.ouranos.ca/fr/pdf/ouranos_chapitre-6.pdf> [accessed June 11, 2009].

Graham, L.P., Andréasson, J. and Carlsson, B. (2007) Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods — a case study on the Lule River Basin, Climatic Change, 81:293-307.

Gray, D.R. (2004) The gypsy moth life stage model: Landscape-wide estimates of gypsy moth establishment using a multi-generational phenology model, Ecological Modelling, 176:155-171.

Gray, D.R. (2008) The relationship between climate and outbreak characteristics of the spruce budworm in Eastern Canada, Climatic Change, 87:361-383.

Greenwood, J.S., Soulos, G.P. and Thomas, N.D. (2000) Undercover: guidelines for shade planning and design, Cancer Council South Australia, 188 p., <http://www.cancersa.org.au/aspx/Under_Cover_Guidelines.aspx> [accessed June 11, 2009].

Grondin, G. and Guimond, A. (2005) Impact du dégel du pergélisol sur les infrastructures de transport aérien et routier du ministère des Transports du Québec au Nunavik, Route-Roads, 326:42-49.

Hamilton, L.C., Brown, C. and Keim, B.D. (2007) Ski areas, weather and climate: Time series models for New England case studies, International Journal of Climatology, 27:2113-2124.

Hansen, A.J., Neilson, R.R., Dale, V.H., Flather, C.H., Iverson, L.R., Currie, D.J., Shafer, S., Cook, R. and Bartlein, P.J. (2001) Global change in forests: Responses of species, communities, and biomes, Bioscience, 51:765-779.

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S. and Samuel, M.D. (2002) Climate warming and disease risks for terrestrial and marine biota, Science, 296:2158-2162.

Hauer, F.R., Baron, J.S., Campbell, D.H., Fausch, K.D., Hostetler, S.W., Leavesley, G.H., Leavitt, P.R., McKnight, D.M. and Stanford, J.A. (1997) Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada, Hydrological Processes, 11(8):903-924.

Health Canada. (2005) Exercice de chaleur accablante, DDH Environnement ltée report, #05-044, Montreal, 48 p.

Health Canada. (2009) Qualité de l'air et ses effets sur la santé, Health Canada, <http://www.hc-sc.gc.ca/ewh-semt/air/out-ext/effe/health_effects-effets_sante-fra.php> [accessed June 11, 2009].

Hersteinsson, P. and MacDonald, D.W. (1992) Interspecifc competition and the geographical distribution of red and arctic foxes Vulpes vulpes and Alopex lagopus, Oikos, 64:505-515.

Hesslein, R. H., Turner, M.A., Kasian, S.E.M. and Guss, D. (2001) The Potential for Climate Change to Interact with the Recovery of Boreal Lakes from Acidification — A Preliminary Investigation Using ELA's Database, report prepared for the Climate Change Action Fund.

Hill, D., White, V., Marks, R., Theobald, T., Borland, R. and Roy, C. (1992) Melanoma prevention: Behavioral and nonbehavioral factors in sunburn among an Australian urban population, Preventive Medicine, 21(5):654-669.

Hudon, C. (2004) Le lac St-Louis est-il à risque ? Les niveaux d'eau et l'eau potable, Environment Canada, <http://www.qc.ec.gc.ca/csl/inf/inf040_f.html> [accessed September 4, 2009].

Hudon, C., Gagnon, P., Amyot, J.-P., Létourneau, G., Jean, M., Plante, C., Rioux, D. and Deschênes, M. (2005) Historical changes in herbaceous wetland distribution induced by hydrological conditions in Lake Saint-Pierre (St. Lawrence River, Quebec, Canada), Hydrobiologia, 539:205-224.

Huggins K., Frenette, J.-J. and Arts, M.T. (2004) Nutritional quality of biofilms with respect to light regime in Lake Saint-Pierre (Quebec, Canada), Freshwater Biology, 49:945-959.

Huntingford, C., Hemming, D., Gash, J.H.C., Gedney, N. and Nuttall, P.A. (2007) Impact of climate change on health: What is required of climate modellers?, Transactions of the Royal Society of Tropical Medicine and Hygiene, 101:97-103.

Huntley, B. and Birks, H.J.B. (1983) An Atlas of Past and Present Pollen Maps for Europe: 0-13,000 Years Ago, Cambridge University Press, Cambridge, 667 p.

Hydro-Québec. (2006) Plan stratégique 2006-2010, Hydro-Québec, 54 p., <http://www.hydroquebec.com/publications/fr/plan_strategique/> [accessed September 22, 2009].

Infrastructure Canada. (2004) L'évaluation des besoins en infrastructure du Canada: une analyse d'études clés, Infrastructure Canada, 14 p.

Infrastructure Canada. (2006) L'adaptation des infrastructures du Canada aux changements climatiques dans les villes et les collectivités: une analyse documentaire, Infrastructure Canada, 25 p.

Institut de la statistique du Québec. (2003) Perspectives démographiques du Québec et des régions, 2001-2051, 2003 edition, Institut de la statistique du Québec.

Institut de la statistique du Québec. (2005a) Bulletin statistique régional, Montréal, Institut de la statistique du Québec, <http://www.stat.gouv.qc.ca/regions/profils/bulletins/06_Montreal.pdf> [accessed June 11, 2009].

Institut de la statistique du Québec. (2005b) Population et occupation du territoire, régions administratives de Montréal et de Laval, 2001, Institut de la statistique du Québec, <http://www.stat.gouv.qc.ca/regions/recens2001_06/population06/occupter06.htm> [accessed June 11, 2009].

Institut de la statistique du Québec. (2009a) Perspectives démographiques du Québec et des régions, 2006-2056 édition 2009, Institut de la statistique du Québec, 133 p., <http://www.stat.gouv.qc.ca/publications/demograp/pdf2009/perspectives2006_2056.pdf> [accessed October 20, 2009].

Institut de la statistique du Québec. (2009b) Produit intérieur brut aux prix de base, par activité économique, Québec, 2002-2007, Institut de la statistique du Québec, <http://www.stat.gouv.qc.ca/donstat/econm_finnc/conjn_econm/compt_econm/cea4_1.htm> [accessed October 20, 2009].

Institut de la statistique du Québec and Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec. (2009) Profil sectoriel de l'industrie bioalimentaire du Québec, édition 2008, Institut de la statistique du Québec and Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, 122 p.

Institute for Catastrophic Loss Reduction. (2005) Tempêtes hivernales, Institute for Catastrophic Loss Reduction, <http://www.iclr.org/french/hazards/tempete.htm> [accessed June 11, 2009].

Institut national de santé publique du Québec. (2003a) Les pneus hors d'usage et le risque de transmission de maladies infectieuses par les moustiques. Summary, Institut national de santé publique du Québec, <http://www.inspq.qc.ca/publications/environnement/doc/text7.asp?E=p/> [accessed June 11, 2009].

Institut national de santé publique du Québec. (2003b) Virus du Nil occidental: évaluation des attitudes, des comportements et des connaissances populaires, Institut national de santé publique du Québec, <http://www.inspq.qc.ca/publications/notice.asp?E=p&NumPublication=262> [accessed June 11, 2009].

Institut national de santé publique du Québec. (2005a) Mesures individuelles et collectives pour prévenir la transmission du virus du Nil occidental – Éléments pour un plan global d'intervention, Institut national de santé publique du Québec, <http://www.inspq.qc.ca/pdf/publications/403-PlanGlobalInterventionVNO.pdf> [accessed June 11, 2009].

Institut national de santé publique du Québec. (2005b) Épidémiologie et effets de l'infection par le virus du Nil occidental sur la santé humaine – Mise à jour 2004, Institut national de santé publique du Québec, <http://www.inspq.qc.ca/publications/notice.asp?E=p&NumPublication=408> [accessed June 11, 2009].

Institut national de santé publique du Québec. (2006) Portrait de santé du Québec et de ses régions 2006. Les analyses, Institut national de santé publique du Québec, 131 p., <http://www.inspq.qc.ca/pdf/publications/portrait_de_sante.asp?E=p> [accessed June 11, 2009].

Institut québécois d'aménagement de la forêt feuillue. (2003) Changements climatiques: impacts sur les forêts québécoises, literature review, Institut québécois d'aménagement de la forêt feuillue, 48 p.

Intergovernmental Panel on Climate Change. (2001) Résumé à l'intention des décideurs, *in* Bilan 2001 des changements climatiques: les éléments scientifiques, contribution by Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (ed.), Cambridge University Press, Cambridge and New York, 1-20.

Intergovernmental Panel on Climate Change. (2002) Les changements climatiques et la biodiversité, Technical document V of the Intergovernmental Panel on Climate Change, H. Gitay, A. Suarez, R.T. Watson and D.J. Dokken (ed.), Geneva, 75 p.

Intergovernmental Panel on Climate Change. (2007a) Climate Change 2007: The Physical Science Basis, contribution by Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Salomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignot and H.L. Miller (ed.), Cambridge University Press, Cambridge and New York, 996 p.

Intergovernmental Panel on Climate Change. (2007b) Résumé à l'intention des décideurs, *in* Bilan 2007 des changements climatiques: conséquences, adaptation et vulnérabilité, contributed by Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (ed.), Cambridge University Press, Cambridge and New York, 976 p.

Intergovernmental Panel on Climate Change. (2008) Le changement climatique et l'eau, technical document published by the Intergovernmental Panel on Climate Change, B.C. Bates, Z.W. Kundzewicz, S. Wu and J.P. Palutiko (ed.), IPCC Secretariat, Geneva, 236 p.

International Joint Commission. (2006) Avis aux gouvernements concernant l'examen de l'accord relatif à la qualité de l'eau dans les Grands Lacs, International Joint Commission, <http://www.ijc.org/rel/pdf/advicefinalfrwc.pdf> [accessed May 11, 2009].

Jackson, D.A. and Mandrak, N.E. (2002) Changing fish biodiversity: Predicting the loss of cyprind biodiversity due to global climate change, *in* N.A. McGinn (ed.), Fisheries in a Changing Climate, American Fisheries Society, 319 p.

Jacobson, M.Z. (2008) On the causal link between carbon dioxide and air pollution mortality, Geophysical Research Letter, Vol. 35.

Jaffreux, H. (2008) Un réseau écologique pour préserver la diversité biologique du continent européen, Liaison Énergie-Francophonie, special issue (September 2008):58-62.

Jasinski, J.P. and Payette, S. (2005) The creation of alternative stable states in the southern boreal forest, Quebec, Canada, Ecological Monographs, 75(4):561-583.

Jean, M., Létourneau, G., Lavoie, C. and Delisle, F. (2002) Les milieux humides et les plantes exotiques en eau douce, fiche d'information dans Suivi de l'état du Saint-Laurent, Environnement Canada – Région du Québec, Conservation de l'environnement, Centre Saint-Laurent et Centre de recherche en aménagement et développement de l'Université Laval, 8 p.

Jones, N.K. (2008) On the impact of recent climate change on seasonal floods – a case study from a river basin in Southern Quebec, Canadian Water Resources Journal, 33(1):55-72.

Jones, B. and Scott, D. (2005) Climate change, seasonality and visitation to Canada's National Parks, Journal of Parks and Recreation Administration, 23(4).

Jones, J., Doran, P.J. and Holmes, R.T (2003). Climate and food synchronize regional forest birds abundance, Ecology, 84(11):3024-3032.

Jones-Walters, L. and Mulder, I. (2009). Valuing nature: The economics of biodiversity, Journal for Nature Conservation, 17(4):245-247.

Julien, Y. and Sobrino, J.A. (2009) Global land surface phenology trends from GIMMS database, International Journal of Remote Sensing, 30(13):3495-3513.

Kalkstein, L. and Green, J. (1997) An evaluation of climate/mortality relationship in large U.S. cities and the possible impacts of a climate change, Environmental Health Perspectives 105:84-93.

Keatinge, W.R., Donaldson, G.C., Cordioli, E., Martinelli, M., Kunst, A.E., Mackenbach, J.P., Nayha, S. and Vuori, I. (2000) Heat related mortality in warm and cold regions of Europe: Observational study, British Medical Journal, 321(7262):670-673.

Kennedy, V.S., Twilley, R.R., Kleypas, J.A., Cowan, J.H.Jr., and Hare, S.R. (2002) Coastal and Marine Ecosystems and Global Climate Change: Potential Effects on U.S. Resources, report prepared for the Pew Center on Global Climate Change, Arlington,Virginia, 52 p.

King, N., Morency, P. and Lapierre, L. (2005) Les impacts du transport sur la santé publique, *in* Rapport synthèse: faits saillants des principaux travaux de la Direction, Direction de santé publique de Montréal, 8(3), <http://www.santepub-mtl.qc.ca/Publication/synthese/rapv8n3.pdf> [accessed June 11, 2009].

Kirschbaum, M.U.F. (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage, Soil Biology and Biochemistry, 27:753-760.

Kirschbaum, M.U.F. (2000) Forest growth and species distribution in a changing climate, Tree Physiology, 20:309-322.

Kirshen, P., Ruth, M. and Anderson, W. (2007) Interdependencies of urban climate change impacts and adaptation strategies: A case study of Metropolitan Boston USA, Climatic Change, 86:105-122.

Klinenberg, E. (2002) A Social Autopsy of Disaster in Chicago: Heat Wave, The University of Chicago Press, Chicago, 305 p.

Kling, G.W., Hayhoe, K., Johnson, L.B., Magnuson, J.J., Polasky, S., Robinson, S.K., Shuter, B.J., Wander, M.M., Wuebbles, D.J. and Zak, D.R.. (2003) Confronting Climate Change in the Great Lakes Region, Impacts on Our Communities and Ecosystems, The Union of Concerned Scientists et The Ecological Society of America, 104 p.

Koch, I., Vogel, C. and Patel, Z. (2007) Institutional dynamics and climate change adaptation in South Africa, Mitigation and Adaptation Strategies for Global Change, 12(8):`1323-1339.

Kosatsky,T., King, N. and Henry, B. (2005) How Toronto and Montreal Respond to Heat, Extreme Weather Events and Public Health Responses, p. 167-171.

Kurz, W.A., Stinson, G., Rampley, G.J., Dymond, C.C. and Neilson, E.T. (2008) Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain, Proceedings of the National Academy of Sciences, 105:1551-1555.

La Financière agricole du Québec. (2006) Statistiques annuelles, Assurance récolte, La Financière agricole du Québec, <http://www.fadq.qc.ca/index.php?id=826> [accessed April 24, 2009].

Laforce, S. (2008) Évolution d'une zone inondable sous l'effet des changements climatiques: étude de la rivière du Nord à Lachute, Master's thesis, École des technologies supérieures, Montréal, 318 p.

Lafortune, V., Furgal, C., Angiyou, E., Annanack, T., Einish, N., Etiddloie, B., Tookalook, P. and Savard, J.-P. (2005) Adapting to climate change in Nunavik and Northern Québec: Using traditional and scientific knowledge to enhance local capacity and cope with changing ice conditions, *in* Adapting to Climate Change in Canada 2005: Understanding Risks and Building Capacity, Conference held May 4-7 2005 in Montreal and sponsored by the Climate Change Impacts and Adaptation Program of Natural Resources Canada and the Canadian Climate Impacts and Adaptation Research Network (C-CIARN).

Lafrance, G. and DesJarlais, C. (2006) Impact socio-économique du changement climatique sur la demande d'énergie, research report, Ouranos, 79 p., <http://www.ouranos.ca/fr/publications/resultats.php?q=lafrance&t=> [accessed May 1 2009].

Lamy, S. and Bouchet, V. (2008) Qualité de l'air, changements climatiques et santé, Chap. 4 *in* J. Séguin (ed.), Santé et changementsclimatiques: évaluation des vulnérabilités et de la capacité d'adaptation au Canada, Health Canada, Ottawa, 558 p.

Landry, M., Siron, R. and Mercier, F. (2008) La santé des écosystèmes — c'est dans notre intérêt à tous!, Franc Vert, 5:2.

Laplante, D.P., Barr, R.G., Brunet, A., Galbaud du Fort, G., Meaney, M.L., Saucier, J.F., Zelazo, P.R. and King, S. (2004) Stress during pregnancy affects general intellectual and language functioning in human toddlers, Pediatric Research, 56(3): 400-410.

Larouche, W., Turcotte, R., Cyr, J.-F. and Fortin, L.G. (2008) Étude sur les tendances des débits journaliers moyens aux stations hydrométriques du Québec, internal report, Centre d'expertise hydrique du Québec, 13 p. + appendices.

Larrivée, C. and Simonet, G. (2007) Testing the assumptions: assessing infrastructures vulnerability to climate change, Municipal World, 117(6):27-28, 44.

Larsen, P.H., Goldsmith, S., Smith, O., Wilson, M.L., Strzepek, K., Chinowsky, P. and Saylor, B. (2008) Estimating future costs for Alaska public infrastructure at risk from climate change, Global Environmental Change, 18(3);442-457.

Lawrence, D.M. and Slater, A.G. (2005) A projection of severe near surface permafrost degradation during the 21st century, Geophysical Research Letters, vol. 32, , L24401, doi:10.1029/2005GL025080.

Lease, N., Pichette, A. and Chaumont, D. (2009) Projet d'étude sur l'adaptation aux changements climatiques du secteur de la pomme au Québec, research report, Ouranos, 52 p., <http://www.ouranos.ca/media/publication/154_adaptationauxC-Cpomiculture_154_NancyLease_18nov2009.pdf> [accessed January 29, 2010].

Lebuis, J., Robert, J.-M. and Rissmann, P. (1983) Regional Mapping of Landslide Hazard in Quebec, Symposium on Slopes on Soft Clays, Institut géotechnique de Suède, Linköping, Sweden. Report #17.

Leclerc, M., Boudreau, P., Roy, N., Secretan, Y., El Adlouni, S., Ouarda, T., Chaumont, D., Falardeau, I. and Morneau, F. (2006) Contribution à la recherche d'une solution intégrée au risque d'inondation à Châteauguay, report commissioned by the City of Châteauguay, in collaboration with the Ministère de la Sécurité publique, research report #R841, 280 p.

Lefaivre, D. (2005) Effet des changements climatiques sur les niveaux d'eau du fleuve Saint-Laurent entre Montréal et Québec, Projections pour les années 2050, report prepared for the Comité de concertation navigation du Plan d'action Saint-Laurent phase 4, Institut Maurice-Lamontagne, Direction des Sciences océaniques, 34 p.

Lehoux, D., Dauphin, D., Laporte, P., Morin, J. and Champoux, O. (2005) Recommendation of Water Plans and Final Management Criteria Less Detrimental to Breeding and Migrating Waterfowl Along the St. Lawrence River Within the Lake St. Louis and the Lake St. Pierre Area, final report submitted to Environment Canada, 22 p.

Lemmen, D.S., Warren, F.J., Lacroix, J. and Bush, E. (2008) (ed.). Vivre avec les changements climatiques au Canada: 2007 edition, Government of Canada, Ottawa, 448 p.

Lenderink, G., Buishand, A. and van Deursen, W. (2007) Estimates of future discharges of the river Rhine using two scenario methodologies: Direct versus delta approach, Hydrology and Earth System Sciences, 11:1145-1159.

Lied, K. and Domaas, U. (2000) Avalanche Hazard Assessment in Nunavik and on Côte-Nord, Québec, Canada, Norwegian Geotechnical Institute.

Ligeti, E., Penney, J. and Wieditz, I. (2007) Cities Preparing for Climate Change: A Study of Six Urban Regions, Clean Air Partnership, 90 p.

Limoges, B. (2009) Biodiversité, services écologiques et bien-être humain, Le Naturaliste canadien, 133(2):15-19.

Logan, J.A., Régnière, J. and Powell, J.A. (2003) Assessing the impacts of global warming on forest pest dynamics, Frontiers in Ecology and the Environment, 1(3):130-137.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B, Nösberger, J. and Ort, D.R. (2006) Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations, Science, 312:1918-1921.

Ludwig, R., May, I., Turcotte, R., Vescovi, L., Braun, M., Cyr, J.-F., Fortin, L.G., Chaumont, D., Biner, S., Chartier, I., Caya, D. and Mauser, W. (2009) The role of hydrological model complexity and uncertainty in climate change impact assessment, Advances in Geosciences, 21:63-71.

Luo, Y., Su, B., Currie, W.S., Dukes, J.S., Finzi, A., Hartwig, U., Hungate, B., McMurtrie,, R.E. Oren, R., Parton, W.J., Pataki, D.E., Shaw, M.R., Zak, D.R. and Field, C.B. (2004) Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide, Bioscience, 54:731-739.

Luxmoore, R.J., Wullschleger, S.D. and Hanson, P.J. (1993) Forest responses to CO_2 enrichment and climate warming, Water, Air, and Soil Pollution, 70:309-323.

MacDonald, N.W., Zak, D.R. and Pregitzer, K.S. (1995) Temperature effects on kinetics of microbial respiration and net nitrogen and sulfur mineralization, Soil Science Society of America Journal, 59:233-240.

MacKenzie, W.R., Hoxie, N.J., Proctor, M.E., Gradus, S., Blair, K.A., Peterson, D.E., Kazmierczak, J.J., Addiss, D.G., Fox, K.R., Rose, J.B. and Davis, J.P. (1994) A massive outbreak in Milwaukee of cryptosporidium infection transmitted through the public water supply, The New England Journal of Medicine, 331:161-167.

Mailhot, A., Rousseau, A.N., Lacroix-Vachon, B., Nantel, E. and Villeneuve, J.-P. (2004) Approvisionnement en eau au Québec: cartographie des sites et estimation des volumes d'eau de surface prélevés alimentant les réseaux d'aqueduc municipaux, *in* Eau et changement climatique: comprendre pour mieux s'adapter, 57th National Conference of the Canadian Water Resources Association, Montreal, June 16-18. 2004.

Mailhot, A., Rivard, G., Duchesne, S. and Villeneuve, J.-P. (2007a) Impacts et adaptation aux changements climatiques en matière de drainage urbain au Québec, Institut national de recherche scientifique Eau, Terre et Environnement, 144 p., <http://www.ouranos.ca/media/publication/17_Rapport_Mailhot_infras_2007.pdf> [accessed May 11, 2009].

Mailhot, A., Duchesne, S., Caya, D. and Talbot, G. (2007b) Assessment of future change in intensity-duration-frequency curves for Southern Quebec using the Canadian Regional Climate Model, Journal of Hydrology, 347(1-2):197-210.

Mailhot, A., Duchesne, S., Talbot, G., Rousseau, A.N. and Chaumont, D. (2008a) Approvisionnement en eau potable et santé publique: projections climatiques en matière de précipitations et d'écoulements pour le sud du Québec, research report #R-977 presented to the Institut de santé publique du Québec, Institut national de la recherche scientifique Eau, Terre et Environnement, Québec, 164 p., <http://www.ouranos.ca/media/publication/35_Rapport_Mailhot_sante_2008.pdf> [accessed June 11, 2009].

Mailhot, A., Duchesne, S., Larrivée, C., Pelletier, G., Bolduc, S., Rondeau, F., Kingumbi, A. and Talbot, G. (2008b) Conception et planification des interventions de renouvellement des infrastructures de drainage urbain dans un contexte d'adaptation aux changements climatiques, Natural Resources Canada, 170 p.

Malcolm, J.R., Markham, A., Neilson, R.P., and Garaci, M. (2002) Estimated migration rates under scenarios of global climate change, Journal of Biogeography, 29:835-849.

Mareuil, A. (2005) Impacts des changements climatiques sur les crues extrêmes des rivières: cas de la rivière Châteauguay, Master's thesis. École de technologie supérieure, Montreal, 125 p.

Martin, C., Frenette, J.-J. and Morin, J. (2005) Changes in the spectral and chemical properties of a water mass passing through extensive macrophyte beds in a large fluvial lake (Lake Saint-Pierre, Quebec, Canada), Aquatic Sciences, 67:196-209.

Martin, D., Bélanger, D., Gosselin, P., Brazeau, J., C. Furgal, C. and Déry, S. (2005a) Les changements climatiques, l'eau potable et la santé humaine au Nunavik: stratégies d'adaptation, report prepared for the Climate Change Action Fund, Project A563, 80 p.

Martin, D., Lévesque, B., Maguire, J.S., Maheux, A., Furgal, C., Bernier, J.L. and Dewailly, E. (2005b) Drinking Water Quality in Nunavik: Health Impacts in a Climate Change Context, final report on a project commissioned by ArcticNet and ACADRE (Nasivvik), 87 p.

Mauser, W. and Ludwig, R.. (2002) GLOWA-DANUBE — A research concept to develop integrative techniques, scenarios and strategies regarding global changes of the water cycle, *in* M. Beniston ed.), Climatic Change: Implications for the Hydrological Cycle and for Water Management, Advances in Global Change Research, Kluwer Academic Publishers, Dordrecht and Boston, p. 171-188.

McBean, G. and Henstra, D. (2003) Climate Change, Natural Hazards and Cities, Institute for Catastrophic Loss Reduction Research, 16 p.

McCarty, J. P. (2001) Ecological consequences of recent climate change, Conservation Biology, 15(2):320-331.

McMichael, A.J., Cambell-Lendrum, D.H., Corvalan, C.F., Ebi, K.L, Githeko, A, Scheraga, J.D. and Woodward, A. (2003) Climate Change and Human Health: Risk and responses, World Health Organization, World Meteorological Organization and the United Nations Environment Programme, Geneva, 322 p.

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J. and Taylor, K.E. (2007) The WCRP CMIP3 Multimodel Dataset, a new era in climate change research, Bulletin of the American Meteorological Society, 88(9):1383-1394.

Millerd, F. (2005) The economic impact of climate change on Canadian commercial navigation on the Great Lakes, Canadian Water Resources Journal, 30(5):269-280.

Mills, C.J., Trouton, K. and Gibbons, L. (1997) Symposium Report: Second symposium on ultraviolet radiation related diseases, Chronic Disease in Canada, 18(1) <http://www.phac-aspc.gc.ca/publicat/cdic-mcc/18-1/e_e.html> [accessed June 11, 2009].

Mingelbier, M., Trencia, G., Dumas, R., Dumas, B., Mailhot, Y., Bouchard, C., Manolesco, D.C., Brodeur, P. Hudon, C. and Ouellette, G. (2001) Avis scientifique concernant la mortalité massive des carpes dans le Saint-Laurent durant l'été 2001, Société de la faune et des parcs du Québec, Ministère de l'Environnement du Québec, Biodôme de Montréal, Environment Canada, 22 p.

Mingelbier, M., Brodeur, P. and Morin, J. (2004) Impacts de la régularisation du débit des Grands Lacs et des changements climatiques sur l'habitat des poissons du fleuve Saint-Laurent, Vecteur Environnement, 37(6):34-43.

Mingelbier, M., Brodeur, P. and Morin, J. (2005) Recommandations concernant les poissons et leurs habitats dans le Saint-Laurent fluvial et évaluation des critères de régularisation du système lac Ontario — Saint-Laurent, report submitted to the International Joint Commission and Ministère des Ressources naturelles et de la Faune du Québec, Direction de la recherche sur la faune, 141 p.

Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec. (2006) Surveillance de la santé animale, Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, <http://www.mapaq.gouv.qc.ca/Fr/Productions/santeanimale/surveillance/> [accessed June 11, 2009].

Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec. (2008a) Profil régional de l'industrie bioalimentaire du Québec — estimations pour 2007, Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, 164 p., <http://www.mapaq.gouv.qc.ca/NR/rdonlyres/4213E035-D644-42B5-A184-EF3D877AB7AA/0/Profilregionalbioalimentaire_Complet.pdf> [accessed April 24, 2009].

Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec. (2008b) Statistiques économiques de l'industrie bioalimentaire du Québec, Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, <http://www.mapaq.gouv.qc.ca/Fr/md/statistiques/> [accessed April 24, 2009].

Ministère de la Santé et des Services sociaux du Québec and the Institut national de santé publique du Québec. (2004) Enquête sur la santé au Nunavik (2004), Ministère de la Santé et des Services sociaux du Québec and the Institut national de santé publique du Québec, <http://qanuippitaa.com/fr/what.aspx> [accessed June 11, 2009].

Ministère de la Santé et des Services sociaux du Québec. (2006a) Chaleur accablante et rayons UV. Liste des initiatives, guides et plans, Ministère de la Santé et des Services sociaux du Québec, <http://www.msss.gouv.qc.ca/sujets/santepub/environnement/index.php?chaleur_accablante_rayons_uv> [accessed June 11, 2009].

Ministère de la Santé et des Services sociaux du Québec. (2006b) Smog, Ministère de la Santé et des Services sociaux du Québec, <http://www.msss.gouv.qc.ca/SUJETS/SANTEPUB/environnement/index.php?qualite-de-lair-outils> [accessed June 11, 2009].

Ministère de la Santé et des Services sociaux du Québec. (2008) Programme national de santé publique 2003-2012: mise à jour 2008, Ministère de la Santé et des Services sociaux du Québec, 103p., <http://publications.msss.gouv.qc.ca/acrobat/f/documentation/2008/08-216-01.pdf > [accessed June 11, 2009].

Ministère de la Sécurité publique. (2005) Cartographie des zones exposées aux glissements de terrain dans les dépôts meubles. Guide d'utilisation des cartes de zones de contraintes et d'application du cadre normatif — Saguenay–Lac-Saint-Jean, Ministère de la Sécurité publique, 68 p., <http://www.msp.gouv.qc.ca/secivile/publications/cartes_zones_contraintes/glissements_terrain_2.pdf> [accessed October 10, 2009].

Ministère de la Sécurité publique du Québec. (1996) Rapport de la commission Nicolet sur le déluge du Saguenay, Ministère de la Sécurité publique du Québec.

Ministère de la Sécurité publique du Québec. (1999) Rapport de la commission Nicolet sur la tempête de verglas de janvier 1998, Ministère de la Sécurité publique du Québec.

Ministère de l'Environnement du Québec. (2004) Stratégie québécoise sur la diversité biologique 2004-2007, Ministère de l'Environnement du Québec, 109 p.

Ministère des Finances du Québec. (2005) Impacts des changements démographiques sur l'économie, le marché du travail et les finances du Québec, Ministère des Finances, research document, 33 p., <http://www.finances.gouv.qc.ca/documents/Autres/fr/Impacts_demographiques2005.pdf> [accessed October 20, 2009].

Ministère des Ressources naturelles et de la Faune du Québec. (2001) Évolution de la demande d'énergie et des émissions de gaz à effet de serre au Québec: scénario de référence 1996-2021, Ministère des Ressources naturelles et de la Faune du Québec, <http://www.mrnf.gouv.qc.ca/publications/energie/energie/20014012.pdf> [accessed June 19, 2009].

Ministère des Ressources naturelles et de la Faune du Québec. (2005) Évolution de la demande d'énergie, scénario de référence, horizon 2016, Ministère des Ressources naturelles et de la Faune du Québec, <http://www.mrnf.gouv.qc.ca/publications/energie/energie/horizon-2016.pdf> [accessed June 19, 2009].

Ministère des Ressources naturelles et de la Faune du Québec. (2006a) Gros plan sur l'énergie: stratégie énergétique, Ministère des Ressources naturelles et de la Faune du Québec, <http://www.mrn.gouv.qc.ca/energie/strategie/index.jsp> [accessed October 29, 2009].

Ministère des Ressources naturelles et de la Faune du Québec. (2006b) Ressources et industrie forestière, portrait statistique, édition 2005-2006, Ministère des Ressources naturelles et de la Faune du Québec.

Ministère des Ressources naturelles et de la Faune du Québec. (2009a) Gros plan sur l'énergie, Ministère des Ressources naturelles et de la Faune du Québec, <http://www.mrnf.gouv.qc.ca/publications/energie/statistiques/consommation-secteur.xls> [accessed May 1 2009].

Ministère des Ressources naturelles et de la Faune du Québec. (2009b) Ressources et industries forestières: portrait statistique, édition 2009, Ministère des Ressources naturelles et de la Faune du Québec, 483 p., <http://www.mrnf.gouv.qc.ca/forets/connaissances/connaissances-statistiques-complete.jsp> [accessed October 20, 2009].

Ministère des Transports du Québec. (2000) Gestion des risques de glissements de terrain liés aux pluies des 19 et 20 juillet 1996 au Saguenay–Lac-St-Jean, Update on the collaboration of the Service de la géotechnique and de la géologie, Direction du Laboratoire des chaussées, Ministère des Transports du Québec, 141 p.

Ministère des Transports du Québec. (2006a) Mandat d'initiative sur l'impact du réchauffement climatique dans le Nord du Québec, submission to the Commission parlementaire sur les transports et l'environnement, Ministère des Transports du Québec.

Ministère des Transports du Québec. (2006b) Les chaussées au Québec: un contexte particulier, fact sheet, <http://www.mtq.gouv.qc.ca/portal/page/portal/grand_public/vehicules_promenade/reseau_routier/chaussees/contexte_particulier_des_chaussees_au_quebec> [accessed October 10, 2009].

Ministère des Transports du Québec. (2006c) La politique québécoise du transport collectif, Ministère des Transports du Québec, <http://www.mtq.gouv.qc.ca/portal/page/potal/Librairie/Publications/fr/transport_collectif/compl_polit_collectif 2006.pdf> [accessed April 19, 2010].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2002) Le chauffage au bois, Ministère du Développement durable, de l'Environnement et des Parcs, <http://www.mddep.gouv.qc.ca/air/chauf-bois/index.htm> [accessed June 11, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2004) Étude sur la qualité de l'eau potable dans sept bassins versants en surplus de fumier et impacts potentiels sur la santé, Ministère du Développement durable, de l'Environnement et des Parcs du Québec, <http://www.mddep.gouv.qc.ca/eau/bassinversant/sept-bassins/index.htm> [accessed June 11, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2005a) Publication du Règlement modifiant le Règlement sur la qualité de l'eau potable, Ministère du Développement durable, de l'Environnement et des Parcs, <http://www.mddep.gouv.qc.ca/eau/potable/brochure/rqep.htm> [accessed June 11, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2005b) Atlas de la biodiversité du Québec — Les espèces menacées ou vulnérables, Ministère du Développement durable, de l'Environnement et des Parcs du Québec, 60 p.

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2006a) Loi sur le développement durable L.R.Q. chapitre D-8.1.1, Ministère du Développement durable, de l'Environnement et des Parcs du Québec, Éditeur officiel du Québec, <http://www.mddep.gouv.qc.ca/developpement/loi.htm> [accessed October 20, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2006b) Le Québec et les changements climatiques, un défi pour l'avenir, Plan d'actions 2006-2012, Ministère du Développement durable, de l'Environnement et des Parcs, <http://www.mddep.gouv.qc.ca/changements/plan_action/2006-2012_fr.pdf> [accessed June 11, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2006c) Cadre de prévention des risques naturels, Ministère du Développement durable, de l'Environnement et des Parcs, <http://www.mddep.gouv.qc.ca/infuseur/communique.asp?no=1029> [accessed October 10, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs. (2008a) Programme d'acquisition de connaissances des eaux souterraines, Ministère du Développement durable, de l'Environnement et des Parcs, <http://www.mddep.gouv.qc.ca/eau/souterraines/programmes/acquisition-connaissance.htm> [accessed May 11, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2008b) Rapport annuel 2005-2006 sur la mise en œuvre de la Stratégie et du Plan d'action québécois sur la diversité biologique, Ministère du Développement durable, de l'Environnement et des Parcs du Québec, 128 p.

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2009a) Fleurs d'eau de cyanobactéries, Ministère du Développement durable, de l'Environnement et des Parcs, <http://www.mddep.gouv.qc.ca/eau/eco_aqua/cyanobacteries/> [accessed May 1, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2009b) Bilan des lacs et cours d'eau touchés par une fleur d'eau d'algues bleu-vert au Québec de 2004 à 2008, Ministère du Développement durable, de l'Environnement et des Parcs du Québec, <http://www.mddep.gouv.qc.ca/eau/algues-bv/bilan/liste_comparative.asp> [accessed June 11, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2009c) Registre des aires protégées, Ministère du Développement durable, de l'Environnement et des Parcs du Québec, <http://www.mddep.gouv.qc.ca/biodiversite/aires_protegees/registre/index.htm> [accessed September 4, 2009].

Ministère du Développement durable, de l'Environnement et des Parcs du Québec. (2010) Règlement sur les émissions de gaz à effet de serre des véhicules automobiles, Ministère du Développement durable, de l'Environnement et des Parcs du Québec, <http://www2.publicationsduquebec.gouv.qc.ca/dynamicSearch/telecharge.php?type=3&file=/Q_2/Q2R6_001.htm> [accessed April 19, 2010].

Minville, M., Brissette, F., Krau, S. and Leconte, R. (2009) Adaptation to climate change in the management of a Nordic water-resources system exploited for hydropower, Water Resources Management,. 23(4):2965-2986.

Mirza, S. (2007) Danger ahead: The Coming Collapse of Canada's Municipal Infrastructure, Federation of Canadian Municipalities, 7 p.

Monette S., Dallaire, A.D., Mingelbier, M., Groman, D., Uhland, C., Richard, J.-P., Paillard, G., Johannson, L.M., Chivers, D.P., Ferguson, H.W., Leighton F.A. and Simko, E. (2006) Massive mortality of common carp (Cyprinus carpio carpio) in the St. Lawrence River in 2001: Diagnostic investigation and experimental reproduction of a lymphocytic encephalitis, Veterinary Pathology, 43: 302-310.

Morin, J. and Bouchard, A. (2000) Les bases de la modélisation du tronçon Montréal–Trois-Rivières, rapport scientifique RS-100, Environment Canada – Quebec Region, Meteorological Service of Canada, Hydrometry Section, Sainte-Foy, 56 p.

Morin, J., Mingelbier, M., Bechara, J.A., Champoux, O., Secretan, Y., Jean, M. and Frenette, J.-J. (2003) Emergence of new explanatory variable for 2D habitat modelling in large rivers: The St. Lawrence experience, Canadian Water Resources Journal, 28:249-272.

Morin, J., Champoux, O., Martin, S., and Turgeon, K. (2005) Modélisation intégrée de la réponse de l'écosystème dans le fleuve Saint-Laurent: rapport final des activités entreprises dans le cadre du Plan d'étude sur la régularisation du lac Ontario et du fleuve Saint-Laurent, scientific report, Meteorological Service of Canada, Quebec area– Hydrology Section, RS-108, Environment Canada, 139 p.

Morin, X., Lechowicz, M.J., Augspurger, C., O' Keefe, J., Viner , D. and Chuine, I. (2009) Leaf phenology in 22 North American tree species during the 21st century, Global Change Biology, 15(4):961-975.

Morneau, F., Michaud, M., Lecours, F., Côté, L. and Roy, D. (2001) Étude d'impact sur l'environnement: projets de protection des berges le long de la route 132 autour de la péninsule gaspésienne, Ministère des Transports du Québec, 84 p.

Mortsch, L., Hengeveld, H., Lister, M., Lofgren, B., Quinn, F.H., Slivitzky, M. and Wenger, L. (2000) Climate change impacts on the hydrology of the Great Lakes St. Lawrence system, Canadian Water Resources Journal, 25(2):153-179.

Music, B. and Caya, D. (2007) Evaluation of the hydrological cycle over the Mississippi River basin as simulated by the Canadian Regional Climate Model (CRCM), Journal of Hydrometeorology, 8(5):969-988.

Music, B., Musy, A. and Roy, R. (2008) The Impact of Climate Change on Hydroelectricity Generation, rscientific report prepared for CEATI International Inc., <www.ouranos.ca/media/publication/147_hydroelectricity_BMusic.pdf> [accessed September 28, 2009].

Music, B., Frigon, A., Slivitzky, M., Musy, A. Caya, D. and Roy, R. (2009) Runoff modelling within the Canadian Regional Climate Model (CRCM): Analysis over the Quebec/Labrador watersheds, IAHS Publications, 333:183-194.

Nantel, E., Mailhot, A., A.N. Rousseau, A.N. and Villeneuve, J.-P. (2005) A methodology to assess historical and current municipal water supply vulnerabilities: An application to Quebec municipalities, *in* Computing and Control for the Water Industry, 8th International Conference, September 5-7 2005 at University of Exeter, U.K., vol. 2, 185 p.

Nature Conservancy (The). (2009) Adapting to Climate Change – Ecosystem-Based Approaches for People and Nature, The Nature Conservancy, 10 p.

Nearing, M.A., Pruski, F.F. and Oneal, M.R. (2004) Expected climate change impacts on soil erosion rates: A review, Journal of Soil and Water Conservation, 59(1):43-50.

Neilson, R.P., Pitelka, L.F., Solomon, A.M. Nathan, R., Midgley, G.F., Fragoso, J.M.V., Lischk, H. and Thompson, K. (2005) Forecasting regional to global plant migration in response to climate change, Bioscience, 55:749-759.

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J. , Myneni, R.B. and Running, S.W. (2003) Climate-driven increases in global terrestrial net primary production from 1982 to 1999, Science, 300:1560-1563.

Nicault, A., Begin, Y., Begin, C., Guiot, J., Savard, M.M. and Marion, J. (2009) Multiproxy Hydro-Climate Reconstructions Over La Grande Hydro-Power Complex in James Bay Area, Northern Québec, 62nd CWRA Annual Conference, June 9-12, Quebec City.

Nickels, S., Furgal, C., Buell, M. and Moquin, H. (2005) Unikkaaqatigiit – Putting the Human Face on Climate Change: Perspectives from Inuit in Canada, joint publication of Inuit Tapiriit Kanatami, the Nasivvik Centre for Inuit Health and Changing Environments at Laval University and the Ajunnginiq Centre at the National Aboriginal Health Organization.

Norby, R.J., DeLucia, E.H., Gielen, B., Calfapietra, C., Giardina, C.P., King, J.S., Ledford, J., McCarthy, H.R., Moore, D.J.P., Ceulemans, R., De Angelis, P., Finzi, , A.C., Karnosky, D.F. Kubiske, M.E., Lukac, M., Pregitzer, K.S., Scarascia-Mugnozza,, G.E. Schlesinger, W.H. and Oren, R. (2005) Forest response to elevated CO_2 is conserved across a broad range of productivity, Proceedings of the National Academy of Sciences of the United States of America, 102:18052-18056.

Noss, RF. (2001) Beyond Kyoto: Forest management in a time of rapid climate change, Conservation Biology, 15:578-590.

Ogden, N.H., Maarouf, A., Barker, I.K., Bigras-Poulin, M., Lindsay, L.R., Morshed, M.G., O'Callaghan, F. Ramay, C.J., Waltner-Toews, D. and Charron, D.F. (2006) Climate change and the potential for range expansion of the Lyme disease vector Ixodes scapularis in Canada, International Journal for Parasitology, 36:63-70.

Oke, T.R. (1982) The energetic basis of urban heat island, Journal of the Royal Meteorological Society, 108(455):1-24.

Ontario Forest Research Institute. (2003) A Synopsis of Known and Potential Diseases and Parasites Associated with Climate Change, Forest Research Information Paper #154, Ontario Forest Research Institute, Queen's Printer for Ontario, 185 p.

Ouellet, V., Champoux, O. and Morin, J. (2005) Modèle d'impacts des fluctuations de niveau d'eau sur la survie hivernale du rat musqué: rapport final des activités entreprises dans le cadre du Plan d'étude sur la régularisation du lac Ontario et du fleuve Saint-Laurent, technical report, Meteorological Service of Canada –Hydrology Section RT-139, Environment Canada, prepared for the Technical Work Group on the environment of the International Lake Ontario -- St. Lawrence River Study, 2005, 75 p.

Ouranos. (2004) S'adapter aux changements climatiques, Ouranos, Montréal, 91 p., <http://www.ouranos.ca/fr/pdf/ouranos_sadapterauxcc_fr.pdf> [accessed May 11, 2009].

Ouranos. (2006) Programmation scientifique, Ouranos, Montréal, <http://www.ouranos.ca/fr/programmation-scientifique/impacts-et-adaptation/impacts-societaux-environnementaux/sante.php> [accessed June 11, 2009].

Owens, S., Gosselin, P., Furgal, C., Proulx, J.-F. And Château-Degat, L. (2006) Nunavik's Public Health Surveillance in Response to a Changing Climate: A Baseline Study, ArcticNet and Centre hospitalier universitaire de Québec, 113 p.

Pacher, G., Minville, M., Frigon, A., Roy, R. and Slivitzky, M. (2009) Climate change and water resources: An approach to adaptive management: The role of hydrology in water resources management, IAHS Publication, 327:136-143.

Parker, W.C., Colombo, S., Cherry, M.L., Flannigan, M.D., Greifenhagen, S., McAlpine, R.S., Papadopol, C. and Scarr, T. (2000) Third millennium forestry: What climate change might mean to forests and forest management in Ontario, The Forestry Chronicle, 76:445-463.

Parkinson, A.J. and Butler, J.C. (2005) Potential impacts of climate change on infectious diseases in the Arctic, International Journal of Circumpolar Health, 64(5):478-486.

Patz, J.A., McGeehin, M.A., Bernard, S.M, Ebi, K.L., Epstein, P.R., Grambsch, A., Gubler, D.J., Reiter, P., Romieu, I., Rose, J.B., Samet, J.M. and Trtanj, J. (2000) The potential health impacts of climate variability and change for the United States: Executive summary of the report of the health sector of the U.S. National Assessment, Environmental Health Perspectives, 108(4):367-376.

Payette, S. (1992) Fire as a controlling process in the North American boreal forest, *in* A Systems Analysis of the Global Boreal Forest, Cambridge University Press, Cambridge, p. 144-169.

Payette, S., Fortin, M.J. and Gamache, I. (2001) The sub-arctic forest-toundra: The structure of a biome under changing climate, Bioscience, 51(9):709-718.

Payette, S., Delwaide, A., Caccianiga, M. and Beauchemin, M. (2004) Accelerated thawing of subarctic peatland permafrost over the last 50 years, Geophysical Research Letters, vol. 31 (L18208): 1-4.

Peixoto, J. P. and Oort, A.H. (1992) Physics of Climate, American Institute of Physics, 520 p.

Peterson, A.T. and Scachetti-Pereira, R. (2004) Potential geographic distribution of Anoplophora glabripennis (Coleoptera: Cerambycidae) in North America, The American Midland Naturalist, 151(1):170-178.

Pfeffer, W. T., Harper, J. T. And O'Neel, S. (2008) Kinematic constraints on glacier contributions to 21st-century sea-level rise, Science 321(5894):1340-1343.

Plummer, D.A., Caya, D., Frigon, A., Côté, H., Giguère, M., Paquin, D., Biner, S. Harvey, R. and de Elía, R. (2006) Climate and climate change over North America as simulated by the Canadian RCM, Journal of Climate, 19(13):3112-3132.

Podur, J., Martell, D.L. and Knight, K. (2002) Statistical quality control analysis of forest fire activity in Canada, Canadian Journal of Forest Research—Revue canadienne de recherche forestière, 32:195-205.

Price, D.T., Halliwell, D.H., Apps M.J. and Peng, C.H. (1999) Adapting a patch model to simulate the sensitivity of Central-Canadian boreal ecosystems to climate variability, Journal of Biogeography, 26:1101-1113.

Price, D., Zimmermann, N., van der Meer, P., Lexer, M., Leadley, P., Jorritsma, I., Schaber, J., Clark, D., Lasch, P., McNulty, S., Wu J. and Smith, B. (2001) Regeneration in gap models: Priority issues for studying forest responses to climate change, Climatic Change, 51:475-508.

Price, D.T. and Scott, D. (2006) Large Scale Modelling of Canada's Forest Ecosystem Responses to Climate Change, final report to the Government of Canada: Climate Change Impacts and Adaptation Division, 53 p.

Pugin, S., Cyr, J.-F., Fortin, L.G. and Turcotte, R. (2006) Une approche par bassin versant pour évaluer l'impact des changements climatiques et la capacité d'adaptation — Développements méthodologiques pour un bassin agricole du Québec méridional, technical report, Ministère du Développement Durable, de l'Environnement et des Parcs.

Public Safety Canada. (2006) Glissements de terrain et avalanches importants des XIX[e] et XX[e] siècles, Public Safety Canada, <http://www.psepc-sppcc.gc.ca/res/em/nh/lsa/lsa-sig-fr.asp> [accessed June 11, 2009].

Pye, H.O.T., Liao, H., Wu, S.,. Mickley, L., Jacob, D.J., Henze, D.K. and Seinfeld, J.H. (2009) Effect of changes in climate and emissions on future sulfate-nitrate-ammonium aerosol levels in the United States, Journal of Geophysical Research, 114, D01205, doi:10.1029/2008JD010701.

Quilbé, R., Rousseau, A.N., Moquet, J.-S., Trinh, N.B., Dibike, Y., Gachon, P. and Chaumont, D. (2008a) Assessing the effect of climate change on river flow using general circulation models and hydrological modelling — Application to the Chaudière River (Québec, Canada), Canadian Water Resources Journal, 33(1):73-93.

Quilbé, R., Rousseau, A.N., Moquet, J.-S., Savary, S., Ricard, S. and Garbouj, M.S. (2008b) Hydrological response of a watershed to historical land use evolution and future land use scenarios under climate change conditions, Hydrology and Earth System Sciences, 12:101-110.

Raulier, F., Bernier, P.Y. (2000) Predicting the date of leaf emergence for sugar maple (Acer saccharum Marsh) across its native range, Canadian Journal of Forest Research, 30:1429-1435.

Réale, D., McAdam, A.G., Boutin, S. and Berteaux, D. (2003) Genetic and plastic responses of a northern mammal to climate change, Proceedings of the Royal Society of London Series B — biological sciences, 270:591-596.

Régie régionale de la santé et des services sociaux de Chaudière-Appalaches. (2001) Avis de santé publique portant sur les risques à la santé associés aux activités de production animale en Chaudière-Appalaches, Régie régionale de la santé et des services sociaux de Chaudière-Appalaches, <http://www.rrsss12.gouv.qc.ca/pdf/Avis-Production_animales-mars_01.pdf> [accessed May 11, 2009].

Régie régionale de la santé et des services sociaux du Nunavik. (2004) Qanuippitaa ? L'enquête de santé du Nunavik, Régie régionale de la santé et des services sociaux du Nunavik, <http://qanuippitaa.com/fr/index.aspx> [accessed May 2, 2007].

Régnière, J., Cooke, B.J., Logan, J.A., Carroll, A.L. and Safranyik, L. (2005) Les changements climatiques et les ravageurs indigènes et exotiques: une nouvelle réalité?, seminar Changements climatiques et foresterie: impacts et adaptation, Baie-Comeau, Quebec, April 20-21.

Renecker, I.A. and Hudson, R.J. (1986) Seasonal energy expenditures and thermoregulatory response of moose, Canadian Journal of Zoology, 64:322-327.

Rivard, C., Marion, J., Michaud, Y., Benhammane, S., Lefebvre, R. and Rivera, A. (2003) Étude de l'impact potentiel des changements climatiques sur les ressources en eau souterraine dans l'Est du Canada, Geological Survey of Canada, public record 1577, 39 p.

Rivard, C., Vigneault, H., Piggott, A.R., Larocque, M., Anctil, F., Tremblay, L. and Rousseau, A.N. (2008) Examining the Impacts of Climate Change and Human Activities on Groundwater Recharge in Canada Using Historical Data, GeoEdmonton 2008: 61st Canadian Geotechnical Conference and 9th Joint CGS/IAH-CNC Groundwater ConferenceEdmonton,Alberta, Sept. 21-24, 2008.

Rizak, S. and Hrudey, E. (2008) Drinking water safety — Challenges for community-managed systems, Journal of Water and Health, 6(suppl. 1):33-41.

Rizzo, B. and Wilken, E. (1992) Assessing the sensitivity of Canada's ecosystems to climatic change, Climatic Change,. 21(1):37-56.

Robichaud, A. and Drolet, R. (1998) Rapport sur l'état du Saint-Laurent — les fluctuations des niveaux d'eau du Saint-Laurent, Joint update, representatives from Environment Canada, Fisheries and Oceans Canada, and the Ministère de l'Environnement et de la Faune du Québec, technical report.

Rochette, P., Bélanger, G., Castonguay, Y., Bootsma, A. and Mongrain, D. (2004) Climate change and winter damage to fruit trees in Eastern Canada, Canadian Journal of Plant Science, 84:1113-1125.

Rodenhouse, N.L., Christeson,, L.M. Parr, D. and Green, L.E. (2009) Climate change effects on native fauna of northeastern forests, Canadian Journal of Forest Research, 39:249-263.

Root, T.L. and Schneider, S.H. (2002) Climate change: Overview and implications for wildlife, *in* S.H. Schneider and T.L. Root (ed.), Wildlife Responses to Climate Change: North American Case Studies, Island Press, Washington, DC, 437 p.

Rosberg, J. and Andréasson, J. (2006) From Delta Change to Scaling and Direct Use of RCM Output, report given at the European Conference on Impacts of Climate Change on Renewable Energy Sources, Reykjavik, Iceland, June 5-9, p. 121-124.

Rose, J.B., Daeschner, S., Easterling, D.R., Curriero, F.C., Lele, S. and Patz, A.J. (2000) Climate and waterborne disease outbreaks, Journal of American Water Works Association, 92(9):77-87.

Rounsevell, M.D.A., Berry, P.M. and Harrison, P.A. (2006) Future environmental change impacts on rural land use and biodiversity: A synthesis of the ACCELERATES project, Environmental Science and Policy, 9:93-100.

Rousseau, A.N., Mailhot, A. and Villeneuve, J.-P. (2003) Connaissons-nous bien la capacité des bassins versants et aquifères régionaux à fournir de l'eau potable à la population du Québec sous de nouvelles conditions climatiques?, 26^e^ Symposium sur les eaux usées et 15^e^ Atelier sur l'eau potable, , Laval, Quebec, September 17-18.

Rousseau, A.N., Mailhot, A., Slivitzky, M., Villeneuve, J.-P., Rodriguez, M.J. and Bourque, A. (2004) Usages et approvisionnement en eau dans le Sud du Québec. Niveau des connaissances et axes de recherche à privilégier dans une perspective de changements climatiques, Canadian Water Resources Journal,. 29 (2):125-138.

Roy, L.A. (1998) Le verglas de 1998 dans le Nord-Est de l'Amérique du Nord, Bulletin d'information en santé environnementale (BISE), Institut national de santé publique du Québec, 9(6), 1998, <http://www.inspq.qc.ca/bulletin/bise/1998/bise_9_6.asp?Annee=1998#article2> [accessed June 11, 2009].

Roy, R., Pacher, G., Adamson, P., Ro L. And Silver, R. (2008a) Adaptive Resources Management for Water Resources Planning and Operations, scientific and technical report commissioned by the World Bank. 96 p.

Roy, R., Chartier, I., Desrochers, G., Guay, F., Minville, M., Pacher, G., Roy, L. and Tapsoba, D. (2008b) Impacts des changements climatiques sur le régime hydrologique au nord du Québec et mesures d'adaptation envisageables, presented at 21e Entretiens Jacques-Cartier, Montréal, Quebec, October.

Rustad, L.E., Melillo, J.M., Mitchell, M.J., Fernandez, I.J., Steudler, P.A. and McHale, P.J. (2000) Effects of soil warming on C and N cycling in Northern U.S. forest soils, *in* R. Mickler, R. Birsdey and J. Horn (ed.), Responses of Northern U.S. Forests to Environmental Change, Springer-Verlag, Berlin Heidelberg, New York, 357-381.

Rustad, L.E., Campbell, J.L., Marion, G.M., Norby, R.J., Mitchell, M.J., Hartley, A.E., Cornelissen, J.H.C., Gurevitch, J. and GCTE-NEWS. (2001) A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming, Oecologia, 126:543-562.

Ruth, M. (2003) Modelling Infrastructure Vulnerabilities and Adaptation to Climate Change in Urban Systems: Methodology and Application to Metropolitan Boston, European Regional Science Association Meetings Jyväskylä, Finland, August 2003.

Savard, J.-P., Bernatchez, P., Morneau, F., Saucier, F., Gachon, P., Senneville, S., Fraser C. and Jolivet, Y. (2008) Étude de la sensibilité des communautés du golfe du Saint-Laurent aux impacts des changements climatiques, synthèses des résultats, 48 p., <http://www.ouranos.ca/media/publication/20_Rapport_Savard_maritime_2008.pdf> [accessed September 4, 2009].

Savary, S., Rousseau, A.N. and Quilbé, R. (2009) Assessing the effects of historical landcover changes on runoff using remote sensing and hydrological modelling, Journal of Hydrological Engineering, 14(6):575-587.

Scherm, H. (2004) Climate change: Can we predict the impacts on plant pathology and pest management?, Canadian Journal of Plant Pathology, 26:267-273.

Schwartz, M.W. (1992) Modeling effects of habitat fragmentation on the ability of trees to respond to climatic warming, Biodiversity and Conservation, 2:51-61.

Scinocca, J.F. and McFarlane, N.A. (2004) The variability of modelled tropical precipitation, Journal of Atmospheric sciences, 61:1993-2015.

Scott, D. (2005) Ski industry adaptation to climate change, *in* S. Gössling and M. C. Hall (ed.), Tourism and Global Environmental Change, Routledge, U.K, 344 p.

Scott, D., Jones, B., Lemieux, C., McBoyle, G., Mills, B., Svenson, S. and Wall, G. (2002a) The Vulnerability of Winter Recreation to Climate Change in Ontario's Lakelands Tourism Region, Department of Geography Publication Series, occasional paper 18, University of Waterloo, Waterloo, Canada. <http://www.fes.uwaterloo.ca/geography/faculty/danielscott/PDFFiles/Winterrecreation_Scott-good%20quality.pdf> [accessed June 19, 2009].

Scott, D., Malcolm, J.R. and Lemieux, C. (2002b) Climate change and modelled biome representation in Canada's national park mandates, Global Ecology & Biogeography, 11:475-484.

Scott, D. and Jones, B. (2006) Climate Change Seasonality in Canadian Outdoor Recreation and Tourism, Department of Geography, University of Waterloo, Waterloo, Canada, <http://www.fes.uwaterloo.ca/geography/faculty/danielscott/PDFFiles/SEASONS_Final%20copy.pdf> [accessed June 19, 2009].

Scott, D. and McBoyle, G. (2007) Climate change adaptation in the ski industry, Mitigation and Adaptation Strategies to global Environmental Change, 12(8):1411-1431.

Scott, D., McBoyle, G. and Minogue, A. (2007) The implication of climate change for the Quebec ski industry, Global Environmental Change, 17(2):181-190.

Secrétariat aux affaires autochtones. (2007) La population autochtone au Québec, Secrétariat aux affaires autochtones, 2007, <http://www.autochtones.gouv.qc.ca/nations/population.htm> [accessed October 20, 2009].

Secretariat of the Convention on Biological Diversity. (2006) Perspectives mondiales de la diversité biologique, second edition, Secretariat of the Convention on Biological Diversity, Montreal, Quebec 83 p.

Secretariat of the Convention on Biological Diversity and The Nature Conservancy. (2008) Ecosystem-Based Adaptation: An Introduction to Benefits and Key Principles, Secretariat of the CBD and The Nature Conservancy.

Seguin, M.K. and Allard, M. (1984) Le pergélisol et les processus thermokarstiques de la région de la rivière Nastapoca, Nouveau-Québec, Géographie physique et Quaternaire, 38:11-25.

Senneville, S. and Saucier, F.J. (2007) Étude de sensibilité de la glace de mer au réchauffement climatique dans le golfe et l'estuaire du Saint-Laurent, Report prepared for Ouranos, 28 p., <http://www.ouranos.ca/media/publication/146_SennevilleetSaucier2007.pdf> [accessed November 9, 2009].

Shuter, B.J., Minns, C.K., Regier, H.A and Reist, J.D. (1998) Étude pancanadienne sur l'adaptation à la variabilité et au changement climatique — secteur des pêches, *in* G. Koshida and W. Avis (ed.), Impacts et adaptation à la variabilité et au changement du climat: questions sectorielles, Environment Canada, Étude pancanadienne sur l'adaptation à la variabilité au changement climatique, VII:. 277-344.

Singh, B., Bryant, C., André, P. and Thouez, J.-P. (2006) Impact et adaptation aux changements climatiques pour les activités de ski et de golf et l'industrie touristique: le cas du Québec, final report, Ouranos project, <http://www.ouranos.ca/fr/publications/resultats.php?q=singh&t=> [accessed May 1, 2009].

Siron, R., Sherman, K., Skjoldal, H.-R. and Hiltz, E. (2008) Ecosystem-based management in the Arctic Ocean: A multi-level spatial approach, Arctic, 61(supp.1):86-102.

Smargiassi, A, Goldberg, M.S., Plante, C., Fournier,, M. Baudouin, Y. and Kosatsky, T. (2009) Variation of daily warm season mortality as a function of micro-urban heat islands, Journal of Epidemiology and Community Health, 63:659-664, <http://jech.bmj.com/cgi/content/full/63/8/659> [accessed June 11, 2009].

Smit, B., Blain, R. and Keddie, P. (1997) Corn hybrid selection and climatic variability: Gambling with nature?, The Canadian Geographer, 41:429-438.

Solomon-Côté, P. (2004) Élaboration d'une classification de terrain en milieu de pergélisol à l'aide d'un SIG, en vue de l'aménagement du territoire: le cas de Salluit au Nunavik, Master's thesis, Département de géographie, Université Laval, Québec, 113 p.

Sottile, M.-F. (2006) Changements climatiques pour la révision des normes d'efficacité énergétique dans les nouveaux bâtiments, study carried for the Agence de l'efficacité énergétique, 20 p., <http://www.ouranos.ca/media/publication/44_Rapport_Sottile_Climat_2006.pdf> [accessed May 1, 2009].

Spittlehouse, D.L. and Stewart, R.B. (2004) Adaptation to climate change in forest management, BC Journal of Ecosystems and Management, 4:7-17.

Stankey, G.H., Clark , R.N. and Bormann, B.T. (2005) Adaptive Management of Natural Resources: Theory, Concepts and Management Institutions, general technical report PNW-GTR-654, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, 73 p.

Statistics Canada. (2005) Bulletin d'analyse — régions rurales et petites villes du Canada, Statistics Canada, 2005,. 6:6.

Statistics Canada. (2006) L'âge de l'infrastructure publique au Canada, short analysis, V. Gaudreau and P. Lemire, Investment and Capital Stock Division, Statistics Canada, 13 p.

Statistics Canada. (2007) Recensement de l'agriculture, section 1 — un portrait statistique de l'agriculture, Canada et provinces: années de recensement 1921 à 2006, Statistics Canada, <http://www.statcan.gc.ca/pub/95-632-x/2007000/t/4185570-fra.htm#24> [accessed April 24, 2009].

Stoneham, M., Earl, C. and Baldwin, L. (2001) Creating Shade at Public Facilities: Policy and Guidelines for Local Government, 2nd edition, Australian Institute of Environmental Health, 101 p., <www.health.qld.gov.au/ph/documents/hpu/20267.pdf> [accessed June 11, 2009].

Stirling, I., N.J. Lunn et J. Iacozza. (1999) Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change, Arctic, 52 (3): 294-306.

Strode, P.K. (2003) Implications of climate change for North American wood warblers (Parulidae), Global Change Biology 9:1137-1144.

Swansberg, E. and El-Jabi, N. (2001) Impact of Climate Change on River Water Temperatures and Fish Growth, report prepared for the Climate Change Impacts and Adaptation Program, Natural Resources Canada.

Tanguay, J. and Roussel, J.-J. (2000) Un système d'aide aux décisions hivernales, Innovation Transport, bulletin scientifique et technique, #9.

Tanner, C.E., Staudt, M., Adamowski, R., Lussier, M., Bertrand, S. and Prichard, R.K. (1987) Seroepidemiological study for five different zoonotic parasites in Northern Quebec, Canadian Journal of Public Health, 78(4):262-266.

Tarasov, L. and Peltier, W.R. (2004) A geophysically constrained large ensemble analysis of the deglacial history of the North American ice-sheet complex, Quaternary Science Reviews, 23(3-4):359-388.

Tardif, I., Bellerose, C. and Masson, E. (2006) Environnements et santé: le point de vue des Montérégiens, Bulletin d'information en santé environnementale (BISE), Institut national de santé publique du Québec, 17(6):1-6, <http://www.inspq.qc.ca/pdf/bulletins/bise/BISE-17-6.pdf> [accessed June 11, 2009].

Tecsult. (2008) Analyse coûts-avantages de solutions d'adaptation à l'érosion côtière pour la Ville de Sept-Îles, report carried out for the Ville de Sept-Îles. 90 p.

Thieden, E., Philipsen, P.A., Heydenreich, J. and Wulf, H.C. (2004a) UV radiation exposure related to age, sex, occupation and sun behaviour based on time-stamped personal dosimeter readings, Archives of Dermatology, 140:197-203.

Thieden, E., Philipsen, P.A., Sandby-Moller, J., Heydenreich, J. and Wulf, H.C. (2004b) Proportion of lifetime UV dose received by children, teenagers, Journal of Investigative Dermatology, 123:1147-1150.

Thomas, M.K, Charron, D.F., Waltner-Toews, D., Schuster, C., Maarouf, A.R. and Holt, J.D. (2006) A role of high impact weather events in waterborne disease outbreaks in Canada, 1975-2001, International Journal of Environmental Health Research, 16(3):167-180.

Tremblay, C., Jacques, L., Prévost, C., Noiseux, M, Blackburn, M. and Boileau, L. (1998) Les impacts du verglas de 1998 sur la santé des Montérégiens, Bulletin d'information en santé environnementale (BISE), Institut national de santé publique du Québec, 9(6), Nov-Dec 1998, <http://www.inspq.qc.ca/bulletin/bise/1998/bise_9_6.asp?Annee=1998#article1> [accessed June 11, 2009].

Tremblay, M., Furgal,, Lafortune, V., Larrivée, C., Savard, J.-P., Barrett, M., Annanack, T., Enish, N., Tookalook, P. and Etidloie, B. (2006) Climate change, communities and ice: Bringing together traditional and scientific knowledge for adaptation in the North, in R. Riewe and J. Oakes (ed.), Climate Change: Linking Traditional and Scientific Knowledge, Aboriginal Issues Press, University of Manitoba, Winnipeg, p. 185-201.

Turcotte, R., Fortin, L.G., Pugin, S. and Cyr, J.-F. (2005) Impact des changements climatiques sur les plans de gestion des réservoirs Saint-François et Aylmer: résultats préliminaires, report submitted to the Canadian Dam Association Annual Conference, Calgary, Oct. 3-5, 2005.

Turgeon, K., Champoux, O., Martin, S. and Morin, J. (2005) Modélisation des grandes classes de milieux humides de la plaine inondable du fleuve Saint-Laurent: considération de la succession des communautés végétales, scientific report, Meteorological Service of Canada, Quebec — Hydrology Section RS-107, Environment Canada, 89 p.

United Nations. (1993) Convention on Biological Diversity, United Nations, Recueil des Traités, 1760 (I-30169): 169-382, <http://www.cbd.int/convention/convention.shtml> [accessed September 4, 2009].

Van Cleve, K., Oechel, W.C. and Hom, J.L. (1990) Response of black spruce (Picea mariana) ecosystems to soil temperature modification in interior Alaska, Canadian Journal of Forest Research, 20:1530-1535.

Verburg, P.S.J. (2005) Soil solution and extractable soil nitrogen response to climate change in two boreal forest ecosystems, Biology and Fertility of Soils, 41:257-261.

Verhaar, P.M., Biron, R., Ferguson, I. and Hoey, T. B. (2010) Numerical modeling of climate change impacts on Saint-Lawrence River tributaries, Earth Surface Processes, 35(10):1184-1198.

Vescovi, L., Rebetez, M. and Rong, F. (2005) Assessing public health risk due to extremely high temperature events: climate and social parameters, Climate Research, 30:71-78.

Vescovi, L., Cyr, J.-F., Turcotte, R, Ludwig, R., Braun, M., Fortin, L.G. and Chaumont, D. (2009) A multi-model experiment to assess and cope with climate change impacts on the Chateauguay watershed in Southern Quebec, accepted for publication in The 3rd UN World Water Development Report: Water in a Changing World.

Ville de Montréal. (2005) Le plan stratégique de développement durable de Montréal, Ville de Montréal, <http://www2.ville.montreal.qc.ca/cmsprod/fr/developpement_durable/plan_strategique> [accessed June 11, 2009].

Villeneuve, C. (2008) La grande inconnue, Journal of Water Science, 21(2):129-133.

Villeneuve, J.P., Fougères, D., Gaudreau, M., Hamel, P.-J., Poitras, C., Sénécal, G., Trépanier, M., Vachon, N., Veillette, R., Duchesne, S., Mailhot, A., Musso, E. and Pelletier, G. (1998) Synthèse des rapports INRS-Urbanisation et INRS-Eau sur les besoins des municipalités québécoises en réfection et construction d'infrastructures d'eaux, INRS-Urbanisation et INRS-Eau, research report #R517-b, 50 p., <http://www.inrs-ete.uquebec.ca/pub/r517b.pdf> [accessed October 20, 2009].

Vincent, L.A. and Mekis, É. (2006) Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century, Atmosphere Ocean, 44(2):177-193.

Visser, M.E. et C. Both. (2005) Shifts in phenology due to global climate change: The need for a yardstick, Proceedings of the Royal Society of London Series B — biological sciences, 272:2561-2569, <http://www.rug.nl/biologie/onderzoek/onderzoekgroepen/dieroecologie/publications/2Visser05.pdf> [accessed September 4, 2009].

Wall, E., Smit, B. and Wandel, J. (2004) Canadian Agri-Food Sector Adaptation to Risks and Opportunities from Climate Change — position paper, Canadian Climate Impacts and Adaptation Research Network 9C-CIARN — Agriculture, 68 p.

Waller, B., Pichora, E. and Marrett, L. (2008) Deuxième enquête sur l'exposition au soleil: rapport de l'atelier, Chronic Diseases in Canada, 20(1):43-46.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J., Fromentin, J.-M., Hoegh-Guldberg, O. and Bairlein, F. (2002) Ecological response to recent climate change, Nature, 416:389-395.

Warren, F., Barrow, E., Schwartz, R., Audrey, J., Mill B. and Riedel, D. (2004) Impacts et adaptations liés aux changements climatiques: perspective canadienne, Natural Resources Canada.

Watson, R.T., Patz, J., Gubler, D.J., Parson, E.A. and Vincent, J.H. (2005) Environmental health implications of global climate change, Journal of Environmental Monitoring, 7:834-843.

Weber, M.G. and Flannigan, M.D. (1997) Canadian boreal forest ecosystem structure and function in a changing climate: Impact on fire regimes, Environmental Reviews, 5:145-166.

Wietze L. and Tol, R.S.J. (2002) Impact of climate on tourist demand, Climatic Change, 55(4):429-449.

Williamson, T., Colombo, S., Duinker, P., Gray, P., Hennessey, R., Houle, D., Johnston, M., Ogden, A. and Spittlehouse, D. (2009) Les changements climatiques et les forêts du Canada: des impacts à l'adaptation, Sustainable Forest Management Network and Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, 112 p.

World Bank. (2007) Addressing Climate Change-Driven Increased Hydrological Variability in Environmental Assessments for Hydropower Projects — A Scoping Study, 37 p.

World Health Organization. (2003) Climate change and human health: risks and responses, World Health Organization, <http://www.who.int/globalchange/publications/cchhsummary/en/> [accessed June 11, 2009].

World Health Organization. (2005) Climat et santé, World Health Organization, <http://www.who.int/mediacentre/factsheets/fs266/fr/> [accessed June 11, 2009].

World Health Organization. (2008) Plans d'action sanitaire contre la chaleur, F. Matthies et al. (ed.), World Health Organization — European Regional Office, 58 p.

Wotton, B.M. and Flannigan, M.D. (1993) Length of the fire season in a changing climate, The Forestry Chronicle, 69:187-192.

Wrona, F., Prowse, T., Reist, J., Beamish, R., Gibson, J.J., Hobbie, J., Jeppesen, E., King, J., Korhola, A., Macdonald, R., Power, M., Skvortsov, V., Keock, G., Vincent, W. and Levesque, L. (2005) Freshwater Arctic ecosystems, Chap. 7 *in* Arctic Climate Impact Assessment, Cambridge University Press, London, p. 353-452.

Yagouti, A., Boulet, G., Vincent, L.A., Vescovi , L. And Mekis, É. (2008) Observed changes in daily temperature and precipitation indices for Southern Quebec, 1960-2005, Atmosphere-Ocean, 46(2):243-256.

Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A. (2000) Temperature and precipitation trends in Canada during the 20th century, Atmosphere-Ocean, 38(3):395-429.

Ziska, L.H. and Goins, E.W. (2006) Elevated atmospheric carbon dioxide and weed populations in glyphosate treated soybean, Crop Science, 46:1354-1359.

Ziska, L.H. and McClung, A.M. (2008) Differential response of cultivated and weedy (red) rice to recent and projected increases in atmospheric carbon dioxide, Agronomy Journal, 100:1259-1263.

TABLE 8 REFERENCES

(1) Ministère des Transports du Québec. (2005) Adapter les transports aux changements climatiques. Dégel du pergélisol, Ministère des Transports du Québec.

(2) Ouranos. (2005) Le changement climatique au Québec nordique et ses enjeux, technical day held in Montréal, on May 3, 2005.

(3) Karstein, L. and Domaas, Y. (2000) Évaluation des risques d'avalanche au Nunavik et sur la Côte-Nord du Québec, Canada, Norwegian Geotechnical Institute, report carried out for the Ministère de la Sécurité publique du Québec, 35 p.

(4) Beaulac, I. and Doré, G. (2005) Impacts du dégel du pergélisol sur les infrastructures de transport aérien et routier au Nunavik et adaptations – état des connaissances, Sciences and Engineering Faculty, Université Laval, Québec, 141 p.

(5) Allard, M., Fortier, R. and Gagnon, O. (2002) Problématique du développement du village de Salluit, Nunavik, Québec, Centre d'études nordiques, Université Laval, Québec, 121 p.

(6) Beaulieu, J. and Rainville, A. (2005) Adaptation to climate change: Genetic variation is both a short- and a long-term solution," The Forestry Chronicle, 81:704-709.

(7) Environment Canada, (1997) Environment Canada website, <http://cwfis.cfs.nrcan.gc.ca/fr/current/cc_fw_f.php> [accessed May 2, 2007].

(8) Irvine, J. (2004) Climate Change, Adaptation, and "Endangered" Salmon in Canada, report at the Species at Risk 2004 Pathways to Recovery Conference, Victoria, British Columbia, March 2-8, 2004.

(9) Canada Economic Development. (2007) Section Programme développement économique Canada-Régions du Québec, Economic Development Canada

(10) Ouranos. (2007) Programme Environnement maritime, Ouranos, <http://www.ou ranos.ca> [accessed May 2, 2007].

(11) Ouranos. (2007) Changement climatique et usages de l'eau dans le bassin versant de la Châteauguay, technical day held in Montreal.

(12) Mehdi, B., Mrena, C. and Douglas, A. (2005) S'adapter aux changements climatiques: une introduction à l'intention des municipalités canadiennes, Canadian Climate Impacts and Adaptation Research Network (C-CIARN), 35 p.

(13) Morneau, F., Michaud, M., Lecours, F., Côté, L. and Roy, D. (2001) Étude d'impact sur l'environnement: projets de protection des berges le long de la route 132 autour de la péninsule gaspésienne, principal report, Ministère des Transports du Québec, 84 p.

(14) Dubois, J.-M. Bernatchez, M. P., Bouchard, J.-D., Daigneault, B., Cayer D., and Dugas, S. (2006) Évaluation du risque d'érosion du littoral de la Côte-Nord du St-Laurent pour la période de 1996 à 2003, Conférence régionale des élus de la Côte-Nord, report presented to the Comité interministériel sur l'érosion des berges de la Côte-Nord,291p.<http:/www.crecotenord.qc.ca/index.php?option=com_docman&task=catview&gid=97&Itemid=278> [accessed 28 juillet 2009]. <http://www.crecotenord.qc.ca/index.php?option=com_docman&task=cat_view&gid=97&Itemid=278> [consultation : 28 juillet 2009].

(15) Bélanger, G., Rochette, P., Castonguay, Y., Bootsma, A., Mongrain, D., and Ryan, D.A.J. (2002) Climate change and winter survival of perennial forage crops in Eastern Canada, Agronomy Journal, 94:1120-1130.

(16) Agriculture and Agri-Food Canada. (2002) Monitoring Drought on the Canadian Agricultural Landscape, Prairie Agroclimate Unit/National Agroclimate Information Service, Agriculture Agri-Food Canada, agro-meteorological workshop held in Dorval, Quebec, December 9-10, 2001.

(17) Smit, B. and Wall, E. (2003) Adaptation to Climate Change Challenges and Opportunities: Implications and Recommendations for the Canadian Agri-Food Sector, Standing Senate Committee on Agriculture and For estry, Ottawa.

(18) Cyr, J.-F. and Turcotte, R. (2005) Bassin de la rivière Châteauguay: projet du CEHQ et Hydrotel, technical workshop held in Montreal, February 24, 2005.

(19) Lemmen, D.S. and Warren, F.J. (2004) Agriculture, *in* Impacts et adaptation liés aux changements climatiques: perspective canadienne, Government of Canada, p. 59-69.

(20) Garneau, M., Breton, M.C., Guay, F., Fortier, I., Sottile, M.F. and Chaumont, D. (2006) Hausse des concentrations des particules organiques (pollens) causée par le changement climatique et ses conséquences sur les maladies respiratoires des populations vulnérables en milieu urbain, Climate Change Action Fund — Impacts et Adaptation Component, project A571, <http://www.ouranos.ca/media/publication/34_Rapport_Garneau_sante_2006.pdf> [accessed June 11, 2009].

(21) National Health Service. (2005) Heatwave Plan for England Reducing Harm from Protecting Health and Extreme Heat and Heatwaves, National Health Service, 16 p.

(22) Observatoire Nationale sur les effets du Réchauffement Climatique. (2005) Un climat à la dérive: comment s'adapter?, Report presented to the Prime Minister and Parliament, ONERC, <http://www.ecologie.gouv.fr/IMG/pdf/onercdocfrancaise.pdf> [accessed May 2, 2007].

(23) McBean, G. and Henstra, D. (2003) Climate Change, Natural Hazards and Cities, Institute for Catastrophic Loss Reduction Research, 16 p.

(24) Kirshen, P., Ruth, M., and Anderson, W. (2005) Integrated Impacts of Climate Change on and Adaptation Strategies for Metropolitan Areas: A Case Study of Metropolitan Boston, World Water & Environmental Resources Congress, 2005, Impacts of Global Climate Change, Anchorage.

(25) Ducas, S. (2004) Conférence sur le plan d'urbanisme de la Ville de Montréal, *in* Les Journées annuelles de la santé publique, November 30, 2004.

(26) Ebi, K.L., Teisberg, T. J., Kalkstein, L.S., Robinson, L. and Weiher, R.F. (2004) Heat Watch/Warning Systems save lives — Estimated costs and benefits for Philadelphia 1995-98, Bulletin of American Meteorological Society, 85:1067-1073.

(27) Doyon, B., Bélanger, D. and Gosselin. P. (2006) Effets du climat sur la mortalité au Québec méridional de 1981 à 1999 et simulations pour des scénarios climatiques futurs, Institut national de santé publique du Québec, 75 p. <http://www.inspq.qc.ca/publications/default.asp?E=p&NumPublication=538> [accessed June 11, 2009].

(28) Giguère, M. and Gosselin, P. (2006) Impacts des événements climatiques extrêmes sur la santé: examen des initiatives d'adaptation actuelles au Québec, Institut national de santé publique, 27 p., <www.ouranos.ca/media/publication/41_Feuillet_INSPQ_Evenements20Extremes_Adapations_Oct_2006.pdf> [accessed June 11, 2009].

(29) Ministère de la Santé et des Services sociaux. (2004) Quand il fait chaud pour mourir, Ministère de la Santé et des Services sociaux, <http://publications.msss.gouv.qc.ca/acrobat/f/documentation/2004/04-269-01.pdf> [accessed May 2, 2007].

(30) Observatoire Nationale sur les effets du Réchauffement Climatique. (2005) Collectivités locales et changement climatique: êtes-vous prêt ? Un guide pour l'adaptation à l'attention des collectivités locales, ONERC, <http://www.ecologie.gouv.fr/IMG/pdf/guide_adaptation_2^{e}_ed.pdf> [accessed May 2, 2007].

(31) Gouvernement du Québec. Loi provinciale sur la sécurité civile, Gouvernement du Québec, <http://www2.publicationsduquebec.gouv.qc.ca/dynamicSearch/telecharge.php?type=2&file=/S_2_3/S2_3.htm> [accessed May 2, 2007].

(32) Criteria Review for projects of l'Agence d'efficacité énergétique, personal communication.

(33) Canadian Climate Impacts and Adaptation Research Network.

(34) Proceedings of the Symposium on climatic change and forestry, impacts and adaptation, held in Baie-Comeau, on April 20 and 21, 2005.

(35) Bryant, C., Singh, B., Thomassin, P. and Baker, L. (2007) Vulnérabilités et adaptation aux changements climatiques au Québec au niveau de la ferme: leçons tirées de la gestion du risque et de l'adaptation à la variabilité climatique par les agriculteurs, Ouranos, 49 p., <http://www.ouranos.ca/media/publication/149_Bryant1.pdf> [accessed April 24, 2009].

(36) DesJarlais, C. Guide pour décideurs sur l'adaptation aux changements climatiques, Ouranos project in press. Also see economic evaluation tools by UKCIP, <http://www.ukcip.org.uk/resources/tools/> [accessed May 2, 2007].

(37) Singh, B., Bryant, C., André, P. and Thouez, J.-P. (2006) Impact et adaptation aux changements climatiques pour les activités de ski et de golf et l'industrie touristique: le cas du Québec, final report, Ouranos project, 2006, <http://www.ouranos.ca/fr/publications/resultats.php?q=singh&t=> [accessed May 1st, 2009].

(38) Ministère des Transports du Québec. (2006) Presentation made in Sept-Îles, Ministère des Transports du Québec, on June 2, 2006.

(39) Dore, M.H.I. and Burton, I. (2001) The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions, report prepared for the Climate Change Action Fund, Natural Resources Canada.

(40) Milton, J., Lam, K.-H., Trentin, S. and Jean-Grégoire, N. (2005) Vers une réduction de la vulnérabilité des municipalités aux phénomènes atmosphériques extrêmes *in* S'adapter aux changements climatiques au Canada en 2005: comprendre les risques et renforcer nos capacités, Conference of the Canadian Climate Impacts and Adaptation Research Network (C-CIARN), held in Montreal, May 4 -7, 2005.

(41) Mailhot, A., Rivard, G., Duchesne, S. and Villeneuve, J.-P. (2007) Impacts et adaptation aux changements climatiques en matière de drainage urbain au Québec, Institut national de recherche scientifique Eau, Terre et Environnement, 144 p., <http://www.ouranos.ca/media/publication/17_Rapport_Mailhot_infras_2007.pdf> [accessed May 11, 2009].

(42) Fortin, L.G., Turcotte, R., Pugin, S., Cyr, J.-F. and Picard, F. (2007) Impact des changements climatiques sur les plans de gestion des réservoirs Saint-François et Aylmer au Sud du Québec, Canadian Journal of Civil Engineering, 34(8):934-945.

(43) Thuiller, W. (2003) BIOMOD: Optimizing predictions of species distributions and projecting potential future shifts under global change, Global Change Biology, 9:1353-1362.

(44) Ouranos. (2005) Biodiversité et changement climatique, workshop by the Association canadienne-française pour l'avancement des sciences, McGill University, Montreal, May 13, 2005,.

(45) Gerardin, V. and McKenney, D.I. (2001) Une classification climatique du Québec à partir de modèles de distribution spatiale de données climatiques mensuelles: vers une définition des bioclimats du Québec, Direction du patrimoine écologique et du développement durable, Ministère de l'Environnement du Québec, contribution by the Service de la cartographie écologique.

(46) Klein, J.T., Aston, J., Buckley, E.N, Capobianco, M., Mizutani, N., Nicholls, R.J., Nunn, P.D. and Ragoonaden, S. (2000) Coastal-adaptation technologies, Chap. 15 *in* Special Report on Technology Transfer, Intergovernmental Panel on Climate Change, Geneva.

(47) Wrona, F., Prowse, T., Reist, J., Beamish, R., Gibson, J.J., Hobbie, J., Jeppesen, E., King, J., Korhola, A., Macdonald, R., Power, M., Skvortsov, V., Keock, G., Vincent, W. and Levesque, L. (2005) Freshwater Ecosystems and Fisheries, Chap. 8 *in* Arctic Climate Impact Assessment, Cambridge University Press, London, p. 353-452.

(48) Great Lakes and St. Lawrence River Basin Water Resources Regional Council (2005) Entente sur les ressources en eaux durables du bassin des Grands Lacs et du fleuve Saint-Laurent, Conseil régional des ressources en eau des Grands Lacs et du fleuve Saint-Laurent, <http://www.mddep.gouv.qc.ca/eau/grandslacs/2005/Entente.pdf> [accessed May 11, 2009].

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GLOSSARY

Acclimatation
Process by which a species adapts to a new climate.

Active layer
The topmost layer of soil that is subject to freeze/thaw alternations and lies above the permafrost.

Adaptation
Adjustment in natural or human systems in response to climatic stimuli and their effects in order to moderate harm or exploit beneficial opportunities. There are various types of adaptation, anticipatory, autonomous, spontaneous and planned adaptation.

Adaptive capacity
The whole technological, social and financial human resources available to implement effective adaptation measures.

Albedo
A measure of the light reflected by an object. Bright objects have a high albedo, and dark objects a low albedo.

Anoxia
An absence of dissolved oxygen in an aquatic medium or submerged sediment (adjective: anoxic).

Anthropogenic
Resulting from or produced by human activity.

Cooling degree-days
A measure of the difference between the mean temperature for a given day and a reference temperature (22 °C to 25 °C) expressing air conditioning needs.

Cultivar
A variety of a plant species artificially grown having characters making it useful for agriculture, forestry, or horticulture.

Evapotranspiration (rate of)
The quantity of water transformed into vapour from evaporation from the soil and plant transpiration.

Extreme event
An event that is rare according to the statistics on its occurrence in a given area. While the definition of the term "rare" varies considerably, a rare meteorological event should normally be at least in the 10, or 90 percentile tail of the distribution.

Growing degree-days
A measure of the difference between the mean temperature for a given day and a reference minimum temperature that varies by crop and that expresses the quantity of heat available for plan growth.

Growing season
The period during which temperature, humidity and luminosity conditions are adequate for growth of a given crop or forest. It varies according to species and cultivars.

Heating degree-days
A measure of the difference between the mean temperature for a given day and a reference temperature (15º C to 18º C) expressing domestic heating needs.

Hydraulicity
Natural inputs of water in a given period, usually one year.

Hydrological
Concerning the study of water (cycle, balance, regime, condition, event).

Hypolimnion
The lowermost thermal layer of water in a lake or landlocked sea, always cold and with a uniform temperature.

Morbidity (rate of)
The ratio of sick individuals to the total number of a specific population.

Mortality (rate of))
The ratio of deaths to the total number of a specific population.

North Atlantic oscillation (NAO)
A climatological phenomenon of the North Atlantic, the NAO index is the fluctuation in the difference of atmospheric pressure at sea level between the Icelandic Low and the Azores High.

Nunavik
The part of Québec's territory that lies north of the 55th parallel.

Permafrost
All soil or rocks whose temperature remains below 0º C for at least two consecutive years.

Phenology
The study of the variations, as a function of climate, of the life cycles of animals and plants, such as migration dates, the cueing of reproductive behaviour or moulting, date of blossoming or leaf fall (adjective: phenological).

Phytosanitary
Pertaining to the health of plants.

Post-glacial isostatic adjustment
The rise of landmass due to an isostatic adjustment following the melting of the ice that covered the continent during the last Ice Age. In the St. Lawrence valley, the rate of rise is about 2mm/year.

Progradation
The building forward or outward of a sediment construction (for example, a beach) by the deposition of sediments in front of each other rather than on top of each other.

Regulation
The action of managing a stream by reducing the differences between periods of high and minimum flows.

Resource-reliant communities
Said of communities where the exploitation of natural resources represents a moderately large or very large proportion of employment and revenue.

Risk
The combination of the probability of an event occurring and the consequences of the event (for example, the probability of a heavy rainfall multiplied by the magnitude of flooding associated with that particular rain event).

Scenario
Description of what could occur based on a consistent set of assumptions. Climate scenarios describe the possible evolution of an ensemble of climatic variables. Socioeconomic scenarios describe the demographic, economic and social evolutions of the society.

Sensitivity
Degree to which a system is affected, whether positively or negatively, by climate variability or climate change.

SILA network
In Inuktitut, sila means "the climate and the environment around us." The SILA network comprises 75 meteorological stations in the North that record weather information year round including air temperature, the temperature at the soil surface and within the soil, humidity, wind velocity and direction, the concentrations of mercury and ozone in the air, ultraviolet rays and spruce growth.

Smog
This word is a contraction of smoke and fog. This pollution is spread through the atmosphere by aerosols, occurring in part naturally and in part from human activity.

Snow Water Equivalent (SWE)
The depth of water obtained when a layer of snow is completely melted, expressed in millimetres for the corresponding horizontal surface area. Depending on the density of the snow, less or more water is obtained. The rule of thumb for light density snow is that 10 cm of snow is equivalent to 10 mm of water, or a ratio of 10:1.

Spruce stand
A forest composed mostly of spruce trees.

Squat
A reduction in water pressure under a vessel's hull as a function of its speed, causing it to settle deeper than its static mean draught.

Thermokarst
Depressions in and subsidence of land due to voids left in the soil from the melting of the permafrost.

Tundra
A northern territory characterized by the absence of trees and the presence of shrubs, lichens, and mosses.

Vulnerability
The degree to which a system is sensitive and unable to adapt to the negative effects of climate change, including climate variability and extreme events.

Water stress
The stress caused to plants or animals by water deficiency.

Winter maintenance
All measures and techniques used to ensure traffic safety on wet roads, including efforts to deal with snow accumulation, ice and frost so that vehicles traveling on the road surface maintain the best possible traction.

LIST OF ACRONYMS

CDB	Convention on Biological Diversity
CGCM	Coupled Global Climate Model from CCCma (Canadian Center for Climate Modelling and Analysis)
CIP	Canadian Institute of Planners
CRCM	Canadian Regional Climate Model
FCM	Federation of Canadian Municipalities
GCMs	Global climate models
GDP	Gross Domestic Produt
IJC	International Joint Commission
INSPQ	Institut national de santé publique du Québec
IPCC	Intergovernmental Panel on Climate Change
ISQ	Institut de la statistique du Québec
MAMROT	Ministère des Affaires municipales, des Régions et de l'Occupation du territoire, Québec
MAPAQ	Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec
MDDEP	Ministère du Développement durable, de l'Environnement et des Parcs, Québec
MFQ	Ministère des Finances du Québec
MRNF	Ministère des ressources naturelles et de la faune, Québec
MSP	Ministère de la Sécurité publique, Québec
MSSS	Ministère de la Santé et des Services Sociaux, Québec
MTQ	Ministère des Transports du Québec
NLWIS	National Land and Water Information Service
SRES	Special Report on Emission Scenarios
SWE	Snow Water Equivalent
WHO	World Health Organization

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