Implications of a 2°C global temperature rise on Canada's water resources

Athabasca River and oil sands development
Great Lakes and hydropower production

Executive Summary

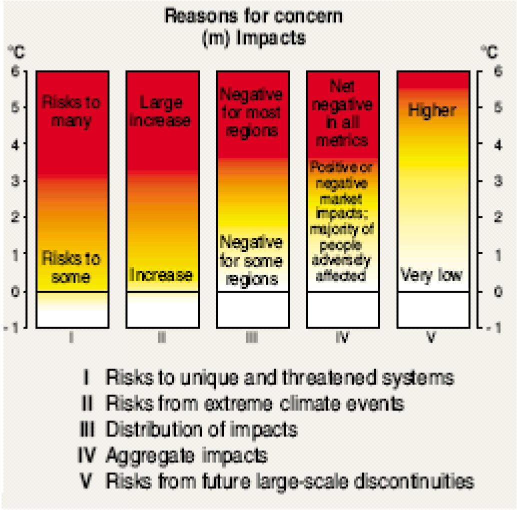
Human activities, notably the release of carbon dioxide (CO_2) into the atmosphere through burning of fossil fuels, have already led to an increase in annual mean global temperature of 0.8°C between 1900 and 2005. Temperature changes have not been uniform globally but have varied over regions. In Canada, mean annual temperature has increased by 1.2°C between 1948 and 2005, while northern British Columbia, the Yukon and the Mackenzie Basin have experienced warming of 2°C or above.

Reviews of scientific studies indicate that the risks arising from projected anthropogenic climate change increase significantly and systematically with increasing temperature (Figure 1). Below a 1°C increase the risks are generally low but in some cases not insignificant, particularly for highly vulnerable ecosystems and/or species. In the 1–2°C increase range risks across the board increase significantly, and at a regional level are often substantial. Above 2°C the risks increase very substantially. In the context of Canada, earlier studies found that a 2°C global warming could lead to loss of favorable habitat for valuable commercial marine species in the Northwest Atlantic, reduction in abundance of key commercial tree species in Ontario, and a 1.5°-10°C warming in the Arctic, threatening plant and animal species and the cultural survival of the Inuit.

Key Findings (I)

- Following the global trend of warming (0.8°C between 1900 and 2005), mean annual temperature over Canada and its regions have also been increasing over recent decades. The rate of warming over Canada (1.2°C between 1948 and 2005, and more in some regions), has been substantially greater than the global rate.
- In recent decades, mean annual temperatures have been increasing over the Athabasca River basin and the Great Lakes- St. Lawrence River regions. Lake levels and river flows have diminished as a result of increased evaporation under the warmer temperatures and for the Athabasca, retreat of glaciers in the headwaters (Table 1).

Figure 1 Risks of climate change damage with increasing degrees of global warming (IPCC, 2001).



The present study complements the existing literature on the impacts of 2°C global warming on Canada by examining the impacts of climate change on (i) the Athabasca River and oil sands production and (ii) the Great Lakes and hydropower production. These case studies show that, like the rest of the world, the Athabasca River and the Great Lakes regions have seen increases in mean temperatures and changes in precipitation patterns in recent decades. As a result, flows in the Athabasca River have decreased by about 20% between 1958 and 2003, and water levels in the Great Lakes remained consistently low between 1998 and 2001 during record hot and dry years (Table 1). Observed trends are reasonably reliable harbingers of changes in coming decades. Climate models project that global warming is likely to reach 2°C above pre-industrial times by the period 2026-2060. By this time, different regions in Canada could warm by 2°-6°C. In particular, the minimum flows in the Athabasca River are likely to diminish by 7-10% and water levels in the Great Lakes could fall by 0.08 – 1.18 m. In the case of the Great Lakes – St. Lawrence region, a 2°C global warming would translate into a decrease of 2-17% in hydropower production on the St. Lawrence River. Earlier estimates show that such warming could result in annual loss in electricity production in Ontario of $240 million to $350 million (Canadian dollars at 2002 prices). In addition, climate change is likely to bring an increased frequency and severity of hot spells in summer. This would further increase the region’s peak summer energy demand, potentially resulting in more brownouts. At the same time, in order to meet ever-increasing energy demands, reduction in hydropower production could mean increased power generation from fossil-fuel or nuclear power plants, thus accelerating climate change and generating other environmental problems.

Key Findings (II)

- Under a 2°C global warming, the annual runoff and minimum flows of the Athabasca River are expected to continue to decline. The projected rate of water use in the oil sands projects from the Athabasca River will be even more unsustainable. The combined impacts of water withdrawals from oil sands project and climate change could threaten the productivity of the Peace Athabasca Delta, compromise the fair sharing of water with downstream jurisdictions in the Mackenzie River system, and fail to meet Alberta's flow requirements downstream of the oil sands projects for ecosystem support.

- Under a 2°C global warming, water levels in the Great Lakes are expected to fall. Hydropower production from the Great Lakes is likely to be reduced, leading to economic losses and potential increase in power generation from fossil-fuel or nuclear power plants, thus accelerating climate change and generating other environmental problems.

Table 1 Observed and projected changes in the Great Lakes – St. Lawrence River and Athabasca River regions.

	Observations over the past century		Projections for 2°C global warming	
	Great Lakes – St. Lawrence River	**Athabasca River**	**Great Lakes – St. Lawrence River**	**Athabasca River**
Temperature	+0.5°C[a]	+1.5 to +1.8°C[c]	+2.2 to 4.0°C	+3.4 to +3.8°C
Lake levels / Annual runoff	Low lake levels in response to recent record hot and dry years	-19.8%[e] (annual runoff)	-0.08 to -1.18m (lake levels)	-3 to -30% (annual runoff)

Data is presented for periods during which data is available. This applies throughout the report.
a For the period 1948-2005; b For the period 1895-1995; c For the period 1961-2000; d For the period 1971-2000; e For the period 1958-2003.

In the case of the Athabasca River, the projected rate of water use in the oil sands projects will be even more unsustainable under climate change. The combined impacts of water withdrawals from oil sands project and climate change will have serious consequences beyond the area of the projects themselves. These include:

- threats to the productivity of the Peace Athabasca Delta,
- compromise of fair sharing of water with downstream jurisdictions in the Mackenzie River system, and
- downstream water quality and ecosystem degradation.

Recommendations

Climate change and water withdrawals need to be taken into account in an agreement between the three provinces and two territories (B.C., Alta., Sask., NWT, and Yukon) concerning sharing of the waters of the Mackenzie River system and protection of water quality.

In addition, ***Alberta should consider withholding approval of any oil sands projects and their water taking permits*** until:

i) substantial water conservation measures are introduced, and
ii) assurances can be given that instream flow needs to protect ecosystems in the lower Athabasca River can be met in face of the changing climate.

Key Recommendations

- Climate change and water withdrawals need to be taken into account in an agreement between the three provinces and two territories (B.C., Alta., Sask., NWT, and Yukon) concerning sharing of the waters of the Mackenzie River system and protection of water quality.
- Alberta should consider withholding approval of any oil sands projects and their water taking permits until:
  - substantial water conservation measures are introduced, and
  - assurances can be given that instream flow needs to protect ecosystems in the lower Athabasca River can be met in face of the changing climate.
- Plans should be developed by the province of Ontario for alternative energy projects to compensate for decline in hydropower from the Great Lakes system and greater summer peak demand in a warming climate.
- Climate change impact risks need to be incorporated into water and energy management plans, in order to prepare for the uncertainties associated with climatic and hydrological changes that we can no longer avoid.

Water availability in the populated and large water-use regions of Canada is expected to fall as a result of climate change. At the same time, energy demands and oil sands production in Canada are expected to continue to rise. Increased demand and use of fossil fuel energy in Canada and for exports are the leading causes of the continuous growth in the country's greenhouse gas emissions, only accelerate the effects of climate change. One-sixth of Canada's increase in greenhouse gas emissions growth since 1990 has come from the country's increased oil and gas exports to the United States, and up to half of the new growth in emissions by 2010 is expected to come from the oil sands.

It is in the best interest of government authorities, industry and citizens to take immediate actions to manage energy demand, improve energy efficiency, increase the use of renewable energy sources and require carbon neutral energy production. At the same time, water and energy managers, electricity suppliers and regulatory bodies need to incorporate climate change into their management plans, in order to prepare for the uncertainties associated with climatic and hydrological changes.

Dangerous Levels of Climate Change:
Canada and its Water Resources

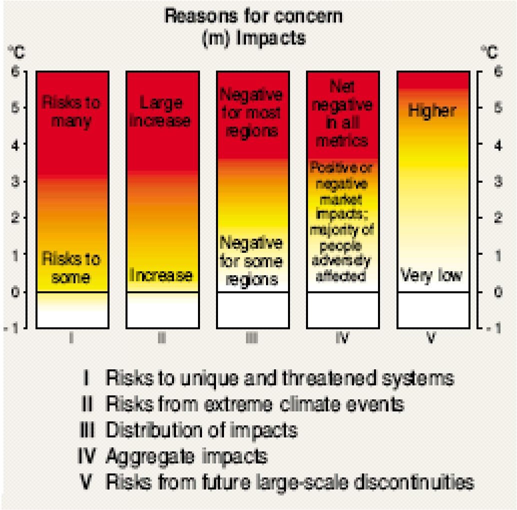
1. A Global Definition

The UN Framework Convention on Climate Change sets the policy framework for international efforts to tackle the climate problem. Its guiding principle is to avoid "dangerous anthropogenic interference with the climate system." The basis for determining what constitutes "dangerous anthropogenic interference" varies among regions—depending both on the local nature and consequences of climate change impacts, and also on the adaptive capacity available to cope with climate change (IPCC, 2001). Developing countries, small states and Arctic communities are especially vulnerable to impacts of climate change, such as sea level rise and increase in frequency of extreme weather events, and some areas are already experiencing dangerous interference.

Human, or anthropogenic, activities, notably the release of carbon dioxide (CO_2) through burning of fossil fuels in the atmosphere, have already led to an increase in annual mean global temperature of 0.8°C between 1900 and 2005 (Hansen, 2005). This relatively small amount of warming has already led to observable changes worldwide. Across the globe, species are changing their phenology and geographical distribution. Heat waves are occurring with greater intensity and frequency, glaciers are melting throughout most of the world, and drought is intensifying in many regions (Warren, 2006). Sea surface temperature is increasing in response to anthropogenic warming (Santer et al., 2006), and is fuelling more intense tropical cyclones (Emmanuel, 2005).

Reviews of scientific studies indicate that the risks arising from projected anthropogenic climate change increase significantly and systematically with increasing global mean temperature (Hare, 2006; 2003). Below a 1°C increase the risks are generally low but in some cases not insignificant, particularly for highly vulnerable ecosystems and/or species (Figure 1). Above a 1°C increase risks increase significantly, often rapidly for vulnerable ecosystems and species. In the 1–2°C increase range risks across the board increase significantly, and at a regional level are often substantial. World oceans and Arctic ecosystems could be damaged (Warren, 2006). Above 2°C the risks increase very substantially, involving potentially large numbers of extinctions or even ecosystem collapses, major increases in hunger and water shortage risks as well as socio-economic damages, particularly in developing countries (Hare, 2006). By a 3°C increase, few ecosystems could adapt (Warren, 2006).

Figure 1 Risks of climate change damage with increasing degrees of global warming (IPCC, 2001).



Limiting global greenhouse gas atmospheric concentrations to levels that would limit temperature increases to no more than 2°C global average warming above pre-industrial times has been adopted as a framework for the European Union, as well as by other international organizations, such as the World Wide Fund for Nature (WWF) and the World Conservation Union (IUCN). Research studies show that a 2°C global warming is not far away in the future - results from global climate models show that a 2°C warming is likely to be reached between the years 2026 and 2060 (New, 2005).

2. Towards a Canadian Definition

Between 1948 and 2005, Canada has warmed by 1.2°C (Environment Canada, 2006a). This warming has not been uniform across the country. During the same period, northern British Columbia, the Yukon and the Mackenzie Basin experienced the largest warming - of 2°C and above - while Atlantic Canada experienced the least warming – of 0.1°C. Projections of climate models indicate that, at the time of 2°C global warming, different regions across Canada are likely to warm by 2°-6°C above pre-industrial levels (CCIS Project, 2003).

Recent studies have highlighted the impacts of a 2°C global warming on various aspects of ecosystems and livelihoods in Canada (Rosenstrater, 2005; Tin, 2005). In the Northwest Atlantic, 2°C global warming is likely to lead to an increase in sea surface temperature of 1.5-2.2°C which could encourage the spread of invasive species but reduce the extent of favorable habit for valuable commercial species (Van Guelpen et al., 2005). Warmer conditions over Ontario could lead to declines in dominance for key commercial tree species such as black spruce, jack pine, and sugar maple. Increased stress brought about by change in climatic conditions will presumably make species more susceptible to disease and pest problems. In the future, it is possible that only the more climatically tolerant species persist at a site, or species may become relegated to refugia where conditions are still satisfactory (Malcolm et al., 2005). In the Arctic, where a cover of snow and ice exist quasi-permanently, any warming that reduces the extent of these cold white surfaces could result in amplified warming in the Arctic. As a result, a global warming of 2°C is expected to result in a warming of 4°-10°C in the winter and 1.5°-3.5°C in the summer in the Arctic (New, 2005), potentially leading to the disappearance of numerous plant and animal species. For the Inuit and other Arctic Indigenous population, climate change is a matter of cultural survival (Watt-Cloutier et al., 2005). Their uniqueness as people with cultures based on harvesting marine mammals, hunting or fishing, is at risk because climate change is likely to deprive them of access to their traditional food sources. While they experience stress from other sources that threatens their lifestyles and cultures, climate change magnifies these threats (ACIA, 2005).

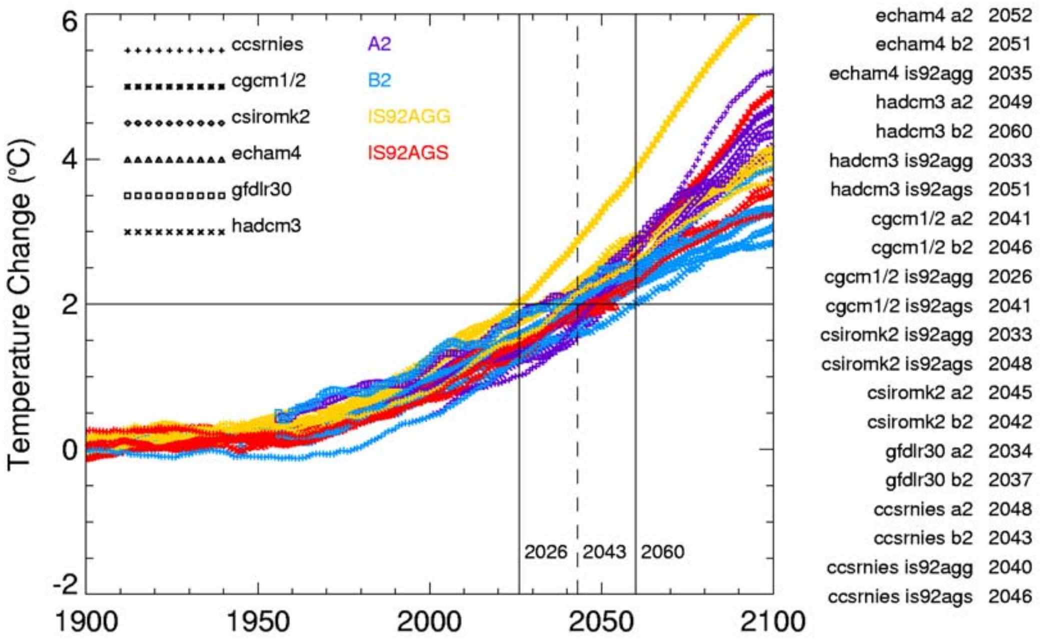
The present study aims to contribute towards the process of defining a level of dangerous climate change in Canada by examining the impacts of a 2°C global warming on the nation's freshwater resources using case studies from the Athabasca River and the Great Lakes region. Canada has a relative abundance of water, possessing 9% of the world's renewable freshwater, yet only 0.5% of the global population. Despite Canada's abundance of water, this valuable resource is now under pressure from growing and often conflicting human requirements, which is likely to be exacerbated by the effects of climate change. (Hengeveld et al., 2005; Lemmen and Warren, 2004). Climate models project that, during the coming decades, water resources are likely to become more abundant in northern Canada but less abundant and more variable in southern Canada. Increased evaporation of surface water under warmer climates and altered precipitation patterns are expected to cause summer droughts in the interior of southern Canada to become more frequent, more intense, and of longer duration. In western Canada, these shortages are likely to be exacerbated by the gradual disappearance of alpine glaciers that currently provide much of the freshwater input in regional streams and rivers in summer (Hengeveld et al., 2005; Lemmen and Warren, 2004).

Against this backdrop, the present study examines the impacts of climate change on (i) the Athabasca River and oil sands production, and (ii) the Great Lakes and hydropower production. The study focuses on a 2°C warming but also includes results from a 1.5°C and 4°C to help to identify needs for short- and long-term planning, respectively.

The identification of the period of a 2°C warming is based on work conducted by New (2005) where monthly data from six coupled ocean-atmosphere global climate models forced by scenarios of future greenhouse gas emissions were examined. The IS92a and SRES emission scenarios published by the UN Intergovernmental Panel on Climate Change (IPCC) in 1992 and 2000 were used. These scenarios describe a wide range of future population, socio-economic development possibilities and they all have equal probabilities. For each model, control-run surface temperature data were used to calculate a "pre-industrial" mean temperature climatology, and these were spatially averaged to calculate a global mean pre-industrial surface temperature. For each climate change simulation, the global temperature fields were spatially averaged to calculate time-series of global mean annual temperature, which were then differenced from the "pre-industrial" global mean temperature. The resulting global mean temperature-anomaly series were then smoothed with a 21-year moving average, and the date at which the 21-year mean global temperature anomaly exceeded 2°C was taken as the time of 2°C global temperature change. The time at which the simulated global mean temperature exceeds the control run global mean by 2°C (Y2C) ranges from between 2026 and 2060 (Figure 2). The inter-model spread for a single scenario (e.g. B2) is nearly as large as the total spread; however, there is a tendency for the scenarios with greater accumulated radiative forcing (IS92aGG, A2) to exhibit a greater rate of warming, and an earlier Y2C.

Based on interpreting results from Figure 2, we consider it appropriate to use GCM output for the periods centered on 2030, 2050 and 2090 as proxies for 1.5°C, 2°C and 4°C global warming respectively in this study.

Figure 2. Global mean annual temperature anomalies relative to control climatology, smoothed with a 21-year moving average. Vertical lines indicate the range in time at which the 21-year global mean temperature anomaly exceeds +2°C. Figures on the right show the time at which the 21-year mean global temperature anomaly exceeds +2°C for each GCM-scenario combination.



echam4 a2	2052
echam4 b2	2051
echam4 is92agg	2035
hadcm3 a2	2049
hadcm3 b2	2060
hadcm3 is92agg	2033
hadcm3 is92ags	2051
cgcm1/2 a2	2041
cgcm1/2 b2	2046
cgcm1/2 is92agg	2026
cgcm1/2 is92ags	2041
csiromk2 is92agg	2033
csiromk2 is92ags	2048
csiromk2 a2	2045
csiromk2 b2	2042
gfdlr30 a2	2034
gfdlr30 b2	2037
ccsrnies a2	2048
ccsrnies b2	2043
ccsrnies is92agg	2040
ccsrnies is92ags	2046

3. The Athabasca River, the Great Lakes and Climate Change

The case studies in the following chapters are primarily based on reviews of scientific literature with an emphasis to link the wealth of existing information to different levels of global warming. Some new analysis is also included. They show that, like the rest of the world, the Athabasca River and the Great Lakes regions have seen increases in mean temperatures and changes in precipitation patterns in recent decades. As a result, flows in the Athabasca River have decreased by about 20% between 1958 and 2003[1], and water levels in the Great Lakes remained consistently low between 1998 and 2001 during record hot and dry years. Our review of all the climate change impact assessments in the Great Lakes region shows that there is a large body of research that supports the point that water levels are likely to decline under climate change. Recent estimates indicate that, under 2°C global warming, water levels in the Great Lakes could fall by 0.08 – 1.18 m, leading to a 2-17% loss in hydropower production in the St. Lawrence River. On the other hand, by the time of 2°C global warming, the minimum flows in the Athabasca River are expected to diminish by 7-10%. Flows will be insufficient to satisfy the needs of oil sands production, as well as other industrial, commercial, agricultural, municipal and environmental users, including the biologically rich Peace Athabasca Delta.

Water availability in the populated and large water-use regions of Canada is expected to fall as a result of climate change. At the same time, energy demands and oil sands production in Canada are expected to continue to rise. The National Energy Board estimates that oil sands production would increase by nearly 200% by the year 2010 (NEB, 2006), while at the same time, national energy demand would increase by about 20% (NEB, 2003). Increased demand and use of energy will lead to increase in emissions of CO_2 and other greenhouse gases and will only accelerate the effects of climate change. Already, between 1990 and 2004, Canada’s greenhouse gas emissions have increased by over 26% (Environment Canada, 2006b). One-sixth of this increase has come from the country’s increased oil and gas exports to the United States[2], and up to half of the new growth in emissions by 2010 is expected to come from oil sands productions[3].

It is in the best interest of government authorities, industry and citizens to take immediate actions to manage energy demand, improve energy efficiency, increase the use of renewable energy sources and require carbon neutral energy production. At the same time, water and energy managers, electricity suppliers and regulatory bodies need to incorporate climate change into their management plans, in order to prepare for the uncertainties associated with climatic and hydrological changes.

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[1] Data is presented for periods during which data is available. This applies throughout the report.

[2] According to Canada’s national inventory on greenhouse gases (GHG) 1990-2004 (Environment Canada, 2006b), national GHG emissions increased by 159 MT between 1990 and 2004. GHG emissions associated with exports oil and gas increased by 26 MT, making up16%, or one-sixth of the increase in national emissions.

[3] According to Canada’s third national report on climate change (Government of Canada, 2001), national GHG emissions for 2010 were projected to be 98 MT above 1990 levels. According to the Pembina Institute (Woynillowicz et al., 2005), GHG emissions from oil sands productions are projected to reach 45-50 MT by 2010.

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Oil and water – Will they mix in a changing climate?
The Athabasca River story

James P. Bruce

1. Abstract[4]

Unless major efforts are made soon to reduce global greenhouse gas emissions, a 2ºC rise in global mean temperature by about mid century, and 4 degrees increase by late in the century, are expected. Central and northwestern parts of Canada will warm even more rapidly. This effect has already been observed with the greenhouse gas-driven climate change to date. This has resulted for the Athabasca River basin, in up to three times the 0.6ºC increase in average global temperature rise, observed to 2000. With a 2ºC rise in global mean temperature by 2050, the increase in the Athabasca River basin is projected to be 3.5ºC to 4ºC. With little change in precipitation, shrinking glaciers in the headwaters, and increased evaporation with higher temperatures a decline in flows of the Athabasca River has been measured just below Fort McMurray in the period 1972-2004. This trend is expected to continue with continued increases in greenhouse gas concentrations.

This river is the main source of water for oil sands developments, which use large amounts of water to extract oil from bitumen. For deposits deeper than about 75m, the water is used in the "in situ" method through steam injection. For shallower deposits, water is needed for mining and processing the bitumen scraped from the landscape, along with peat, trees and other vegetation, in strip mining operations. The latter process uses 2 to 4.5 barrels of water for every barrel of oil produced, although several companies are investigating measures to conserve water. The oil sands yielded more than one million barrels/day in 2005, and the known deposits, in an area larger than England, make Alberta second only to Saudi Arabia in oil reserves. Projected production by 2015 is expected to more than double.

Climate change is exacerbated by carbon dioxide and methane from oil sand developments. This results in the largest single source of growth of greenhouse gas emissions in Canada. At the same time, lower flows of the Athabasca River with climate change, and increased water withdrawals as new oil sands projects develop, threaten instream flow needs in the lower Athabasca River. These factors together put the projects and their water supply on a collision course. Instream flow needs are critical for protecting downstream ecosystems and for the First Nations and other communities who rely on fishing, hunting and trapping in the lower Athabasca, including in the Peace Athabasca Delta. The Delta is also being adversely affected by warmer winters.

Withdrawals for oil sands development, from the river, and adjacent groundwater which affects the river, have been projected to reach as much as 19m^3/sec. with planned and projected developments. Minimum winter flows in recent years have dropped to as

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[4] Note: This review has been prepared in a semi-popular style, based on sound scientific findings. It is hoped that it will be accessible to a wide audience.

low as $75m^3$/sec (2001-2002). Yet projects have apparently been approved on the basis that the long term average winter flow has been $169m^3$/sec, without taking downward trends into account. Projections of Athabasca River flows to 2050 have been made. This is about the latest expected date of 2ºC average global warming, and the expected time of near completion of oil sands bitumen extraction. These projections use global climate model results driving a proven hydrologic model. They suggest further declines in annual runoff of up to 30%, but additional declines in minimum flows of 7% to 10%. The Alberta government has proposed calculation of instream flow needs (IFN) on the river below the project, which, in a Yellow alert case (short-term impacts) would require that total withdrawals be limited "voluntarily" to 10% of minimum flow, i.e. $7.5m^3$/sec on occasion in winter 2001-2002, and up to 10% less in future. This is far less than the $19m^3$/sec (or even $11.2m^3$/sec in a more conservative estimate) expected to be required with full project developments. Indeed, flows less than $110m^3$/year have been observed in 10 of the past 24 years, requiring some withdrawal reductions under this guideline even with the conservative estimate of requirements. Thus, presently projected rates of oil sands development will have to be curtailed if reasonable instream flow requirements are to be met downstream. There are many scientific uncertainties surrounding these issues discussed briefly in the text, which should also lead to a precautionary approach in approving additional water withdrawals.

In addition to the widespread, devastating, environmental effects in the area of the projects themselves, the combined impacts of project water withdrawals and climate change can have other serious consequences. These include:

- threats to the productivity of the Peace Athabasca Delta,
- compromise of fair sharing of water with downstream jurisdictions in the Mackenzie River system, and
- downstream water quality and ecosystem degradation.

The many measures and research activities advanced by the Pembina Institute (Griffiths, et al., 2006) should be adopted to reduce the environmental footprint of oil sands development.

Climate change and water withdrawals need to be taken into account in an agreement between the three provinces and two territories (B.C., Alta., Sask., NWT, and Yukon) concerning sharing of the waters of the Mackenzie River system and protection of water quality.

In order to assess the compatibility between oil sands projects and ecosystems' water needs, consideration was given to:

- the projected water requirements of fully developed oil sands projects (estimated 11.2 to $19m^3$/sec);
- Alberta's Instream Flow Needs guidelines which have been defined in order to protect downstream ecosystems; and
- the minimum flows of the Athabasca River in the past 25 years.

It was found that, even at the lower end of the water withdrawals from oil sands projects, there would have been 10 times during the past 25 years where the minimum flows of the Athabasca River would have been insufficient to avoid short term impacts on ecosystems. For longer term ecosystem impacts, the recommended water restrictions on oil sands project withdrawals, indicate that minimum flows would not have met full development needs in 34 of the past 35 years. (See fig. 3)

Climate change is projected to continue to decrease the mean and minimum flows of the Athabasca River at Fort McMurray. Inadequate water will be available for full oil sands development, unless significant water savings can be achieved in the projects.

2. Introduction: Purpose of study

A globally averaged warming of 2ºC rising to 4ºC are expected to occur by the middle and before the end of this century, unless significant efforts are made in all countries to reduce greenhouse gas emissions. Central and northwest Canada have been experiencing much greater warming than the global average to date, and this is expected to continue, with average temperatures in this region increasing 3.5ºC to 4ºC by mid-century.

The Intergovernmental Panel on Climate Change (IPCC), in its Third Assessment Report (2001) summarized studies that showed that up until the mid 1960s, natural forcing factors, such as changes in sun's energy, earth's orbit and volcanic emissions, had significant effects along with greenhouse gases on the global mean temperature fluctuations, and related climate. However, since about 1970, the rising concentrations of greenhouse gases have been the almost exclusive cause of the rapid warming observed. These IPCC findings have been reinforced by later studies (Meehl, et al., 2004) (Knutson, et al., 2006). Greenhouse gases and aerosol concentrations will undoubtedly be the driving factors on changes in earth's climate, over this century, and beyond. Thus, observed trends since 1970 in geophysical factors, such as temperature and precipitation, river flows and water levels, are reasonably reliable harbingers of changes in coming decades.

This is especially so if extension of trends since 1970 are consistent with projections by Atmosphere-Ocean General Circulation Models (AOGCMs) driven by scenarios of present and future greenhouse gas emissions and concentrations.

The Athabasca River, and oil production involving river water, have two important connections to human-induced climate change. The first, and perhaps most obvious, are the emissions of greenhouse gases from the energy industry in the basin, a major contribution to the global burden. The second is the impact of the changing climate on flows of the Athabasca River, the main source for the water-voracious oil sands projects. Both of these issues have been previously examined separately. The Oil Sands have been studied from an environmental perspective by Pembina Institute researchers including suggested means of reducing greenhouse gas emissions. (Griffiths, et al., 2006, Woynillowicz and Severson-Baker, 2006). The impact of climate change on the Athabasca River and the Peace Athabasca Delta has been the subject of a number of scientific papers (Burn, et al., 2004, Gan and Kerkhoven, 2004, Pietroniro, et al., 2006, Woo and Thorne, 2003 and Schindler and Donahue, 2006).

However, there has been little analysis of the combination of the trends in water availability due to climate change, and the trends in water demand for the oil sands project. Nor has there been much analysis of downstream impacts of these combined stresses on water quantity, quality and ecosystem sustainability. This analysis addresses these issues to the extent that available data and knowledge permit. Uncertainties remain. This paper suggests actions required to reduce adverse impacts.

3. Description of the oil sands projects – greenhouse gas emissions

3.1 Description

The Wall Street Journal headline was “As prices surge, oil giants turn sludge into gold” in an article by Russell Gold, reprinted by the Globe and Mail, 27 March 2006. The sub-heading was “France’s Total (Oil Company) leads push in northern Alberta to process oil sands”, with other international major companies close behind in percentage of oil reserves. Announced investment in oil sands recovery from 2006-2015 amount to $125 billion. (NEB, 2006)

Two types of operations are undertaken as described by Gold:

- One uses “colossal” drum boilers to generate steam, which is pumped underground to about 90m. This produces a tar-like mix of oil and sand from which the crude is extracted.
- In other nearby operations, on oil-soaked sands within 75 metres of the surface, bitumen is obtained by “scraping away an ancient forest of spruce and poplars” and large areas of peat and muskeg. These “scrapings” are dumped into 2-storey trucks which, “when fully loaded, weigh as much as a Boeing 747”.

The first of these processes is usually called “in situ” recovery either a Cyclical Steam Simulation (CSS) or Steam Assisted Gravity Drainage (SAGD) process. (Griffiths, et al., 2006). The second is termed mining or sometimes “strip mining”. The mining projects are around Fort McMurray, mostly to the north and close to the Athabasca River. “In situ” recovery is practiced in the more southern Cold Lake region in the Beaver River watershed on the Alberta-Saskatchewan border, as well as adjacent to the area being mined near the Athabasca River. Some of these projects are south east of Fort McMurray and in the Peace River Basin. (see Fig. 1)

Figure 1
Location map of oil sands projects

Eric Leinberger, *University of British Columbia*

3.2 Water Use

Both processes use large amounts of water. The mining operations leading to synthetic crude oil, or upgraded bitumen, uses 2 to 4.5 m^3 of water (net) per cubic metre of synthetic crude oil (Griffiths, et al., 2006). Water allocations by Alberta to mining projects from the Athabasca River add up to 359 million m^3 per year (twice the amount of water required for Calgary); although to 2005 such allocations have not been fully used. Additional licenses for ground water, surface waters and diversions amount to 159 million m^3 per year. A further 50% increase in the total water requirements is expected when currently planned projects proceed. The Alberta EUB (2006) expects that production of bitumen will more than double by 2015. Only about 10% of the water used is returned to the river since the water becomes heavily polluted in the process and is held in huge storage ponds. Reclamation methods have not yet proven viable (Alberta EUB, 2004). These projects also have other significant impacts on water resources. To begin mining operations, the companies must drain wetlands, peatlands, muskeg and forests, interrupting streams and groundwater to prevent flooding of the mine sites.

The mining operations result in “enormous volumes” (Gold, 2006) of liquid waste. These wastes are stored in large ponds, really lakes, with high concentrations of metal pollutants and napthenic acid, often used as a drying agent in paints. These lakes now cover 50km^2 and are expected to extend over the landscape for many years to come since, according to the National Energy Board (2004), “There is currently no demonstrated means to reclaim fluid fine tailings.”

“In situ” production also uses less water but substantial amounts of both groundwater and surface waters to meet steam requirements. Waters taken are mostly not directly from the Athabasca River. This process uses typically 0.2m^3 to 0.5m^3 to extract 1m^3 of oil from the bitumen and additional water for the upgrading process where this is undertaken. Bitumen reserve areas for “in situ” operations cover 14 times as much land as that suitable for mining. However, the recovery rate from mining is much higher than from “in situ” recovery (Griffiths et al., 2006). Total in situ and mineable reserves are estimated at 174 billion barrels. Only 2.8% of the total available had been extracted by 2005 (Alberta EUB, 2004).

These environmental damages related to bitumen production by both mining and in situ production could eventually affect an area about 1/5 the size of Alberta, or about the size of England or Greece, since this is the extent of the deposits. The deposits are all in the boreal forest region.

3.3 Emissions – Greenhouse Gases and others

By 2015, the Fort McMurray region (population 61,000) is projected to emit more greenhouse gases than Denmark (population 5.4 million). This does not take into account the loss of carbon sequestration by the peat lands and forests being destroyed, nor the emissions from these natural sources when, or immediately after, they are scraped away. Between 1990 and 2000, oil sands production was the fastest growing single emission source in Canada, up 47%, making it difficult to meet national Kyoto targets. This trend has continued unabated and total emissions are projected to rise from 28 to 67 Mt/year between 2002 and 2015. (NEB, 2006).

Oil sands production exceeded 1 million barrels per day in 2005, originally not projected to occur until 2012 (CBC, 1 May 2006). 59% was from mined areas and 41% from in situ production. (EUB 2006) Sulphur dioxide and NOx emissions are such as to cause acid deposition in downwind areas especially in northern Saskatchewan. Small particles with harmful health effects ($PM_{2.5}$) as they lodge in human and animal lungs, are also likely to have serious downwind effects as ground is laid bare. Bare ground has been shown in USA to be a large source of small, $PM_{2.5,}$ particles. (Saxton, 1995)

There is no sign that the growth in exploitation of the oil sands will slacken. Continuing high oil prices globally, with western Canada now holding the largest known reserve after Saudi Arabia, means large profits for the companies involved and an economic and employment boom in Alberta. As Alberta's Energy Minister put it, "It's worth it. There is a cost to it, but the benefits are substantially greater". (Globe and Mail, 27 March, 2006) Development is encouraged by low provincial royalty charges (1% until producers recover capital costs), and a federal accelerated capital cost allowance. (Reguly, 2006)

Many, concerned with greenhouse gases and climate change, had hoped that higher prices would reduce oil consumption. So far there has been little evidence of this in North America, but much evidence that the higher prices have driven oil producers to exploit dirtier "unconventional" sources with much higher energy input costs and emissions per barrel of oil than conventional fields. This is particularly evident in Alberta, but is also occurring in the very large unconventional sources of Venezuela. Most of the Canadian oil sands production is exported to USA. Bitumen produced from mining was upgraded to synthetic crude oil (SCO) amounting to 200 million barrels in 2005. In situ production was mainly not upgraded and marketed as bitumen. (Alberta EUB 2006)

For more information, the reader is referred to a comprehensive description of the oil sands projects and their environmental footprint which has been published by the Pembina Institute (Griffiths, et al., 2006), as well as Alberta EUB reports.

4. Athabasca River and Climate Change

4.1 Description

The Athabasca River is the southernmost tributary of the Mackenzie River which drains to the Arctic Ocean, from Canada's largest watershed (1.7 million km^2). The Athabasca rises on the east slopes of the Rocky Mountains from the Athabasca glacier, flows across central Alberta, then turns northward near Fort McMurray, through the Peace Athabasca Delta into Lake Athabasca. The Delta, one of the most productive in the world, is also fed by the Peace River which arises in the British Columbia mountains and flows eastward across northern Alberta. The Peace River flows are affected by a large dam and reservoir in British Columbia, but the Athabasca is an unregulated river. Its drainage basin to the gauge below Fort McMurray is 133,000 km^2. The oil sands projects draw water from the river mostly between Fort McMurray and the Delta. The Athabasca contributes 7% of the flow of the Mackenzie River, the Peace 24%, and the Liard 27% (Fig. 1).

4.2 Historic River Flows and Water Demands

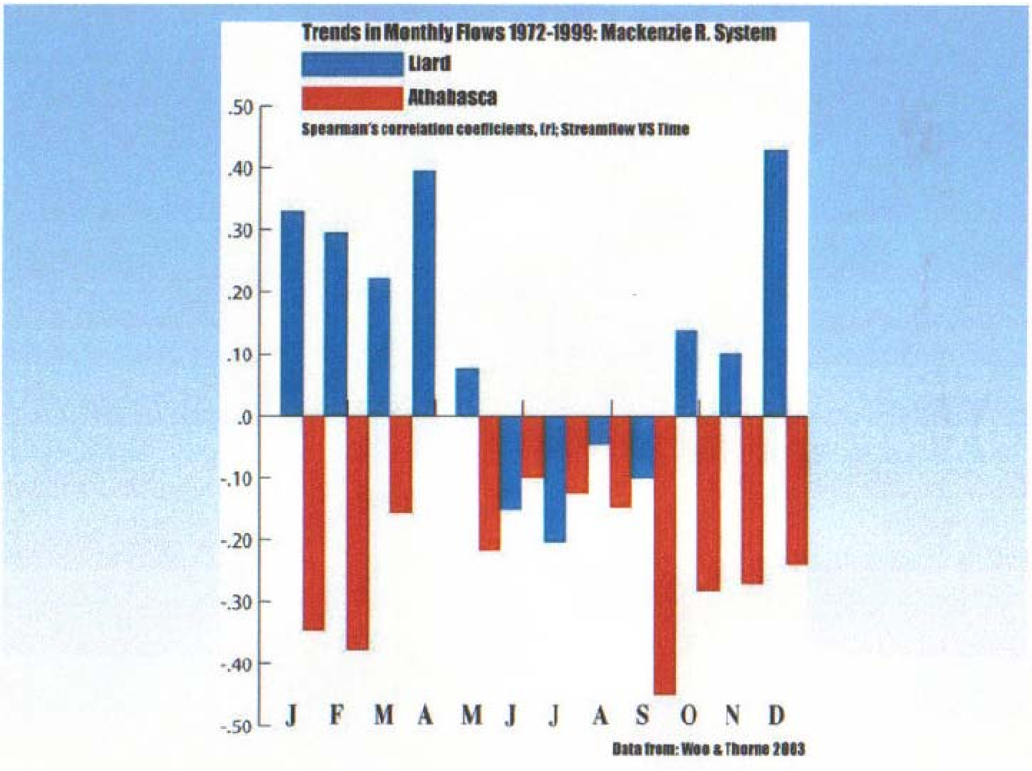
The annual average flow (1961-2000) of the Athabasca River at the gauging station below Fort McMurray, was a very substantial 630 m^3/sec. It is the winter low flow period, averaging 169 m^3/sec over this period, mostly under an ice cover, which is of most concern in connection with oil sands water withdrawals. It should be noted that Environmental Impact Statements for some individual Oil Sands Projects base their water takings on flow and climate data averaged for the period 1953-1999. (e.g. CNRL-Horizon Oil Sands Project Statement, 2003) The total projected water takings are estimated by the companies to be 8.5 to 11.5% of the minimum flow calculated on this historic average. (CNRL 2003) Since in 2004, the predicted freshwater use, including groundwater for the in situ enhanced oil recovery was less than 1/3 of actual use (5.5 mill m^3 vs. 16.2 mill m^3 actual) (Griffiths, 2006), it is probably reasonable to assume that the higher percentage (11.5% of average minimum) or more, is a likely outcome. 11.5% of 169 m^3/sec is 19.4 m^3/sec.

The Oil Sands Mining activities, however, are not the only withdrawals authorized on the Athabasca River. They represent 2/3 of the licensed allocations, with other industrial and commercial users being another 23%. Agricultural and municipal allocations account to about 1.5%. (Griffiths, et al., 2006) These are mostly before the river reaches Fort McMurray, and the oil sands area located beyond the "below Fort McMurray" gauging station.

4.3 *Observed Trends in Athabasca River Flow*

Several studies have documented the trends in flow of the river (Burn, Aziz and Pietroniro, 2004, Woo and Thorne, 2003, Schindler and Donahue, 2006). Woo calculated Spearman's correlation coefficients which, with declining flows over time, are negative. These were indeed negative for every month but April (zero) for the 1972-1999 period. (Fig. 2)[5] The declines were statistically significant, at the 10% level, in the critical low flow months of January and February, and substantially negative but not significantly so in November and December.

Figure 2
Trends in Monthly Flows 1972-1999 Mackenzie R. System



In the Schindler and Donahue 2006 paper, the summer flow at the below Fort McMurray gauge declined 19.8% from 1958-2003, but 33.3% (significant at 5% level) since 1970, when greenhouse gases became the dominant driving force in the changing climate. This paper also provides analyses of past trends in temperature, snowfall, etc. over the Prairies consistent with declining Athabasca River flows. The work of Burn, Aziz and Pietroniro (2004) considered trends at 13 gauging stations in the Athabasca

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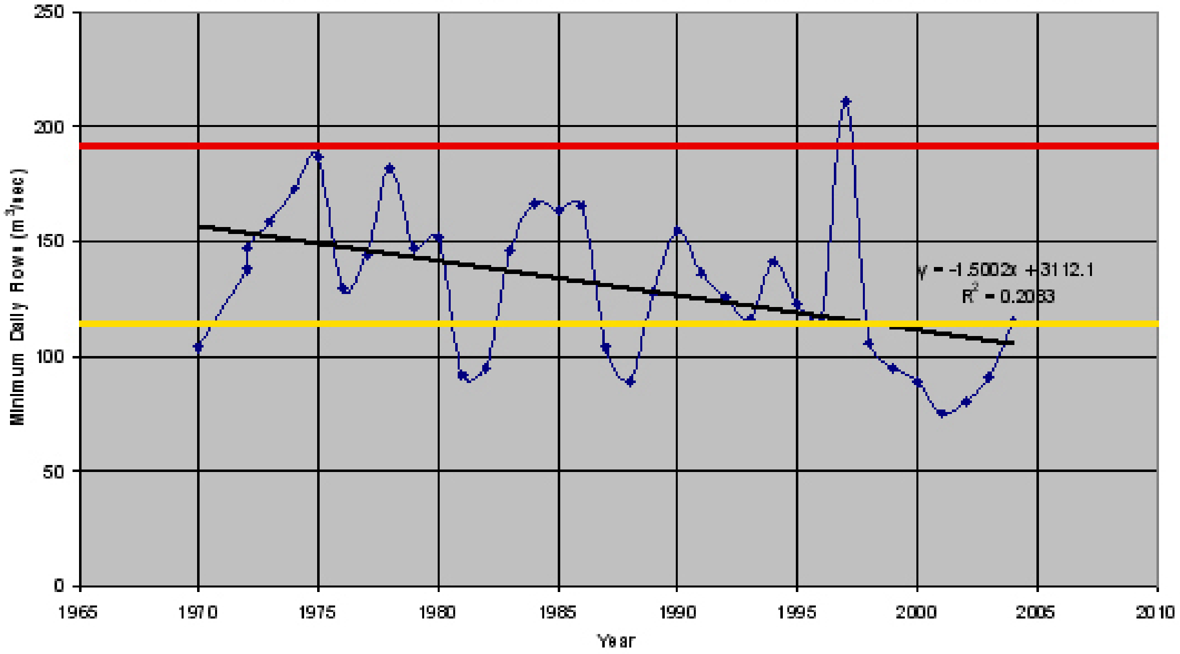
[5] Fig 2 also shows time trends for the Liard River, a more northerly tributary of the Mackenzie River arising in the Yukon, with trends towards greater flows, winter and spring, but declining trends June to September. (see Sec. 4.4)

basin. 58% of the stations had downward trends in annual mean flow from 1971-2000. For 1961-2000, the negative trends were not quite as pronounced but with statistically significant declines in flows for the below Fort McMurray station in January and February, as well as for the 25% percentile flows (at a rate of minus 3.2m^3/sec/decade) were determined. Some headwater stations showed increased minimum flows 1961-2000. The spring freshet date was also shown to be significantly earlier at a number of stations near and just downstream of the headwaters. Minimum daily flows, below Fort McMurray, declined to 75 m^3/sec in 2001 (December) (Fig. 3). Minimum flows in the decade of the 1970s averaged 151m^3/sec compared to 110m^3/sec on average from 1995-2004, a 27% reduction.

Figure 3
Annual Minimum Daily Flows (m^3/sec)
Athabasca River at Fort McMurray

With flow requirements of both oil sands development and protection of downstream ecosystems



Alberta requirements for protection of downstream ecosystems
- Yellow impact (short term impacts) allows 10% of minimum flows for oil sands projects
- Red impact (long term impacts) allows 6% of minimum flows for oil sands projects

Based on estimated water requirements at full oil sands development: 11.2 m3/sec (lower estimate)

From these analyses, it could be inferred that higher winter air temperatures in the headwaters, in the warming climate, has maintained minimum winter flows near the headwaters from snow and glacier melt. However, this advantage has been overwhelmed by losses in the long traverse across Alberta. Increased water withdrawals before the Fort McMurray gauge did not contribute significantly to this trend. It should be noted that the

Athabasca glacier has shrunk 25% (Watson, 2004) over the last century and will soon, if not now, be providing reduced melt water.

Air temperatures rose 1.5ºC to 1.8ºC in the period 1961-2000 in this region. (Environment Canada) From 1971-2000 autumn precipitation declined about 6%, and winter precipitation by about 12%. In spring, rain amounts increased while snow declined with a net positive trend. Summer rainfall was essentially unchanged, leaving annual precipitation up about 4%. Annual evapotranspiration losses increase as temperatures of shallow water bodies and soils increase. Estimates of this effect are about 15% increase per degree C in a similar climate in northern Europe. (Jurak, 1989) Schindler and Donahue, 2006, related Potential Evapotranspiration (PET) increases to air temperature changes in western Canada using a modified Thornthwaite method.[6] They calculated that a 1ºC increase for Fort Chipewyan near the mouth of the Athabasca River, would result in an additional 29 mm PET. However, PET assumes that all surfaces in the basin are continuously wet or have ready access to moisture. This condition rarely occurs in the whole Athabasca River basin, so actual evapotranspiration losses are much less than potential. Nevertheless, the rate of increase in evapotranspiration as temperatures rise, suggests that significant increases in precipitation would be required to maintain flows. Such increases in precipitation are not consistent with 35 years trends, nor those projected by climate models. Thus, increases in actual evapotranspiration are expected to overwhelm small increases or decreases in precipitation, in coming decades.

The minimum daily flows at the Fort McMurray gauge from 1970-2004 show great variability from year to year. However, the downward trend to recent years is very evident in the plot of Fig. 3 with the winter flows in the 2001-2002 drought reaching the lowest values. If one assumes a continuation of the recent trends in future decades, minimum flows by 2050 could be as low as $37 m^3$/sec. Paleo-climate records of past conditions from tree-ring analysis suggest that even more severe drought periods can be expected in future (Sauchyn, D., et al., 2002). Schindler and Donahue, 2006, note that paleodiatom studies confirm these tree-ring results. Climate models also project more severe droughts in future over continental interiors. (IPCC 2001)

4.4 Future Climate, Flows and Water Levels

The future evolution of the climate of the Athabasca basin can be estimated in two main ways. One is through use of Atmosphere-Ocean Global Climate Models (AOGCM's) driven with estimates of future greenhouse gas emissions and concentrations. A second approach, generally more suitable for the near future, i.e. 20 to 30 years, is through projection of the observed trends from the 1960s to 2005, responding almost exclusively to greenhouse forcing. When there is agreement between these two approaches, greater confidence can be placed in the results.

There are perhaps a dozen major climate modeling groups world-wide. In selecting appropriate models to use in a particular region, it is important to choose those

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[6] Thornthwaite method – a technique for estimating evapotranspiration from continuously wet surfaces (i.e. Potential Evaportranspiration) from monthly mean temperatures and length of daylight.

models which have best simulated the observed climatic conditions and trends for that area. An analysis was undertaken for the Mackenzie Basin of 7 model results compared to the actually observed conditions (Dornes, et al, 2004). For temperature all models performed well in simulating 1961-1990 temperature, especially:

1. CCSR-NIES (Japan) – a little too warm in winter,
2. CGCM2 (Canada) – a little warm in fall and winter,
3. ECHAM4 (Germany) – a little warm in winter,
4. HadCM3 (United Kingdom) – a little cool in summer.

The situation was very different for precipitation, CCSR overestimated by as much as 100% in all seasons. CGCM2 also overestimated substantially, especially in winter. ECHAM4 was fairly close to observed values over the summer period but also overestimated the winter precipitation. HadCM3 was just the opposite, with good simulation of winter precipitation and significant over- estimates for spring and summer. From these results, and consideration of availability of projections with different greenhouse gas scenarios, it was decided to use ECHAM4, CGCM2, and HadCM3, but to keep in mind the bias, that all of the models overestimated precipitation as compared to observed values.

The good agreement for temperature between trend extension and the AOGCM projections is illustrated in Fig. 4. This shows that linear extension of the 1961 to 2000 temperature trend and model results for 2025, 2055 and 2085 give similar amounts of annual warming, with HadCM3 being somewhat cooler in 2025 and 2055. The model projections are from Gan and Kerkhoven, 2004, and are averages from 4 different IPCC-SRES[7] scenarios of emissions (A1F1, A21, B11, B21) and the projection years shown in Fig. 4, are in the middle of 30 year time slices.

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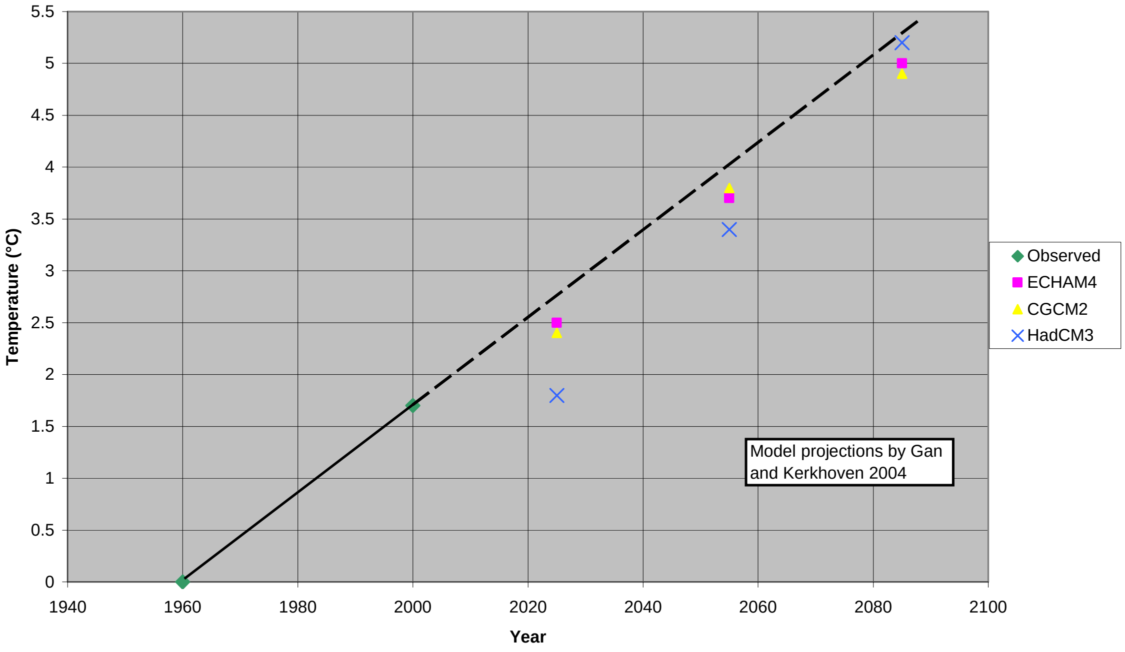
[7] SRES (Special Report on Emission Scenarios) were developed by the IPCC, 2000, and are projections to 2100 of future global greenhouse gas and sulphate aerosol emissions under various assumptions of population growth, economic change, energy and technology uses.

Figure 4
Temperature Trends and Projections
Athabasca River Basin



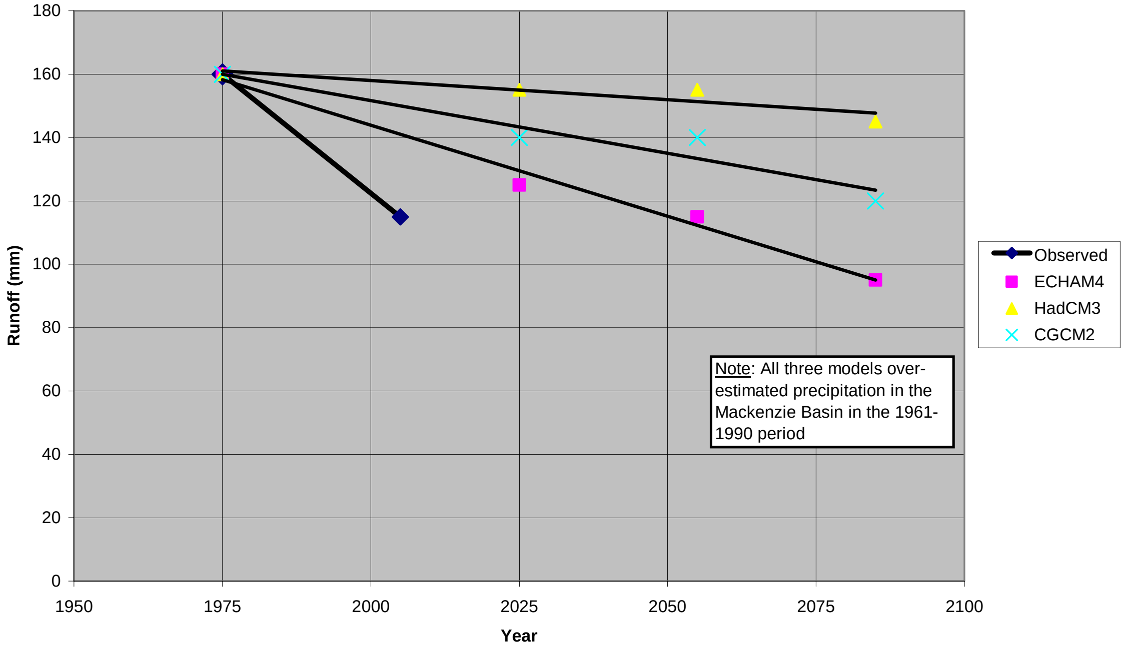
Model projections by Gan and Kerkhoven 2004

As expected, a similar concurrence is not evident for precipitation. The observed average annual trend (see above) is upward about 4% for the period from 1976, less than needed to offset evaporation increases. ECHAM4, the model which best simulated the 1961-1990 seasonal and annual precipitation although over- predicting winter amounts, projects on average for the 4 emission scenarios, future declines in precipitation of 1-3%. CGCM2 projects increased precipitation of 4% up to 2055 and 8% by 2085. But it must be recalled that CGCM2 overestimated annual precipitation 1961-1990. HadCM3 model indicates greater precipitation by 8% to 12% later in this century, but also overestimated the 1961-1990 annual by about 30%. Linear extension of the 4% observed increase 1976-2000 would suggest future increases between those given by CGCM2 and HadCM3. In short, precipitation will increase or decline slightly, so any increases in the decades to 2055 will likely continue to be more than offset by increased evaportransporation in the warming climate.

4.5 Modeling of Future Flows

Efforts to model the combined effects of temperature and precipitation changes on flow of the Athabasca River have been undertaken under MAGS (Mackenzie GEWEX[8] Study, Gan and Kerkhoven, 2004). Fig. 5. illustrates the changes projected by the three models. All models project declines in annual runoff. As expected, ECHAM4 projects largest runoff declines in mm over the basin. These are from 160mm currently to 125 by (2010-2039), 112mm by 2040-2069 and under 100mm by 2070-2099. The most optimistic, HadCM3 averaged over 3 SRES scenarios, a decline of about 5mm by the first period, about the same for the second, and about 15mm for the third. CGCM2 and other models were between these results. Hence, the projected decline ranges from 3% to 30% for the time of 2°C global warming, as represented by the model period 2040-2069. It should be noted that the results are much more model dependent rather than being affected by the 4 different SRES emission scenarios used. Minimum flows under future climates, declined less than mean annual runoff by the model runs. The largest modeled decline was 10% and the average decline 7% for all models used.

Figure 5
Observed and Projected Annual Runoff
Athabasca River below Fort McMurray



Note: All three models over-estimated precipitation in the Mackenzie Basin in the 1961-1990 period

To convert from the climate parameters to runoff, the analysts (Gan and Kerkhoven) used a modified version of an atmospheric-land surface model developed by Meteo France (Kerkhoven and Gan, 2005). The original model was ISBA (Interactions between Soil, Biosphere and Atmosphere) a land surface vertical water budget model. It was modified to provide for non-linear formulations for surface and subsurface runoff, and also for the heterogeneity of the Athabasca Basin. The new formulation was dubbed

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[8] GEWEX – Global Water and Energy Cycle Experiment, a component of the World Climate Research Program. (WMO, ICSU)

MISBA and was shown to realistically simulate average, maximum and minimum flows of the Athabasca using 40 years of data. The WATFLOOD hydrological model from the University of Waterloo gave a 29% overestimation of flows below Fort McMurray. (Toth, et al, 2006)

It should be noted that natural variations in climate in Alberta, driven in part by the Pacific Decadal Oscillation (PDO), may have made a contribution to the warmer, drier conditions of the past 25 years. However, climate models incorporate such natural modes of variability in their projections to the future (Wang and Schimel, 2003). Thus, just as there are significant variations from the overall trend, from year to year, or decade to decade, in the observed data (Fig. 3), such fluctuations above and below the overall downward trend are to be expected in future.

4.6 Ice Effects

Ice cover and ice jams can have effects on river levels such as on the lower Athabasca. In general, it was found that warmer winters result in hydrodynamic effects which resulted in short lived lower levels and flows in both the Athabasca and Peace Rivers near their outlets. Warmer winters also result in lower levels of lakes in the Peace Athabasca Delta (see 4.2) (Leconte, Pietroniro, 2006). This has effects with a longer term than on the rivers, that propagate from winter and spring through to summer. In summer under Geophysical Fluid Dynamic Laboratory (Princeton University) and ECHAM4 models, by 2080 average decline in levels is estimated at 0.29m, in years with projected level decreases. (see also estimates in 4.2)

Maintaining water levels in the Delta is key to preserving its biological productivity. (Environment Canada, 2005), and this is threatened by both climate change and water withdrawals on the Athabasca River.

5. Combined Downstream Impacts of Climate Change and Oil Sand Projects

5.1 Instream Flow Needs

The Athabasca River after a 1538 km journey, flows into Lake Athabasca through the Peace Athabasca Delta. The lower reach, below Fort McMurray, including the oil sands region is habitat for a number of prized fish species. Walleye, Northern Pike and Goldeye are among 31 species found there (Woynillowicz and Severson-Baker, 2006). This part of the river also provides a migratory route for fish from Lake Athabasca to reach spawning areas upstream of Fort McMurray. Adequate flows and quality are needed to support the ecosystems which include these fish species. Another concern is that the mining activity removes such wooded fen, a large hydrologic "capacitor" and its removal will serve to make the lower Athabasca River more "flashy", i.e. higher high flows and lower low flows. Quantification of this effect is not possible at present but it will increase downstream ecosystem vulnerability.

Instream Flow Needs (IFNs) calculations are being developed by Alberta as a guide to provide aquatic ecosystems with sufficient flow under the "Water for Life" strategy.[9] An "Interim Framework" for the lower Athabasca was implemented in January 2006 with public comment requested by March 2006. (Alberta Environment, 2006) The Interim Framework defines 4 categories or "zones" of increasing impact, Green, Yellow, Red and Black. While the IFN Interim Framework does not mention climate change impacts on flow, it does call for a reliable monitoring system which would trigger "management actions" in the oil sands projects. With the projected lower flows with climate change, these diversion limitations would have to be invoked more frequently, interrupting oil production operations. For example, the Yellow Zone (short term ecological impacts) management actions call for a voluntary target of withdrawals limited to 10% of available river flow. If we take the minimum flows observed in the declining trends to winter 2003-2004, this would mean a total diversion for oil sands projects of as little as 7.5m^3/sec., much less than the maximum19m^3/sec. estimated by the oil companies as the projected requirements (up to 11.5% of minimum flow, based on historic average of 169m^3/sec.) (CNRL, Horizon Oil Sands, Environmental Impact Statement) or even the more conservative estimate of 11.2m^3/sec.[10] For the Red Zone, when long term ecological impacts are anticipated, the proposed cumulative diversion rate target is only 6% of minimum flow, approximately 1/2 to 1/3 of projected requirements of the projects. Indeed minimum winter flows less than 110m^3/sec, which are less than enough to support the conservative demand estimate with Yellow Zone conditions, have been observed in 10 of the past 24 winters, and are projected to be more frequent in future.

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[9] Alberta's Water for Life strategy is designed to protect safe drinking water and aquatic ecosystems through effective management that also supports sustainable economic development.

[10] Note: Golder Associates in material for the CEMA group estimated approved and planned operations would require a peak of only 11.21m^3/sec.

To assess the adequacy to protect ecosystems, the suggestions in the interim framework have been under review by the multi-stakeholder Cumulative Environmental Management Association. (CEMA) Some participants consider that these guidelines are not sufficiently precautionary, given the large unknowns associated with the lower Athabasca ecosystems, and impacts of climate change (Woynillowicz and Severson-Baker, 2006).

In future, minimum flows would continue to decline another 7% to 10% as projected by a number of climate models over the coming four decades (Gan and Kerkhoven, 2004), the amount of water allowed to be diverted by these Guidelines would decline further, as the demand from the projects increases. This should increase the urgency of the Oil Sands projects operators to find ways to reduce their needs through storage, recycling and other means especially in winter months. A number of suggestions and recommendations have been provided by Pembina Institute. (Woynillowicz and Severson-Baker, 2006)

5.2 Peace Athabasca Delta (PAD)

The PAD is fed by the two rivers (Peace and Athabasca), and is in Wood Buffalo National Park, one of Canada’s most extensive. It is one of the world’s largest freshwater deltas and an internationally recognized wetland under the RAMSAR Convention, an international agreement to protect wetlands, as well as being a UNESCO World Heritage Site. It includes large undisturbed grass and sedge meadows, and is home to extensive populations of waterfowl, muskrat, beaver and wood bison. It has been used traditionally by many First Nations hunters and trappers as a major source of income and sustenance.

The Delta wetlands require periodic high water to survive. This was compromised by the initial filling of the W.A.C. Bennett hydro-electric dam’s reservoir on the Peace River in British Columbia between 1968 and 1971. Some weirs were subsequently constructed in the Delta at the joint expense of federal and provincial governments in order to sustain adequate levels. It is known that the periodic flooding required to maintain wetland health is often due to ice jams in winter and spring months.

It has been found that, in general, warmer winters lower river levels for short durations, as water flows into the Delta. However, the effects of lowering water levels on the Delta itself, are much longer lasting, extending into summer. Milder winters, more frequent in the warming climate, could reduce the ice cover season by 28 days with lowered Delta levels by almost 10cm. (Leconte, et al. 2006) *Note: other estimates give declines of up to 29cm – section 3.5.*

While ice jams of significance occur in the lower Athabasca which, when released, can contribute to valuable temporary flooding of the Delta, it is the jams on the lower reaches of the Peace River which are mainly responsible for flooding of the PAD (Prowse, et al, 1996). Operation of the Bennett Dam by B.C. Hydro in a manner that would stimulate formation of ice jams on the lower Peace were recommended by

National Water Research Institute, Environment Canada, and were successfully undertaken in 1996. The influence of climate change on ice jam formation and release is a complex issue but has been studied. (Beltaos & Prowse, 2001). Warmer winters, in general, as well as lowered flows due to effects of withdrawals, and climate change on the Athabasca River, will contribute to lower water levels and adverse impacts in the biologically productive PAD.

5.3 Water Quality Concerns

Little data are readily available on downstream water quality impacts of the oil sands projects and most of the waste water from the projects is stored in huge ponds on site or recycled rather than discharged to the river. Concerns focus on fish contamination, since they are a main dietary source for First Nations and Métis communities downstream.

Mobilization of naturally occurring arsenic can occur in nearby wells from **in situ** steam projects of the Cyclic Steam Stimulations (CSS) type, and aquifers can be contaminated due to leaks from casing failures. Waste water disposal in deep saline aquifers, below the bitumen level, has caused limited concern since it is usually done with impermeable layers above and below. However, a geophysicist from University of Alberta points out that “We haven’t measured how water migrates from one area to another…….There is no such thing as an impermeable layer.” (E. Nyland, Edmonton Journal, Oct. 17, 1999)

For mining operations, dewatering of basal aquifers is at times necessary to prevent flooding of the mining areas. For example, the Canadian Natural Resource’s Horizon mine may reduce discharge of groundwater into the Athabasca River by up to 30,000m^3/day according to the company’s environmental impact statement. The effects of this type of groundwater disruption on water quality are not well understood.

However, the major water quality concerns relate to the tailing ponds where waste waters are stored, and their long term management. These are said to be among the largest structures on the planet made by humans, and in 2004 already covered over 50 km^2 of landscape. While the companies are vigilant in their monitoring of these highly contaminated lakes, the threat of seepage into groundwater and soils, and the threat of breaches of containment hang over the area. This is a special concern in the long term, after the mining operations have ended.

Methane, a powerful greenhouse gas, produced by methangenic bacteria is emitted from the tailing ponds. Napthenic acids and other substances that are found in the residual bitumen in the tailing ponds are persistent in the environment, are toxic to fish and birds and cause fish tainting. Measurements to date of such acids indicate below 1 mg/l concentrations in the river but up to 110 mg/l in tailing pond waters, which have been found to be acutely toxic to aquatic organisms and mammals. Hundreds of forms of these acids are found in the bitumen being removed and processed. (Griffiths, et al., 2006)

The growth of NO_x and SO_2 emissions from oil sands projects is increasing acid deposition in water bodies in the region, especially those downwind in the prevailing wind directions (W, NW). Increased release of mercury is also a concern, expressed by the Mikesew Cree First Nations because of their dependence on fish. This could arise from the stripping of wetlands and small watersheds in mining the bitumen. Some of these areas contain high mercury levels naturally, and this can be mobilized into the river by the projects. Whole small watersheds, or a large part of them, tributary to the Athabasca (e.g. Muskeg River) are being re-routed or essentially obliterated by the large scale surface mining activities. The impacts of these changes on the hydrologic system and water quality in the Athabasca River are not well understood. (Griffiths, et al., 2006) In addition to impacts on lower Athabasca River from oil sands projects, increased biological oxygen demand and other contaminants from pulp and paper mills are a concern.

5.4 Effects in Downstream Jurisdictions

The Athabasca is a tributary of the much larger Mackenzie River System which flows northward through the Northwest Territories to the Arctic Sea. As noted earlier, with climate change, declining flows on average in the most southerly tributary, the Athabasca, are more than offset by increasing annual discharge from the more northerly Liard which rises in the Yukon. (Fig. 2) This latter basin has received substantially more precipitation in the past three to four decades and this is projected to continue with greenhouse forcing, although summer flows have been declining. In the Peace River from 1972 to 1999, winter and spring flows have been increasing (D.J.F.M.A.) but summer and autumn flows declining. (Woo and Thorne, 2003)

The net effect of these changes on the main stem of the Mackenzie River as indicated in the changing climate from 1972 to 1999, has been lowering of discharge over summer and fall, significant at the 10% level in November, but increasing flows from December to May. (Woo and Thorne, 2003) The variability from year to year of monthly flows has increased significantly in the Mackenzie in spring (A.M.J.) and in December. On the Athabasca, this increased variability from year to year is evident in March, May, August and September. (Woo and Thorne, 2003) Increased variability in future flows has also been projected with continuing climate change, in other modeling work (Pietroniro et al., 2006).

Of major concern, with lower summer flows on the Mackenzie, is navigation by barges for re-supply of northern communities in summer. The climatic trends, of lower summer flows and greater variability, exacerbated to a small extent by water withdrawals from the Athabasca, can jeopardize this vital low cost transportation of essential goods. In addition, with lower flows, pollution concentrations from all sources increase.

Alberta is an active supporter of the Prairie Provinces water sharing agreement, overseen by the Prairie Provinces Water Board, to provide for passing of agreed amounts of water of a high quality to Saskatchewan and thence Manitoba on the eastward flowing Saskatchewan River system. While the Mackenzie River Basin Transboundary Water Agreement aims at "equitable utilization" of waters of the Basin, there is, as yet, no binding agreement or regulatory provision as on the Saskatchewan River. Such a binding agreement has not been signed by British Columbia and Alberta with the Northwest Territories or Saskatchewan on sharing the waters of the Mackenzie River system. Saskatchewan borders on Lake Athabasca affected by Athabasca and Peace River flows. In view of increasing withdrawals of water in Alberta, combined with the effects of climate change, a firm agreement between the provincial and territorial governments is urgent. This agreement should reflect commitments on water sharing and protecting water quality.

6. Conclusion and Recommendations

Conclusion:

The projected rate of water use from the Athabasca River, in the Oil Sands projects, is unsustainable. This is in spite of efforts to date of some operators to conserve and recycle water. Estimates of water requirements for all projects as presently planned and projected exceed Alberta's "Interim Framework" target for protection of aquatic ecosystems downstream in the Athabasca River in recent winter low flow periods. The annual flow and winter low flows on the Athabasca River, the main source of water supply, have been decreasing with climate change in the period from 1970 to 2004. This decline is expected to continue with still growing global emissions of greenhouse gases, including those from the Oil Sands Projects themselves, and continuing changes in climate.

Recommendations:

1. Climate change and water withdrawals need to be taken into account in an agreement between the three provinces and two territories. (B.C., Alta, Sask., NWT and Yukon) concerning sharing of the waters of the Mackenzie River system and protection of water quality.

2. The Government of Alberta should consider withholding approval of any oil sands projects and related water taking licenses until:
   i) substantial water conservation measures are implemented in the projects, and
   ii) assurances can be made that Instream Flow Needs to protect ecosystems in the lower Athabasca can be met in the face of the changing climate.

3. Research and practices should be accelerated by the oil producing companies to reduce water demands through recycling, re-use and alternative processes in existing projects. (See recommendations of Woynillowicz and Severson-Baker, 2006)

4. Since oil sands projects are likely to be among those adversely affected by climate change, in their own interests, the companies should redouble efforts to improve technology to reduce greenhouse gas emissions from the full range of their operations and for both carbon dioxide and methane.

5. Measures to reduce pollution and direct environmental damages from the projects themselves as suggested by Pembina Institute (Griffiths, et al., 2006) should be actively pursued.

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Hydrological Changes in the Great Lakes – St. Lawrence Basin under Climate Change and Impacts on Hydropower Generation

Tina Tin

1. Abstract

This study presents a review of existing scientific studies on observed and projected changes in the climatic and hydrologic conditions of the Great Lakes – St. Lawrence Basin. Our primary focus is on the impacts of a 2°C global warming on hydropower generation in the region, but results from a 1.5°C and 4°C warming are also briefly discussed.

From 1895 to 1999, annual mean temperatures have increased by 0.7°C for the southern portion of the Great Lakes and St. Lawrence basin. From 1948 to 2005, a warming trend of 0.5°C has been recorded. Total precipitation has increased from 1895 to 1995. However, an extension of a trend for the period 1996 to 2005 is inconclusive. Since 1860, annual water levels in the Great Lakes have only fluctuated about 2 m from measured maximum and minimum levels. Recently, lake levels dropped dramatically from highs in 1997 and remained low through to 2001, as a result of exceptionally hot and dry conditions.

Under a 2°C global warming, results from sensitivity experiments using global climate models and scenarios of greenhouse gas emissions indicate a warming of the Great Lakes – St. Lawrence Basin by 2.2°C to 4°C, accompanied by an increase of precipitation of 1% to 16%. Warmer temperatures are likely to increase evapotranspiration rates by 8% to 27% which could offset the increase in precipitation. Hydrologic modeling based on results from six climate change scenarios obtained from transient climate models (HadCM2, CGCM1, HadCM3, CGCM2) and IPCC emission scenarios (IS92a, SRES) indicate a high likelihood that both lake levels and outflow could decrease under a 2°C global warming. Lake outflows could reduce by 5% to 26%, accompanied by a decrease in lake levels of 0.08 m to 1.18 m. Further analysis showed that reductions in lake levels and outflow would lead to a loss in hydropower generating capacity in the Great Lakes – St. Lawrence Basin, where the Canadian provinces of Ontario and Quebec and the American state of New York operate hydropower facilities. Under a 2°C global warming, recent estimates indicated hydropower generating capacity on the St. Lawrence River could be reduced by 2 to 17%. Earlier estimates show that annual loss in electricity production in Ontario could amount to $240 million to $350 million (Canadian dollars at 2002 prices).

The conclusion from reviewing all the climate change impact assessments in the Great Lakes region is that there is a large body of research that supports the point that water levels are likely to decline due to climate change. Under a few climate change scenarios, a 2°C global warming led to smaller negative or small positive impacts on the hydropower production of the Great Lakes. However, in light of the potential scope of

negative impacts on hydropower production, against a backdrop of ever-increasing energy demand, it would be in the best interest of electricity suppliers and regulatory bodies to consider the potential impacts of climate change in their mid- and long-term planning. In addition, it is equally important that government authorities, industry and citizens take immediate actions to mitigate the effects of climate change. By 2050 – the time of 2°C global warming – energy demands nationally are expected to increase by 60-100% while hydropower generating capacity in the Great Lakes is expected to fall. If levels of CO_2 are allowed to continue to rise in the atmosphere, a 4°C global warming could mean that the water needs for Hydro Quebec may not be able to be met at all. In order to meet energy demands, reduction in hydropower production is likely to lead to increase in power generation from fossil-fuel or nuclear power plants, thus accelerating climate change and generating other environmental problems. Managing energy demand, improving energy efficiency and increasing the use of renewable energy sources will contribute towards the reduction of CO_2 emissions and thus, mitigation of climate change, while improving energy security at the same time.

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2. Introduction

The Great Lakes - St. Lawrence Basin watershed encompasses an area of about 1,000,000 km^2 with 25% of the area covered by the lakes themselves. The Great Lakes contain nearly 20% of the world's fresh water supply; yet only 1 percent of the water is renewed annually. The Basin is now home to more than 42 million Americans and Canadians. Water from the lakes and rivers are used for industrial, municipal, domestic and agricultural purposes. It also supports birds, fishes, plants and other wildlife and provides ecosystem services to all inhabitants of the region. The Great Lakes - St. Lawrence River system is used for marine transportation, hydroelectric power generation and recreation. To ensure sufficient flows and water levels for the use of different interests, water levels at Lakes Superior and Ontario are regulated under the International Joint Commission (IJC) through the use of control structures (Sousounis and Bisantz, 2000; Kling et al., 2003; LOSLR, 2006; Croley, 2003).

Hydropower generation benefits from the steady maintenance of flows and water levels. Essentially, the megawatt-hour (MWh) electricity production is largely determined by lake levels and river flows. In general, higher lake levels lead to higher outflows and hence increased power generation. However, if flows are too high, they can exceed the capacity of the plants, and increasing flows will then have diminishing returns.

Hydropower is generated in the Great Lakes – St. Lawrence basin at facilities located on the St. Mary's, Niagara, and St. Lawrence Rivers and at DeCew Falls off the Welland Canal (Figure 1). In the U.S., the New York Power Authority (NYPA) operates one hydroelectric facility at the Niagara Falls and one facility at Massena on the St. Lawrence River. Combined, these two facilities have a net dependable capacity of 3,200 MW, and supplies more than 10% of New York State's electricity (Sousounis and Bisantz, 2000) (Table 1). The U.S. Army Corps of Engineers and the Sault Edison Electric Company also have hydroelectric facilities on the St. Mary's River, providing an available installed capacity of just over 40 MW (Wisconsin Energy Corporation, 2003) – a significant proportion of Michigan's installed hydroelectric capacity of 245 MW (Energy Information Administration, 2006).

In Canada, Ontario Power Generation (OPG) produces approximately one-quarter of its electricity from hydropower, while nuclear and fossil fuel power plants make up the rest of its supply. One-third of OPG's hydropower capacity (or approximately 8% of its total generation capacity) is generated in the Great Lakes. Facilities are located on the Niagara River at Niagara Falls and the Upper St. Lawrence River at Cornwall (Buttle et al., 2004). The Clergue generating station at Sault Ste. Marie on the St. Mary's River which has an installed capacity of 52 MW is now run by Brookfield Power (Brookfield Power, 2006). OPG is in the process of building a tunnel below Niagara Falls to divert more water and increase power output of existing facilities (Ontario Power Generation, 2005). Construction is expected to be completed by the end of 2009.

Figure 1 The Great Lakes-St. Lawrence River drainage basin and the locations of hydroelectric facilities. Based on figure from USACE and GLC (1999).

Production by Hydro Québec is predominantly dependent on hydropower. The company operates three facilities on the St. Lawrence River: on Lakes St. Louise and St. Francis and the St. Lawrence upstream from Montreal and Laval, accounting for approximately 5% of the company's installed hydropower capacity (Hydro Québec, 2005).

Table 1 Hydropower dependence and capacity of the U.S. states and Canadian provinces that operate hydropower facilities in the Great Lakes-St. Lawrence Basin

Province / State	**Hydropower capacity**	**Share of hydropower in energy mix**	**Percentage of total hydropower capacity generated in the Great Lakes-St. Lawrence Basin**
Michigan	241 MW[1]	<1%[4]	16% [1,7]
New York	4,145 MW[1]	18%[5]	~80% [1,8]
Ontario	7,700 MW[2]	~25%[6]	~8% [6]
Quebec	34,570 MW[3]	93%[2]	5% [3]

([1] Energy Information Administration, 2006; [2] Ontario Power Authority, 2005; [3] Hydro Québec, 2005; [4] Michigan Public Service Commission, 2006; [5] New York State Public Service Commission; [6] Buttle et al., 2004; [7] Wisconsin Energy Corporation, 2003; [8] NYPA, 2005)

3. Climate and Lake Trends

3.1 Temperature

Within the Great Lakes region, annual mean temperatures have increased by 0.7°C from 1895 to 1999 for the southern portion of the Great Lakes and St. Lawrence lowlands (Mortsch et al., 2000). Warming has continued through to the present, with summer 2005 being the hottest summer in the region since 1948 (Meteorological Service of Canada, 2005a). From 1895 to 1999, Canada has warmed by a statistically significant 1.3°C which has continued to the present (Table 2). Most of the warming has taken place during winter and spring. Notably, winter mean temperatures have increased by 2.1°C from 1948 to 2005.

Put into the context of recent history, 1998 was the warmest year in Canada since nationwide records began (Environment Canada, 2006). 2005 tied with 1999 and 2001 to be the third warmest year in the country. In 1998, the national average temperature was 2.5°C above normal[11]. Over the Great Lakes basin, the average temperature was also 2.3°C above normal in 1998. Statistically, in an unchanging climate, an annual anomaly this large can be expected once about every 1,670 years (Mortsch et al., 2000).

Table 2 Temperature trends over period of 1895-1999[a] (and over 1948-2005[b]) in Canada and in the Great Lakes region.

	Temperature trends over 1895-1999 (Temperature trends over 1948-2005)				
Region	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
Great Lakes Basin / St. Lawrence Lowlands	+1.3°C (+0.7°C)	+0.9°C (+0.5°C)	+0.3°C (+0.5°C)	+0.4°C (+0.0°C)	+0.7°C (+0.5°C)
Canada	+1.5°C (+2.1°C)	+1.6°C (+1.6°C)	+1.2°C (+0.8°C)	+0.9°C (+0.5°C)	+1.3°C (+1.2°C)

[a]Mortsch et al., (2000); [b]Meteorological Service of Canada, (2005b).

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[11] For temperature records, Meteorological Service of Canada defined normal as the average for the period 1951-1980. http://www.smc-msc.ec.gc.ca/ccrm/bulletin/disclaim_e.cfm.

3.2 Precipitation

Total precipitation has increased over the period from 1895 to 1995 over the Canadian Great Lakes – St. Lawrence basin (Table 3). An increasing proportion of annual precipitation is occurring in the form of rain instead of snow, as a result of higher air temperatures (Mortsch et al., 2000; Croley et al., 2003). The trend in increasing annual precipitation is not linear in the Great Lakes Basin and an extension of a trend for the period 1996 to 2005 is inconclusive (Figures 2a-d).

Table 3 Annul and seasonal total precipitation trends in Canada and in the Great Lakes region (Mortsch et al., 2000; Mekis and Hogg, 1997, 1999).

		Total Precipitation Trends (mm change / mean over 10 years)				
Region	**Period**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**
Great Lakes Basin / St. Lawrence Lowlands	1895-1995	*+1.1*	-0.3	+1.0	+1.1	*+2.6*
Canada	1948-1995	*+1.7*	-0.1	*+2.6*	+0.9	*+3.4*

Numbers in italics indicate trend is statistically significant.

From 1900 through 1939, a low precipitation regime predominated with the majority of the years falling below the mean. From about 1940 until recently, a high precipitation regime has existed. Fluctuations during this recent period include high precipitation in the early 1950s, followed by low precipitation in the early 1960s that led to extraordinarily low levels at Lakes Michigan, Ontario, St. Clair and Erie, and a consistently high precipitation regime from the late 1960s through the late 1980s. While the 1940-1990 period is generally above normal, the last 20 of these years are higher still. The year 1985 set new records with the highest precipitation to date (Croley, 2003). From 1995 onwards, annual precipitation has generally decreased, staying closer to average values than in earlier decades. Data from 1951 onwards show an increase in heavy precipitation days, with greater contribution to annual precipitation from very wet days, and increases in daily intensities (SWCS, 2003).

Figures 2 Annual precipitation deviation from average[12] for Lakes
a) Superior, b) Michigan-Huron, c) Erie and d) Ontario
(Data from United States Army Corps of Engineers, Detroit District, 2006)

Fig. 2a) **Lake Superior: Annual Precipitation Deviation From Average**

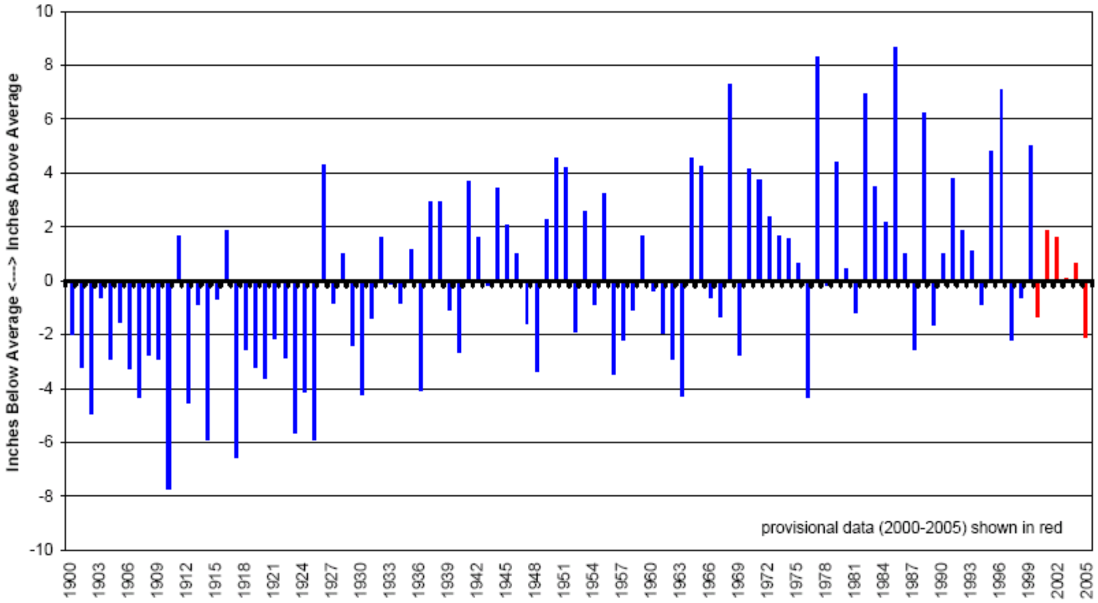
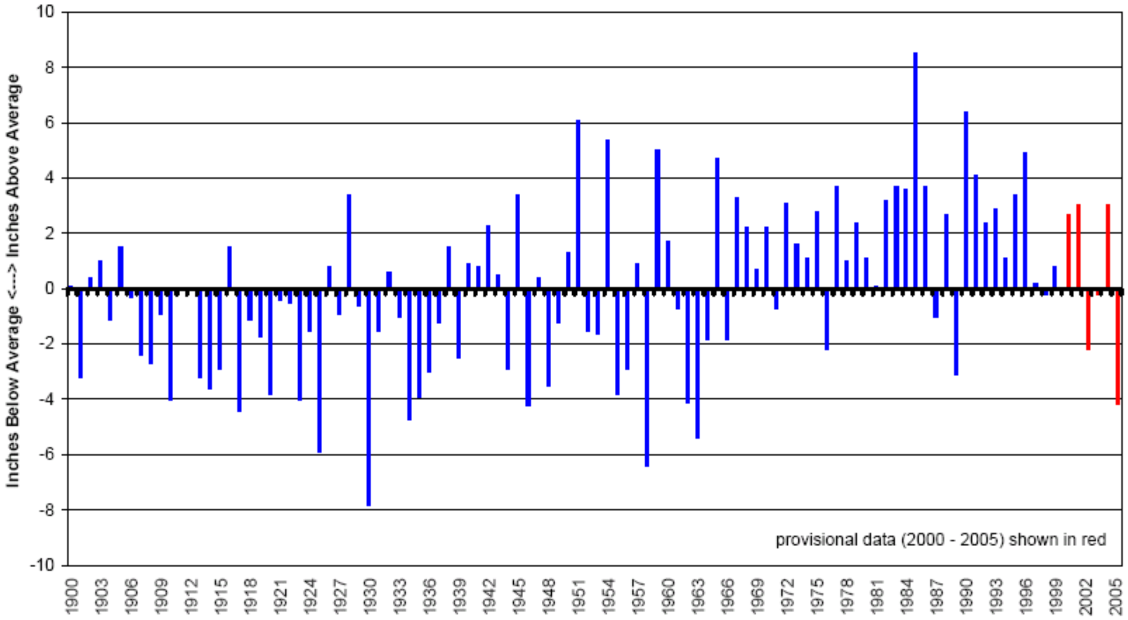


Fig. 2b) **Lake Michigan-Huron: Annual Precipitation Deviation From Average**



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[12] Average derived from period 1900-1999.

Fig. 2c) **Lake Erie: Annual Precipitation Deviation From Average**

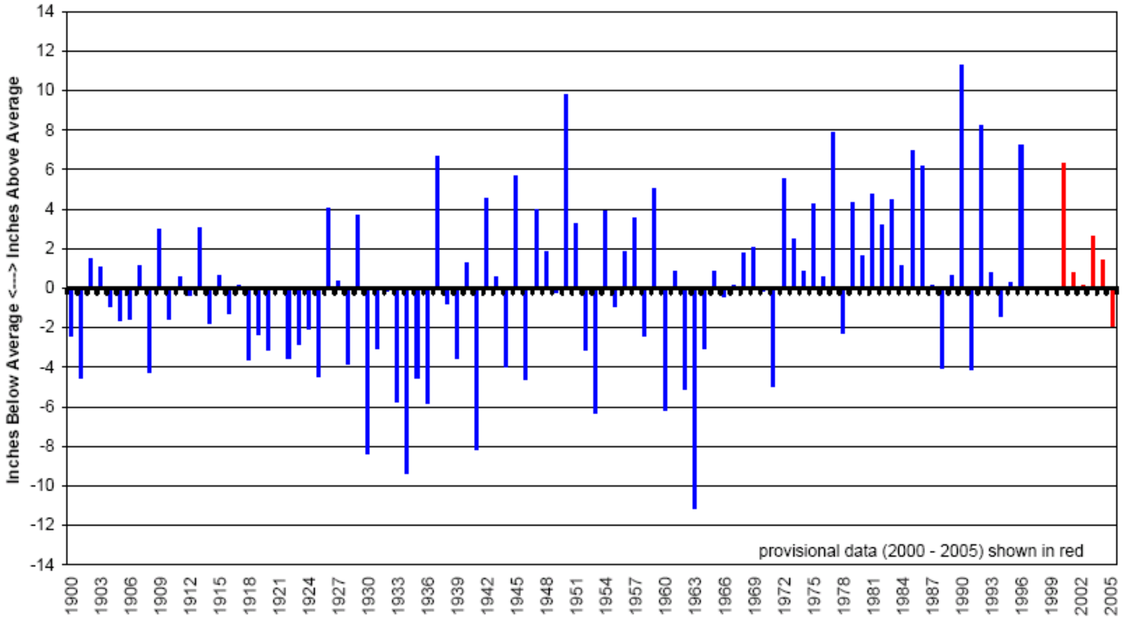
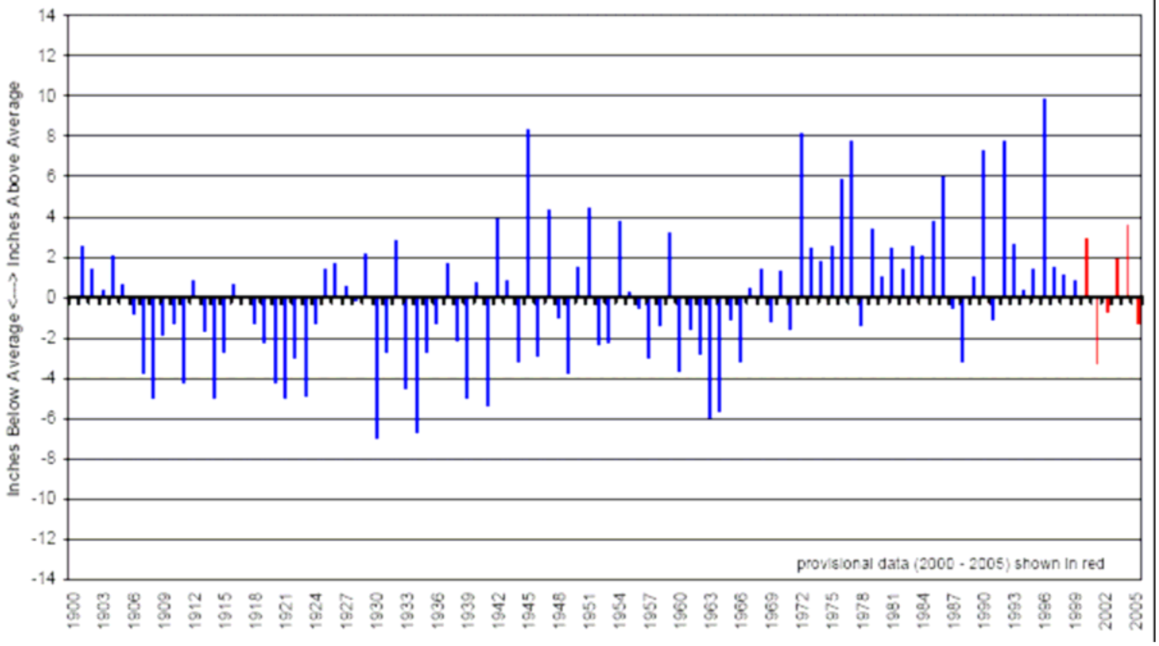


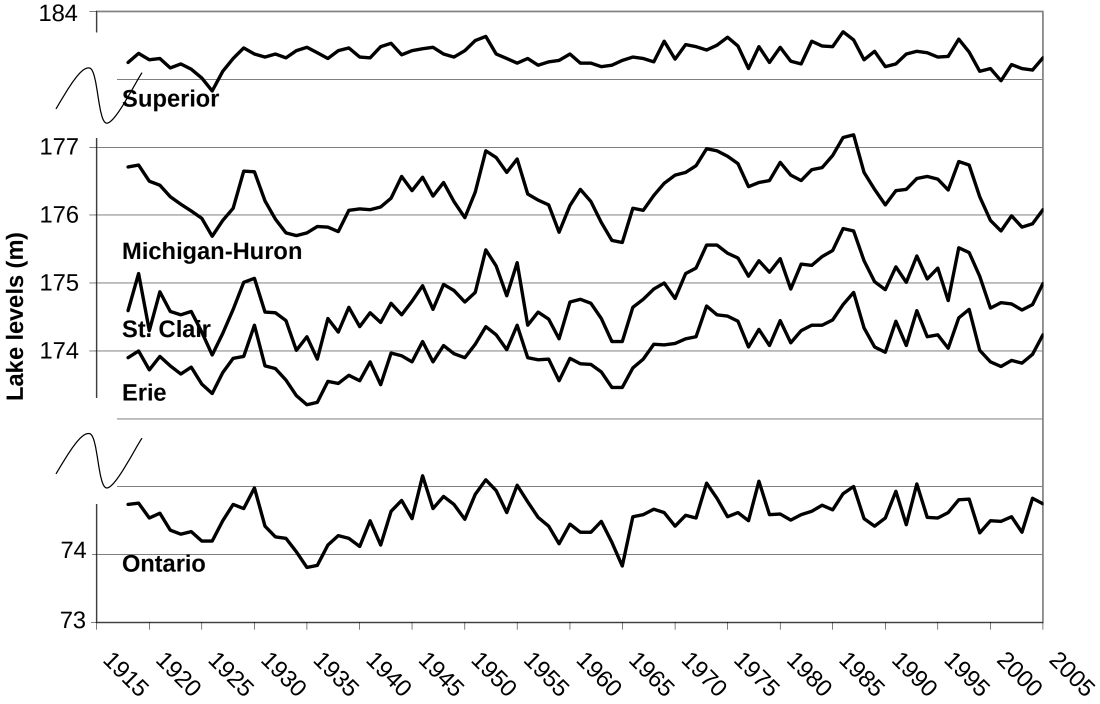
Fig. 2d) Lake Ontario: Annual Precipitation Deviation From Average



3.3 *Lake levels*

Records from 1860 to the present show that the overall range of fluctuations of annual water levels in the Great Lakes is around 2 m (Croley, 2003). Water levels were very high in 1973-75, 1985-86, and 1997 (Figure 3). They were very low in 1934-35 and 1964-65. Since the late 1800s, dredging and navigation improvements in the St. Clair River have lowered Lake Michigan-Huron by 37 to 62 cm. Since the early 1970s, there has been a run of relatively high water supplies (wet weather) with water levels generally above the long-term average. In 1998, lake levels dropped dramatically from highs in 1997 in part because 1998 was the hottest year (+2.3 C) and fifth driest year (-11.5 %) in the region in 51 years (Mortsch et al., 2000). Water levels have remained low through to 2001 (Figure 2). In 2001, southern Ontario experienced the driest 8 weeks on record and Montreal set the summer record with 35 consecutive days without measurable precipitation (Lemmen and Warren, 2004). The Great Lakes – St. Lawrence basin had the driest summer in 58 years (Meteorological Service of Canada, 2005a).

Figure 3 Great Lakes annual average water levels (Data from United States Army Corps of Engineers, Detroit District, 2006).



A study of the monthly mean Great Lakes water levels for the period 1860-1998 has identified important changes in the seasonal cycle of Great Lakes water levels (Lenters, 2001). Study results showed that Lakes Erie and Ontario are rising and falling (on an annual basis) roughly one month earlier than they did 139 years ago. Maximum lake levels for Lake Superior are also slightly earlier in the year, and the amplitude of the seasonal cycle of Lake Ontario is found to increase by 23% over the 139-year period. Some of the changes are consistent with the predicted impacts of global warming on spring snowmelt and runoff in the Great Lakes region. Other potential contributors to the observed trends include seasonal changes in precipitation and human-induced effects such as lake regulation and changes in land use.

3.4 Evapotranspiration

Evapotranspiration is the loss of water to the atmosphere through evaporation from the earth's surface and the transpiration of plants. It plays a crucial role in determining lake levels and flows, together with other factors such as precipitation and runoff into the basin. In general, evapotranspiration increases with temperature. In the Great Lakes – St. Lawrence basin, almost two-thirds of the water that falls returns to the atmosphere through evapotranspiration (Mortsch et al., 2000).

During the year, evaporation from the Great Lakes reaches a minimum during the spring and gradually increases until it reaches a maximum in the late fall or early winter. The high evaporation period is due to very cold dry air passing over warm lake surfaces. Over the land basin, evapotranspiration is largest in the late summer and early fall. When more water is leaving the lake through evaporation than is being provided by precipitation and runoff then lake levels drop (Croley, 2003).

4. Great Lakes Climate Change Impacts Studies

4.1 Overview of studies

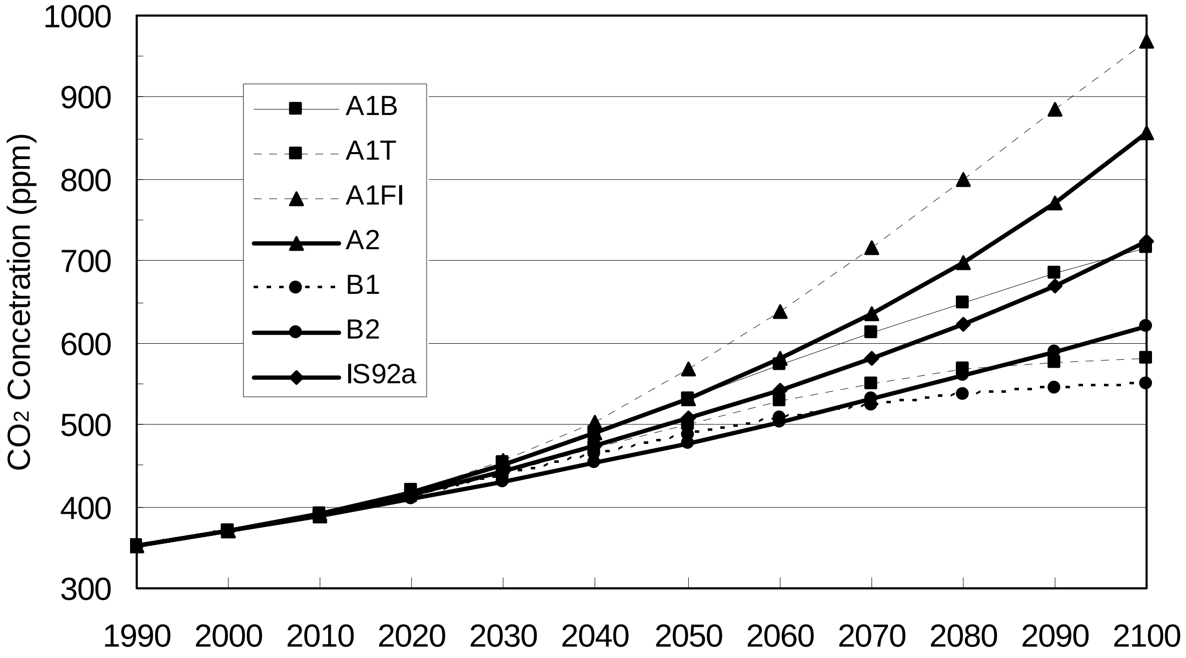
The first climate change impact assessments in the Great Lakes – St. Lawrence Basin have used results from equilibrium-response climate change experiments with atmospheric general circulation models (GCM) to develop climate change scenarios. In these experiments, the global climate system is perturbed by an instantaneous doubling of the atmospheric concentration of carbon dioxide ($2xCO_2$) and allowed to stabilize to a new climate. In the control run, the GCM is run with pre-industrial or current atmospheric concentration of CO_2 ($1xCO_2$). Changes in temperature, precipitation and other climatic parameters are calculated from the difference between the $2xCO_2$ experiment and the control run. The effect of increased sulfate aerosol concentrations in the atmosphere is not included in these experiments (Mortsch et al., 2000). Using the changes in climatic parameters computed from the GCM experiments, hydrological models are then used to estimate the changes in lake levels under climate change.

More recent assessments of climate change impacts use climate change scenarios developed from transient GCM runs. Transient models are full dynamic ocean models coupled to an atmosphere with CO_2 content changing in time. The transient approach effects a delay in warming by incorporating the thermal capacity of the oceans into model. The effect of aerosols is included (Sousounis and Bisantz, 2000).

To use a transient model, the evolution of atmospheric CO_2 concentrations with time needs to be described. Emission scenarios are used to describe possible future trends in atmospheric CO_2. The IS92a scenario published by the Intergovernmental Panel on Climate Change (IPCC) in 1992 (IPCC-TGCIA, 1999) were used for the U.S. National Assessment of the Potential Consequences of Climate Variability and Change and the International Joint Commission (IJC) Reference on Consumption, Diversions and Removals of Great Lakes Water (Lofgren et al., 2000, 2002; Mortsch et al., 1999, 2000). More recently, the IPCC SRES emission scenarios have been used in the International Lake Ontario-St. Lawrence River (LOSLR) Study (Croley, 2003; Mortsch et al., 2005; LOSLR, 2006). The SRES scenarios were published in 2000 and assume different directions for future developments, covering a wide range of key “future” characteristics such as demographic change, economic development, and technological change (Nakicenovic et al. 2000). The climatic parameters computed from the GCM experiments are then used by a hydrological model to estimate the changes in lake levels under climate change.

Figure 4 illustrates the evolution of atmospheric CO_2 concentration according to the different emission scenarios.

Figure 4 Evolution of atmospheric CO2 concentration, according to IPCC emissions scenarios (SRES and IS92a) (New, 2005).



How the results of these various studies can be interpreted in terms of levels of global warming vary due to the different models and emission scenarios used (Table 3). As explained in the Introduction section of this report, New (2005) examined monthly data from six coupled ocean-atmosphere global climate models to assess the likely timing of a 2°C global warming. Based on these results, we use GCM output for the periods centered on 2030, 2050 and 2090 as proxies for 1.5°C, 2°C and 4°C global warming, respectively (introduction section of this report).

Section 4.5 presents results from the latest climate change and hydrological studies. These studies focused on a period centered on the year 2050 and used SRES scenarios and transient models similar to those used in New (2005). Hence, the results from these studies will be interpreted as an assessment of the impact of a 2°C global warming on the Great Lakes-St. Lawrence Basin.

Section 4.4 presents results from recent climate change and hydrological studies. These studies used the IS92a scenario and earlier versions of transient models that were used in New (2005). The results from this section will be used as a proxy for an assessment of the impact of a 1.5°C (for scenarios centered on 2030), 2°C (for scenarios centered on 2050 scenarios) and 4°C (for scenarios centered on 2090 scenarios) global warming.

Section 4.3 presents results from early climate change and hydrological studies. These studies used equilibrium models which are significantly different to the transient models that were used in the studies reported in Sections 4.4 and 4.5. Results from these earlier studies are presented to provide a historical context in the interpretation of more recent results and are not directly comparable. Results from these studies tend to indicate more significant warming than more recent studies, as the cooling effect of aerosols is not included in equilibrium models. These earlier studies are included in order to provide a complete review of all climate change impact assessments that have been completed to date for the Great Lakes-St. Lawrence Basin.

Table 3 Differences between the studies included in Sections 4.3, 4.4, 4.5

Section	Model	Emissions scenario	Representative level of global warming	Can studies be used as proxies for an assessment of impacts arising from its representative level of global warming (column to the left) ?
4.3 Early studies	Equilibrium	2xCO2	Close to 2°C	No; New (2005) defined timing of 2°C warming using transient models which are fundamentally different to equilibrium models.
4.4 Recent studies	Transient (HadCM2, CGCM1)	IS92a	2030 scenarios: close to 1.5°C; 2050 scenarios: close to 2°C; 2090 scenarios: close to 4°C	Yes for CGCM1 scenarios; CGCM1 + IS92a was part of the ensemble used to define timing of 2°C warming in New (2005). Yes but with caution for HadCM2 scenarios; HadCM2 was not included in New (2005) but a newer version of the model HadCM3 was.
4.5 Latest studies	Transient (HadCM3, CGCM2)	SRES A1, A2, B1, B2	2050 scenario can be used as a proxy for 2°C warming	Yes for HadCM3 + A2, HadCM3 + B2, CGCM2 + A2, CGCM + B2 scenarios which were part of the ensemble used to define timing of 2°C warming in New (2005). Yes but with caution for A1, B1 scenarios – not included in New (2005).

4.2 Uncertainties associated with linking climate and hydrological models

GCM outputs have inherent large uncertainties in the GCM components, assumptions and data. In order to assess climate change impacts on a regional scale, GCM outputs often need to be interpolated or downscaled to a finer scale in order to be used in hydrological models. Interpolation or downscaling methods may introduce biases into the data (Croley, 2003).

There is no way of determining which climate change scenario is the "best" prediction of the future climate, the "worst case scenario", or the "average" potential change in climate. Each SRES emission scenario is considered to be equally probable, although the future that each scenario describes can differ greatly from one another, based on the forcing conditions of population growth, economic growth, etc. By using several combinations of GCMs and emission scenarios, a range of possible future climates and model uncertainties are explored. In addition, this approach provides a range of implications that decision makers and policy makers should consider in their planning (Mortsch et al., 2005).

Regardless of the shortcomings of using GCMs to assess climate change impacts on a regional scale, techniques and confidence in model projections have improved significantly over the past decade. They are the best tools available today to help us understand the likely impacts of future climate change. Although not perfect, they provide some indication of future changes which allow us to assess the potential implications and allow us to take strategically prepare for such changes.

4.3 Early Climate Change Impacts Studies – Equilibrium models

Equilibrium GCMs are simplified ocean models which were allowed to come into equilibrium with an atmosphere with CO_2 twice that of pre-industrial times, which is at approximately 560 ppm. A CO_2 level of 560 ppm lies within the period of 2°C global warming described by the IPCC emission scenarios (2026-2060; Figure 4). However, results from equilibrium models are not directly comparable to those from transient models because of the significant difference in model mechanics.

Nevertheless, these early studies show trends that are distinctly similar to those displayed in more recent studies using transient models. All indicate warming in the Great Lakes – St. Lawrence Basin (Table 4). Most indicate a reduction in runoff, despite increases in precipitation in some cases, possibly as a result of increased evapotranspiration under higher temperatures (Mortsch et al., 2000; Croley, 2003).

Table 4 Results from 2 x CO_2 equilibrium GCM studies

Author	River basin	Climate Scenario	Annual temperature changes		Annual precipitation changes		Annual changes in runoff	
			Min.	Max.	Min.	Max.	Min.	Max.
Croley (1990, 1992)	Great Lakes – St. Lawrence basin	GISS84	+4.3°C	+4.7°C	-7%	18%	-41%	-2%
		GFDL87	+5.7°C	+7.2°C	-7%	-4%	0	+8%
		OSU88	+3.2°C	+3.5°C	+5%	+8%	-28%	-19%
Walker (1996)	Bay of Quinte Wateshed, Ontario	CCC GCM1	+1.6°C	+9.6°C	n/a	n/a	-12%	n/a
Sanderson and Smith (1993); Smith and McBean (1993)	Grand River, Ontario	GISS87	+4.7C	n/a	+1.9%	n/a	-11%	n/a
		GFDL87	+5.3C	n/a	+0.4%	n/a	-21%	n/a
		CCC GCM1	+5.7°C	n/a	-6.3%	n/a	-22%	n/a
Morin and Sivitzky (1992)	Moisie River, Quebec	CCC GCM1	+4.2°C	n/a	+1.1%	n/a	-5%	n/a

4.4 Recent Climate Change Impacts Studies – Transient models and IS92a emission scenario

Lofgren et al. (2002) used the transient models CGCM1 from the Canadian Centre, and HadCM2 from the U.K. Hadley Centre under the IPCC emission scenario IS92a, together with a hydrologic model, to derive potential impacts on the water resources of the Great Lakes basin under climate change. The results were used in the U.S. National Assessment of the Potential Consequences of Climate Variability and Change and the IJC Reference on Consumption, Diversions and Removals of Great Lakes Water (Lofgren et al., 2000, 2002; Mortsch et al., 1999, 2000). Buttle et al. (2004) used the same projects hydrological changes to estimate the impacts of climate change on hydropower production in Ontario.

Observed climate data collected from 1,800 meteorological stations in the Great Lakes region during the 42-year period of 1954-1995 were used as input to the hydrological model in order to simulate present hydrological conditions (Croley, 2003; Lofgren et al., 2002). Changes in climatic parameters for a future period are obtained from GCMs, calculated as the difference in GCM results between the GCM's base period of 1961-1990 and the future period. The changes in climatic parameters are then added to the observed climatological data from 1954-1995 to produce future climatic conditions, which are then used as input into the hydrological model to estimate changes in hydrological conditions relative to the present. Although there is a mismatch between the GCM base period of 1961-1990 and the period of observations of 1954-1995, such a methodology has been chosen because the advantage of having a longer and more reliable observation record has been considered to outweigh the disadvantages of the mismatch (Mortsch, pers. comm.).

4.4.1 Temperature and Precipitation Changes

The CGCM1 and HadCM2 display distinct responses to increased greenhouse gases under the IS92a emission scenario in terms of precipitation and air temperature for the various lake basins. CGCM1 has air temperature increases over the Great Lakes in the range of 3°C by 2050, at a time when global warming is expected to reach 2°C (Table 4). It also projects small positive and negative changes in precipitation among the individual lake basins (Table 5). The HadCM2, on the other hand, has a smaller air temperature increase by 2050 than CGCM1 or any of the earlier models presented in Section 4.2 (Table 5). It also has annual mean precipitation increased by factors greater than 5% in each lake basin (Table 6). This makes it less prone to water deficits relative to the base case than CGCM1 (Lofgren et al., 2002). By limiting the analysis to two models and one emission scenario, the range of possible futures is not represented fully.

Table 5 Projected changes in air temperature relative to base period of 1961-1990 (both scenarios have equal probabilities) (Lofgren et al., 2002).

	2030 (~1.5°C rise in global temperature)		**2050 (~2°C rise in global temperature)**		**2090 (~4°C rise in global temperature)**	
Lake	**CGCM1**	**HadCM2**	**CGCM1**	**HadCM2**	**CGCM1**	**HadCM2**
Superior	+1.9°C	+1.2°C	+2.9°C	+1.6°C	+5.4°C	+2.9°C
Michigan-Huron	+2.2°C	+1.0°C	+3.2°C	+1.4°C	+5.6°C	+2.7°C
Erie	+2.5°C	+0.9°C	+3.4°C	+1.3°C	+5.9°C	+2.6°C
Ontario	+2.1°C	+1.0°C	+3.0°C	+1.4°C	+5.4°C	+2.7°C

Table 6 Projected changes in precipitation relative to base period of 1961-1990 (Lofgren et al., 2002).

	2030 (~1.5°C rise in global temperature)		**2050 (~2°C rise in global temperature)**		**2090 (~4°C rise in global temperature)**	
Lake	**CGCM1**	**HadCM2**	**CGCM1**	**HadCM2**	**CGCM1**	**HadCM2**
Superior	+4%	+4%	+5%	+5%	+14%	+16%
Michigan-Huron	+2%	+8%	+4%	+8%	+14%	+20%
Erie	-3%	+8%	-2%	+11%	+5%	+21%
Ontario	+1%	+8%	+1%	+9%	+7%	+17%

It is unclear why future time periods for HadCM2 is more cool and moist compared to those of the CGCM1. Unlike CGCM1 and previously studied models, HadCM2 includes the presence of the Great Lakes as a water surface with significant thermal inertia (Lofgren et al., 2002). It also uses a smaller grid size as well as more atmospheric layers than CGCM1, providing a sharper resolution horizontally and greater resolution above ground. CGCM1 uses more layers in the oceanic analysis and treats water vapor feedback and aerosols differently (Buttle et al., 2004). Differences in the treatment of aerosols could also contribute to the disparity in results. Nonetheless, HadCM2's disagreement with other models widens the range of potential outcomes in hydrologic response to greenhouse warming (Lofgren et al., 2002).

4.4.2 Hydrological Changes

Although CGCM1 projected increased temperature and precipitation for the Great Lakes-St. Lawrence basin, the hydrologic model projected increased evaporation (Table 7) that overbalanced the increased precipitation. At a time of 1.5°C global warming, in 2030, lake levels lower by up to 1.01 m (Table 8). At a time of 4°C global warming, by 2090, lake levels drop by as much as 1.38 m on Lakes Michigan and Huron by. The magnitude of these changes in lake levels is large enough to distinguish them from normal variability, except on Lake Ontario (Lofgren et al., 2002).

A very different picture emerges from using the HadCM2 (Table 8). Although the HadCM2 model also had increases in both temperature and precipitation, the increase in temperature was much less than in CGCM1 and the increase in precipitation was much greater. The wetter climate results in water level rises of up to 0.35 m, but mostly less than 0.10 m. The increases in water levels do not rise above the level of natural variability on any of the lakes (Lofgren et al., 2002).

Table 7 Projected changes in mean annual lake evaporation relative to observed data from 1954 to 1995 (Lofgren et al., 2002).

	2030 (~1.5°C rise in global temperature)		**2050 (~2°C rise in global temperature)**		**2090 (~4°C rise in global temperature)**	
Lake	CGCM1	HadCM2	CGCM1	HadCM2	CGCM1	HadCM2
Superior	+17%	+7%	+24%	+13%	+39%	+19%
Michigan	+15%	+6%	+21%	+10%	+34%	+16%
Huron	+13%	+6%	+22%	+10%	+33%	+17%
Erie	+12%	+6%	+20%	+9%	+29%	+17%
Ontario	+12%	+6%	+20%	+9%	+31%	+16%

Table 8 Projected changes in lake levels relative to observed data from 1954 to 1995 (Lofgren et al., 2002).

	2030 (~1.5°C rise in global temperature)		**2050 (~2°C rise in global temperature)**		**2090 (~4°C rise in global temperature)**	
Lake	CGCM1	HadCM2	CGCM1	HadCM2	CGCM1	HadCM2
Superior	*-0.22m*	-0.01m	*-0.31m*	-0.01m	*-0.42m*	+0.11m
Michigan-Huron	*-0.72m*	+0.05m	*-1.01m*	+0.03m	*-1.38m*	+0.35m
Erie	*-0.60m*	+0.05m	*-0.83m*	+0.04m	*-1.13m*	+0.27m
Ontario	-0.35m	+0.02m	-0.53m	+0.04m	-0.99m	+0.01m

Figures in italics indicate magnitudes of changes which are large enough to be distinguished from natural variability.

4.4.3 Changes in Hydropower Generation

A conclusion from reviewing all the climate change impact assessments in the Great Lakes region is that there is a large body of research that supports the point that water levels are likely to decline due to climate change. Its downstream effects on hydropower generation have been examined by Buttle et al. (2004) and Lofgren et al. (2002).

Buttle et al. (2004) derived monthly flow rates and lake levels from the results of Lofgren et al. (2002) and Mortsch et al. (2000), and estimated changes in hydropower generating capacity in Ontario for 2030 and 2050, at the time of a 1.5°C and 2°C global warming, respectively. The reduction of electricity production projected by CGCM1 under 2°C global warming is commensurate to a reduction of 25-35% of current generating capacity while HadCM2 indicated a small potential increase of 3% (Table 9).

The impacts on electricity production were monetized by multiplying the change in generating capacity with a selected price (Buttle et al., 2004). Results from CGCM1 indicated losses of $240 million to $350 million per year under 2°C warming, while HadCM2 indicated potential gains of up to $25 million per year (Table 10). The HadCM2 scenarios would appear to have positive impacts on electricity supply in Ontario. However, Buttle et al. (2004) concluded that, given the potential scope of negative impacts – as indicated by the CGCM1 scenarios - it would be in the best interest of Ontario's electricity suppliers to consider the potential impacts of climate change in their supply and demand planning.

Table 9 Projected changes in hydropower generation in Ontario from the Great Lakes for 2030 (1.5°C global warming) and 2050 (2°C global warming) (Buttle et al., 2001). Figures represent combined hydropower generation from three generating sites: at the Niagara Falls complex and Saunders station at Cornwall, run by OPG and the Clergue station at Sault Ste. Marie run by Brookfield Power.

		Change in hydropower generation in 2030 (~1.5°C rise in global temperature)		**Change in hydropower generation in 2050 (~2°C rise in global temperature)**	
	Base case	**CCCma1**	**HadCM2**	**CCCma1**	**HadCM2**
Average annual total hydropower energy (OPG, Brookfield Power St. Mary's, Niagara and St. Lawrence river plants)	18.8 TWh	14.0 TWh	19.5 TWh	12.4 TWh	19.4 TWh
Change from base case		-26%	+3%	-34%	+3%

Table 10 Change in annual hydropower generation by price under different climate change scenarios. Post-deregulation price of $52/MWh assumed. Prices kept constant in 2002 Canadian dollars (Buttle et al., 2004).

	Change in hydropower generation in 2030 (~1.5°C rise in global temperature)		**Change in hydropower generation in 2050 (~2°C rise in global temperature)**	
	CCCma1	**HadCM2**	**CCCma1**	**HadCM2**
Change from base case	Loss of $180M to $250M / yr	Gain of up to $25M / yr	Loss of $240M to $350M / yr	Gain of up to $25M / yr

Lofgren et al. (2002) used an interest satisfaction model to quantify the degree to which shipping and hydropower interests in the upper St. Lawrence River and the outlet of Lake Ontario might be satisfied, given the projected changes in lake levels and water supplies. Their results showed considerably reduced interest satisfaction for most of the interests when using the output from the CGCM1. By the time of a 2°C global warming, hydropower needs at the facility at Moses-Saunders at Cornwall, Ontario, could be satisfied less than 2% of the time. By the time of a 4°C global warming, water needs for Hydro Quebec may not be able to be met at all. On the other hand, little change in interest satisfaction was seen when using the HadCM2.

4.5 Latest Climate Change Impacts Studies – Transient models and SRES emission scenarios

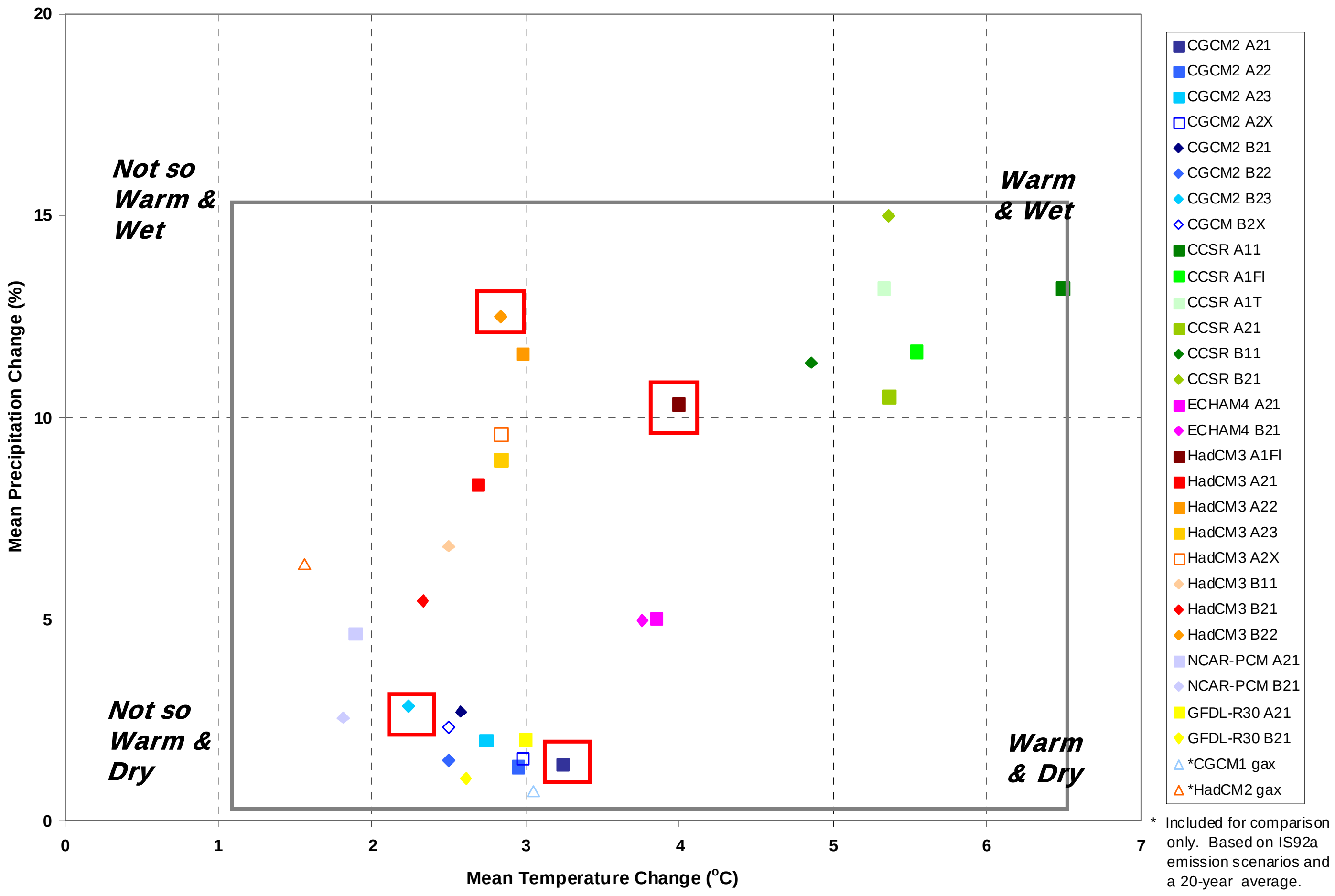
The IJC's International Lake Ontario – St. Lawrence River (LOSLR) study was a five year study that examined the effects of water level and flow variations on all users and interest groups (LOSLR, 2006). As part of the study, four climate change scenarios, for a period centered on 2050, at a time of 2°C global warming, were chosen, in order to examine the impact of climate change on the hydrology of the Great Lakes and St. Lawrence River. The impacts on hydropower generation on the St. Lawrence River were assessed additionally. Observed climate data collected from 1,800 meteorological stations in the Great Lakes region during the 52-year period of 1948-1999 were used as input to the hydrological model in order to simulate present hydrological conditions (Croley, 2003). Changes in climatic parameters for a future period are obtained from GCMs, calculated as the difference in GCM results between the GCM's base period of 1961-1990 and the future period. The changes in climatic parameters are then added to the observed climatological data from 1948-1999 to produce future climatic conditions, which are then used as input into the hydrological model to estimate changes in hydrological conditions relative to the present.

4.5.1 Emission and climate change scenarios

In order to choose four climate scenarios that would capture a range of possible future climate conditions, results from 28 transient, SRES-based emission scenario experiments from six GCMs were considered (Mortsch et al., 2005). By 2050, at a time of 2°C warming, the 28 model experiments indicate that mean annual temperature in the Great Lakes – St. Lawrence region could increase by 1.5°C to 6.5°C. Mean annual precipitation is projected to increase from less than 1% to 15%.

The four experiments selected for the LOSLR study represent the climate change scenarios with 1) warm and wet conditions: HadCM3 A1FI, 2) warm and dry conditions: CGCM2 A21, 3) not as warm and wet conditions: HadCM3 B22, and 4) not as warm and dry conditions: CGCM2 B23 (Fig. 5).

Figure 5 Range of possible temperature and precipitation changes in the Great Lakes – St. Lawrence region under a 2°C global warming, as indicated by 28 climate change scenarios. Red squares indicate the four climate change scenarios chosen for the LOSLR study (Mortsch et al., 2005).



* Included for comparison only. Based on IS92a emission scenarios and a 20-year average.

4.5.2 *Temperature and Precipitation Changes*

The daily average air temperatures for all four climate change scenarios are higher than the base period of 1961-1990. The warming is greatest for the warm and wet scenario (HadCM3 A1F1), followed by the warm and dry (CGCM2 A21), not as warm and wet (HadCM3 B22), and the not as warm and dry (CGCM2 B23) scenarios and for Lakes Michigan and Huron and Georgian Bay (Croley, 2003) (Figure 6, Table 11).

Figure 6 Daily average air temperature in Great Lakes region for the base period of 1961-1990 (base case) and four climate change scenarios under a 2°C global warming (Croley, 2003).

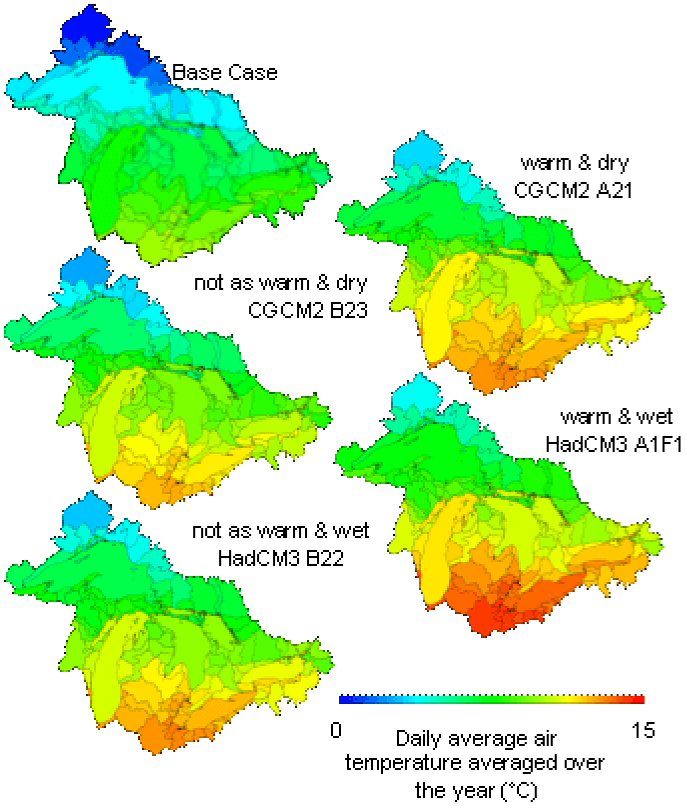


Table 11 Projected changes in mean annual air temperature relative to base period of 1961-1990 for period centered on 2050, at a time of 2°C global warming (Croley, 2003).

	Change in air temperature in 2050 (~2°C rise in global temperature)			
Basin	**Warm and Dry: CGCM2 A21**	**Not as Warm and Dry: CGCM2 B23**	**Warm and Wet: HadCM3 A1FI**	**Not as Warm and Wet: HadCM3 B22**
Superior	+3.0°C	+2.2°C	+3.7°C	+2.7°C
Michigan	+3.6°C	+2.8°C	+3.9°C	+2.9°C
Huron	+3.6°C	+2.3°C	+4.1°C	+3.1°C
Georgian	+3.4°C	+2.4°C	+4.0°C	+3.0°C
St. Clair	+3.5°C	+2.6°C	+4.2°C	+3.1°C
Erie	+3.1°C	+2.4°C	+4.2°C	+3.0°C
Ontario	+3.2°C	+2.2°C	+4.0°C	+3.0°C
Great Lakes-St. Lawrence Basin	+3.2°C	+2.2°C	+4.0°C	+2.8°C

Overland precipitation shows much more variability than air temperature both among scenarios and among lake basins. Table 12 and Figure 7 show that generally precipitation is greater on all lakes and scenarios, except Michigan and Erie, for the not as warm and dry (CGCM2 B23) scenario and Erie for the warm and dry scenario (CGCM2 A21). The largest increase occurs on Georgian Bay for the warm and wet (HadCM3 A1FI) scenario and on Erie for the not as warm and wet (HadCM3 B22) scenario. Precipitation increase is generally less in the CGCM2 scenarios than in the HadCM3 scenarios. This follows a similar trend found in the earlier studies of Lofgren et al. (2002) and Mortsch et al. (2000) where the earlier versions of the models and the IS92a scenario were used.

Figure 7 Annual total precipitation in Great Lakes region for the base period of 1950-1999 (base case) and four climate change scenarios under a 2°C global warming (Croley, 2003).

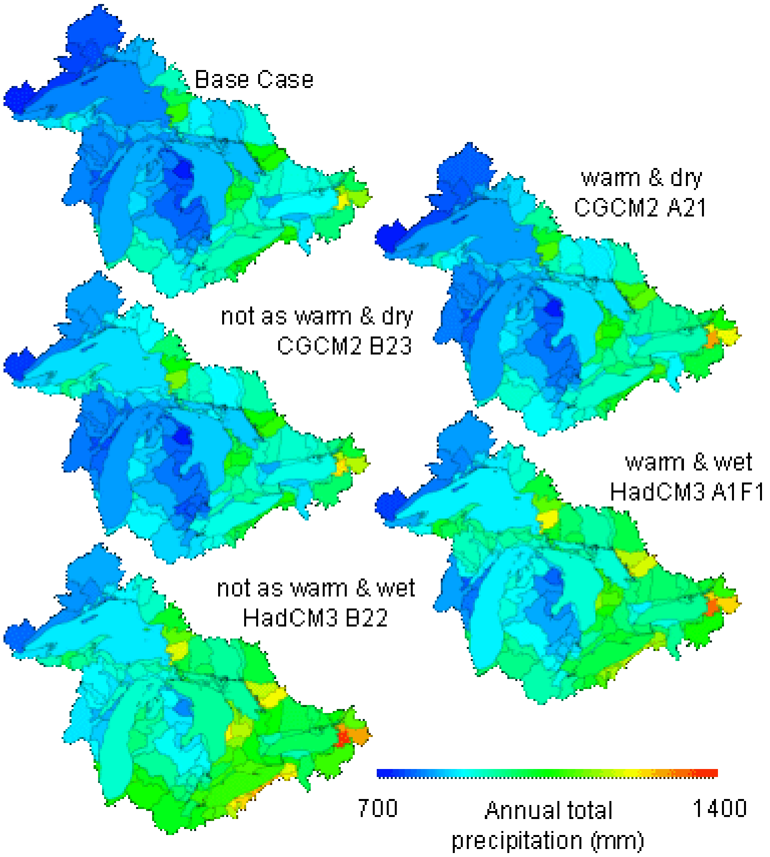


Table 12 Projected changes in mean annual precipitation for 2050, at a time of 2°C global warming (Croley, 2003).

	Change in precipitation in 2050 (~2°C rise in global temperature)			
Basin	**Warm and Dry: CGCM2 A21**	**Not as Warm and Dry: CGCM2 B23**	**Warm and Wet: HadCM3 A1FI**	**Not as Warm and Wet: HadCM3 B22**
Superior	+1%	+6%	+8%	+9%
Michigan	0%	-1%	+7%	+12%
Huron	+2%	+1%	+7%	+14%
Georgian	+3%	+3%	+11%	+13%
St. Clair	+1%	0%	+7%	+15%
Erie	-1%	-4%	+6%	+16%
Ontario	+5%	+1%	+9%	+13%
Great Lakes-St. Lawrence Basin	+1%	+2%	+10%	+13%

4.5.3 Hydrological Changes

The increased air temperatures significantly alter the heat balance of the land and water surfaces. Snow pack is reduced. Depending on the climate change scenarios and lake basins, the decrease in accumulated snow moisture ranges from 26% to 84%. Furthermore, evapotranspiration increases significantly by 8% to 27% (Table 13). The increased evapotranspiration and decreased snow pack give rise to less moisture available in the soil and groundwater zones. A general lowering of soil moisture is most acute for the warm and dry (CGCM2 A21) scenario, accompanied by a corresponding loss of groundwater storage. The net effect of the increased air temperatures, through increased evapotranspiration and decreased moisture storage in the basins, is decreased lake levels (Table 14) (Croley, 2003). Drops in lake levels range from 0.12 m for Lake Superior in the not as warm and wet (HadCM3 B) scenario to 1.18 m for Michigan-Huron in the warm and dry (CGCM2 A21) scenario.

Table 13 Projected changes in mean annual evapotranspiration for 2050, at a time of 2°C global warming (Croley., 2003).

	Change in evapotranspiration in 2050 (~2°C rise in global temperature)			
Lake	**Warm and dry: CGCM2 A21**	**Not as Warm and Dry: CGCM2 B23**	**Warm and Wet: HadCM3 A1F1**	**Not as Warm and Wet: HadCM3 B22**
Superior	+17%	+17%	+27%	+21%
Michigan	+13%	+ 9%	+20%	+20%
Huron	+18%	+13%	+21%	+22%
Georgian	+17%	+13%	+26%	+22%
St. Clair	+17%	+11%	+20%	+22%
Erie	+12%	+8%	+18%	+22%
Ontario	+23%	+12%	+26%	+23%

Table 14 Projected changes in mean annual lake outflow for 2050, at a time of 2°C global warming (Mortsch et al., 2006).

	Change in lake outflow in 2050 (~2°C rise in global temperature)			
Lake	**Warm and dry: CGCM2 A21**	**Not as Warm and Dry: CGCM2 B23**	**Warm and Wet: HadCM3 A1F1**	**Not as Warm and Wet: HadCM3 B22**
Superior	-20%	-6%	-18%	-9%
Erie	-26%	-18%	-22%	-5%
Ontario	-24%	-17%	-21%	-5%

Table 15 Projected changes in mean annual lake levels for 2050, at a time of 2°C global warming (Mortsch et al., 2006; Hebb and Mortsch, 2005).

	Change in lake levels in 2050 (~2°C rise in global temperature)			
Lake	**Warm and dry: CGCM2 A21**	**Not as Warm and Dry: CGCM2 B23**	**Warm and Wet: HadCM3 A1F1**	**Not as Warm and Wet: HadCM3 B22**
Superior	-0.36 m	-0.20 m	-0.33 m	-0.12 m
Michigan-Huron	-1.18 m	-0.73 m	-0.98 m	-0.29 m
Erie	-0.81 m	-0.55 m	-0.67 m	-0.15 m
Ontario	-0.47 m	-0.25 m	-0.32 m	-0.08 m

4.5.4 Changes in Hydropower Generation

As part of the LOSLR study, representatives of Hydro Quebec, Ontario Power Generation (OPG) and New York Power Authority (NYPA) developed quantitative algorithms to relate Lake Ontario levels and St. Lawrence River flows to megawatt-hour electricity production at each generation station. Hydropower production is a function of the outflows and operating head. The head is defined as the difference between the water level immediately upstream of the power station and immediately downstream of the plant. In general, higher water levels on Lake Ontario result in higher outflows. This allows for more megawatt production. However, if flows are too high, they can exceed the capacity of the plants, increasing flows will then have diminishing returns. The algorithms developed for the LOSLR were based on existing models already developed by each of the companies (LOSLR, 2006).

Under 2°C global warming, all climate scenarios project reductions in outflows and lake levels. Such reductions affect hydropower generation (Table 16). Reductions in power production could be as high as 17% under the warm and dry scenario (CGCM2 A21), or can be only about 1% under the not as warm and dry scenario (CGCM2 B23) (Table 15). There is a high likelihood that hydropower generation will decrease in the future as a result of climate change, in the absence of adaptation.

Table 16 Projected changes in hydropower generation on the St. Lawrence River for 2050, at a time of 2°C global warming (Mortsch et al., 2006). Figures represent combined hydropower generation from three generating stations: the Moses-Saunders International Power Project at Cornwall, run by OPG and NYPA, and the Beauharnois-Les Cèdres complex 80 km downstream run by Hydro Québec.

		Change in hydropower generation in 2050 (~2°C rise in global temperature)			
	Base case	**Warm and dry: CGCM2 A21**	**Not as Warm and Dry: CGCM2 B23**	**Warm and Wet: HadCM3 A1F1**	**Not as Warm and Wet: HadCM3 B22**
Average annual total hydropower energy (Hydro Québec, OPG, NYPA St Lawrence river plants)	27.4 TWh	22.6 TWh	24.4 TWh	23.6 TWh	26.8 TWh
Change from base case		-17%	-1%	-14%	-2%

Results from these latest scenarios reaffirm the results from Buttle et al. (2004) and Lofgren et al. (2002). Buttle et al. (2004) showed that, under a 2°C global warming, the hydropower capacity of Ontario could be reduced by up to one-third. Lofgren et al. (2002) showed that water needs at the Moses-Saunders facility may be satisfied less than 2% of the time under the same amount of warming (Section 4.4.3). In their studies, results from the Hadley model (HadCM2) indicated some positive impacts on hydropower production under a 2°C warming, while in these latest scenarios, the results from the next generation of the Hadley model (HadCM3) indicated small negative impacts for the same period.

As discussed in Section 4.4.1, reasons for the differences between the Hadley and the Canadian models are unknown. However, our review of all the climate change impact assessments in the Great Lakes region supports the point that water levels are likely to decline due to climate change. In addition, changes in hydrologic conditions and hydropower production need to be considered against the backdrop of increasing energy demand and possible impacts of climate change on energy demand. Today, per capita Canadian consumption almost equals that of the United States - the world's biggest consumer of energy, and Canada's energy consumption continues to increase (Ménard, 2005). Based on the National Energy Board's scenarios (2003), Canada's energy demands could be 60-100%[13] higher by the year 2050 - at the time of 2°C global warming. Peak energy demand is also linked with extreme temperatures (Colombo et al., 1999). In the case of Toronto, mean peak power demand would increase by 9.5% for a 2°C increase in mean daily maximum temperature. Climate change is likely to further increase the frequency and severity of hot spells in summer (Hengeveld et al., 2005), and by 2050, under a 2°C global warming, maximum temperatures in Canada are likely to increase by 2-4°C (Kharin et al., 2006). As mean peak power increases, more extreme power demand days could occur, potentially resulting in more potential brownouts and similar reduced-capacity phenomena (Colombo et al., 1999). On the other hand, in order

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[13] Assuming an average annual growth rate of 1.0-1.4% (National Energy Board, 2003).

to meet energy demands, reduction in hydropower production is likely to lead to increase in power generation from fossil-fuel or nuclear power plants (LOSLR, 2006), thus accelerating climate change and generating other environmental problems.

Against this backdrop of increase in energy demand and likely reduction in hydropower production, our results support the conclusions of Buttle et al. (2004) that it would be in the best interest of electricity suppliers and regulatory bodies to consider the potential risks of climate change early on in their supply and demand planning. In addition, it is equally important to take immediate actions to mitigate the effects of climate change. Managing energy demand, improving energy efficiency and increasing the use of renewable energy sources will contribute towards the reduction of carbon dioxide emissions and thus, mitigation of climate change, while improving energy security at the same time.

5 Conclusions

Under a 2°C global warming, Great Lakes – St. Lawrence Basin is expected to warm by 2.2°C to 4.2°C, accompanied by an increase of precipitation of up to 16%. Warmer temperatures would likely result in higher evapotranspiration rates which could offset the increase in moisture brought about by increased precipitation. As a result, five out of six climate scenarios indicate reductions in lake levels and outflow under a 2°C global warming. Lake levels could fall by up to 1.18 m.

Reductions in both lake levels and outflow are expected to lead to loss in hydropower generating capacity in the Great Lakes – St. Lawrence Basin. Under 2°C global warming, water needs for hydropower generating capacity on the St. Lawrence River may be reduced by 2-17%; annual loss in electricity production in Ontario could range from $240 million to $350 million (Canadian dollars at 2002 prices). Under a few climate change scenarios, a 2°C global warming led to smaller negative impacts or some small positive impacts on the hydropower production of the Great Lakes. One scenario indicates that there may be a gain of up to $25 million a year for hydropower producers in Ontario.

However, in light of the potential scope of negative impacts on hydropower production, against a backdrop of ever-increasing energy demand, it would be in the best interest of electricity suppliers and regulatory bodies to consider the potential impacts of climate change in their mid- and long-term planning. By 2050 – the time of 2°C global warming – energy demands nationally are expected to increase by 60-100%. Climate change is also likely to increase the frequency and severity of hot spells in the summer, increasing peak power demand, and potentially resulting in more brownouts and other reduced-capacity phenomena. In order to meet energy demands, reduction in hydropower production is likely to lead to increase in power generation from fossil-fuel or nuclear power plants, thus accelerating climate change and generating other environmental problems. Therefore, it is essential that government authorities, industry and citizens take immediate actions to mitigate the effects of climate change. Managing energy demand, improving energy efficiency and increasing the use of renewable energy sources will contribute towards the reduction of CO_2 emissions and thus, mitigation of climate change, while improving energy security at the same time.

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