DFO Literature and Expert Review: Limnological and Hydrological Responses to Climate Change in Canadian Freshwaters: Great Lakes and Prairie Watersheds

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Limnological and Hydrological Responses to Climate Change in Canadian Freshwaters: Great Lakes and Prairie Watersheds

by

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ABSTRACT

Fisheries and Oceans Canada committed to undertake the analysis and modeling of climate trends and projections, as well as an assessment of impacts risks and vulnerabilities for freshwater and marine sub-regions in Canada. This review provides support under this project by providing a summary of the state of science on climate projections in the Great Lakes and Canadian prairies region and how they might impact the physical, chemical, hydrological and fish habitat impacts. The objective of this report is to summarize climate change related research pertaining to climatic variables (including Air Temperature, Humidity, Precipitation, Wind and Carbon Dioxide) and aquatic variables (Water Temperature, Water Levels and Stream Flows, Ice Cover, Waves and Currents, Turbidity, Dissolved Oxygen, pH, Nutrients and Contaminants).

RÉSUMÉ

Pêches et Océans Canada s'est engagé à réaliser l'analyse et la modélisation des tendances et des projections climatiques, ainsi qu'une évaluation des répercussions, des risques et des vulnérabilités en ce qui concerne les sous-régions d'eau douce et de milieux marins au Canada. Le présent examen appuie ce projet en offrant un résumé des données scientifiques sur les projections climatiques dans la région des Grands Lacs et des Prairies et la façon dont elles pourraient avoir des répercussions physiques, chimiques et hydrologiques ainsi que des répercussions sur l'habitat du poisson. L'objectif du présent rapport consiste à synthétiser les recherches liées aux changements climatiques portant sur les variables climatiques (notamment la température de l'air, l'humidité, les précipitations, le vent et le dioxyde de carbone) et les variables aquatiques (la température de l'eau, les niveaux d'eau, le débit des cours d'eau, la couverture de glace, les vagues et les courants, la turbidité, l'oxygène dissous, le pH, les nutriments et les contaminants).

1. CLIMATE CHANGE SCIENCE

1.1 INTRODUCTION TO REVIEW

The Great Lakes basin is home to approximately 40 million people comprising 25% and 10% of the populations of Canada and the United States, respectively (Cherkauer and Sinha 2010). Water levels in the Great Lakes are a major concern as the lakes and their connecting waterways support commercial shipping in excess of 175.3 million tons per year, are vital for urban water supply, support a wide range of fisheries (e.g. 23.6 million fish recreationally harvested in 2005) and habitats for ecologically, economic and socially important fish and wildlife. A great effort is expended in trying to understand and predict the effects of climate change on ecosystems across the planet. As indications that changes in climate are already occurring become increasingly common, the ability to mitigate unwanted changes becomes an increasing need.

Fisheries and Oceans Canada (DFO) is responding to this need by conducting a large risk assessment that will assess impacts and vulnerabilities of ecosystems in Canada to climate change. The ecological risk assessment will contribute to a socio-economic assessment of business risks and possible adaptation strategies within a program entitled the “Aquatic Climate Change Adaptation Services Program” (ACCASP). This report contributes to this process by summarizing the state of climate, limnological and ecological science regarding climate change in both the Prairies and Great Lakes primary drainages

This review provides a summary of:

1. Climate modeling and climate change science
2. Projections of climate change in the Great Lakes and Prairie regions
3. Expected changes to lake limnology and fluvial systems through the primary projected changes in climate including mainly temperature, precipitation, wind and water quality
4. Effects of limnological changes on aquatic organisms including a small section on plants with a greater emphasis on invertebrates and fish
5. Major gaps in knowledge in the current state of aquatic/climate change science
6. Interviews with 11 experts on climate change in Canada

1.2 CLIMATIC PROCESSES

Climate is commonly defined as the weather averaged over a long period of time and is usually described statistically. A standard averaging period is 30 years for the mean and variability of precipitation, temperature and wind, but other periods may be used depending on their purpose. Climate also includes statistics other than the average, such as the magnitudes of day-to-day or year-to-year variations (IPCC 2007).

Weather and climate are determined by the magnitude and distribution of short wave (SW) radiation from the sun and outgoing long wave radiation (OLR) in the earth’s atmosphere (Trenberth *et al*. 2009). Climate and hydrological processes are closely related to the energy budget on earth, which is in turn determined by energy conversions processes occurring within different altitudinal zones (as well as at the interfaces between zones) from the surface of the earth up through the atmosphere, troposphere, and stratospheric interface (Trenberth *et al*. 2009). While many of these processes are known, there are large discrepancies among the quality of data available at each zone which cause difficulties in understanding and predicting climate. For example, new satellite technology with a higher scanning frequency has allowed for very accurate radiation estimates at the top of the atmosphere level. In contrast, due to a scarcity of sample points, calculations of energy radiation at the surface are highly uncertain.

When data points are few, resampling of existing points may be used to fill data gaps, which likely introduce biases (Stephens *et al*. 2011). In consequence, among the numerous models available to predict changes in climate, many show agreement on historical trends but often fail to show consistency in forward looking projections (Andrews and Forster 2009; Stephens *et al*. 2010). Notwithstanding their limitations, these methods have been used to answer some main questions in climate research (Andrews and Forster 2009) including:

1. What is the system response to a climate forcing?
2. How long does it take following a change for the system to reach a steady state?
3. How are changes in temperature going to impact the hydrological cycle?

The surface energy budget is the fundamental equation used in climate models and can be described by (Stephens *et al*. 2010):

$$R = SW\downarrow(1-\alpha) + LW\uparrow - LW\downarrow \quad , \qquad \text{Eq. 1}$$

where R is the net heat flux, SW is the short wave radiation from sun, and LW is the long wave radiation, which can be outgoing or incoming from the heat accumulated in the atmosphere. Absorption, scattering and emission of these sources of radiation ultimately result in an energy surplus at the earth's surface and a deficit in the atmosphere. The surplus energy at the surface evaporates water and contributes to the planet's hydrological cycles. Thus in order to estimate a change in global temperature from fluctuations in incoming and outgoing radiation, the latent heat fluxes (i.e. evaporation and transpiration of water) and sensible heat fluxes (i.e. conductive heat from the Earth's surface) have to be introduced in the equation. We can do this using (Wild 2011):

$$\rho C \Delta z \frac{\delta T}{\delta t} = R - SH - LH \quad , \qquad \text{Eq. 2}$$

where ρ is the air density, C is the specific heat capacity, δT is the temperature variation in δt time, R is the net radiative heat flux, SH is the sensible heat flux and LH is the latent heat flux for various water states. Another equation was used by a study illustrating the role of carbon dioxide forcing across climate models (Andrews and Forster 2009) in which the energy budget surplus at the surface level was described by:

$$N = \sum_j F_j - \sum_j \alpha_j \Delta T \quad , \qquad \text{Eq. 3}$$

where N is the net surface radiation imbalance, F_j are the surface heat fluxes (LW, SW, LH, SH) and α_j are the feedback parameters that determine the change in temperature (ΔT). Analysis of time-dependent surface energy balance using this framework allows distinction between forcing and response. Forcing is identified as the immediate response to a sudden change (F=N as ΔT approaches 0) and the feedback is identified when new perturbed steady state is reached (N=0).

For every one degree increase in temperature (in Kelvins), climate models will typically estimate a 7% increase of column vapour (W), which is in good agreement with the standard estimates of changes in moisture content of air with temperature (i.e. the Clausius-Clapeyron equation). However, this increase in humidity will typically only correspond to about a 2% increase of precipitation. One possible explanation for the difference between W and the precipitation response was given by Andrews and Forster (2009), and involves a positive surface LW feedback and a strong negative LH feedback. While net surface SW and SH change little with ΔT, the strong negative LH feedback has an important influence on the evaporation-condensation process and may explain the lower hydrological cycle sensitivity. Ultimately, these models demonstrate that changes in solar radiation typically have non-linear changes in ambient air temperature, humidity and precipitation.

1.3 HISTORICAL SHIFTS IN CLIMATE

The fundamental climate models demonstrate how incoming radiation can change global temperatures and levels of precipitation but they of course ignore many other contributing factors. Past changes in climate have offered scientists clues to understanding the overall influence of the earth's heterogeneous surface on global climate. Solar radiation varies with shifts in the Earth's orbit and tilt relative to the Sun, both of which change over tens of thousands of years (Ruddiman 2001). Past changes in climate have been identified to be a result of a combination of astronomical phenomena such as the eccentricity cycle (ie. the change of earth's orbit over a period of 100 thousand years [k.y.]), obliquity cycle (ie. the change in earth's tilt over 41 k.y.) and the procession of the equinoxes (10-23 k.y.) superimposed on a longer planetary trend toward a cooler and dryer climate. While the astronomical evolution can explain the superimposed cycles, an explanation for a cooler and dryer long term trend has only just recently been found. First proposed by a team of modellers from Brown University and further developed by Gianinni *et al.* (2003), the Sea Surface Temperature (SST) gradient theory states that an increasing polarized distribution of temperatures at the equatorial latitude of the Indian Ocean and Pacific Ocean basin, triggered climatic changes 2 million years ago in Eastern Africa (about 1 million years after the start of planetary glaciation). Peter de Menocal (2004) analyzed marine paleo-climatic records on the both sides of Africa and traced the biomolecules of leaf waxes to find a strong correlation between the increased percentage of arid adapted C_4 vegetation and glacial periods. More recently, marine records have been used to calibrate the models predicting the rainfall patterns and climatic evolution at a global scale, although in particular in the African continent (de Menocal 2011). These types of studies were used to reproduced the paleo-climatic environment and confirm these long term cooling and drying trends on the planet. Similarly in southwestern North America, Seager *et al*. (2007) concluded, based on results from 24 climate models, that the transition to a more arid climate was related to La Nina-like ocean conditions as the tropics warm and equatorial convection increases. These studies not only helped to explain past climatic events but also illuminated the important influence ocean currents and temperatures have on the global climate.

Past climatic events also shed light on the role of greenhouse gases, clouds and fine airborne particulates in climate change. An important help in elucidating the influence anthropogenic impacts comes from the Medieval Climate Anomaly period (MCA; 800–1300 A.D.). During the MCA, increased irradiance coupled with low volcanic activity produced increased radiative forcing and climate warming (MacDonald 2010). Volcanic eruptions release fine particles into the air which can cool the environment by reflecting incoming solar radiation back out of the atmosphere. The MCA was associated with widespread aridity and increased fires in western North America. Studies on proxy temperature data such as tree circles, paleo-hydrological records and eutrophic lake cores, demonstrated correlations between a temperature rise due to increased radiative forcing, aridity and a multidecadal persistence of La Niña-like conditions in southwestern North America (Cook *et al*. 2009; MacDonald 2010). Following the MCA was a period of modest global cooling called the "Little Ice Age" (LIA; 1350-1850 A.D.) however the causes of this period are a subject of great speculation involving hypotheses of decreased solar radiation, increased volcanic activity, slowing ocean currents, and decreased carbon dioxide concentrations in the atmosphere.

1.4 CLIMATE CHANGE PROJECTION MODELS

The most common models for predicting climate and weather conditions are the Global Circulation Models (GCMs; note that GCM also refers to Global Climate Models of which Global Circulation Models are a component) which can be equally linked to processes within the atmosphere or those within the oceans. The GCMs are a flexible set of models that use some of the relationships described above, combined with a wide range of other models such as ice sheet and chemical transport models, depending on the questions being asked. Most GCMs are spatially referenced by superimposing them on a grid system which can be either rectangular (e.g. latitude and longitude) or based on irregular areas (e.g. ecozones). Some of the more common GCMs include the United Kingdom Meteorological Office's Hadley Centre’s HadCM3 and Geophysical Fluid Dynamics Laboratory (GFDL) CM2 series which are coupled atmosphere-ocean models (Table 1 and 2).

There is a long-standing debate within the climate community as to how the tropical Pacific will respond to increased greenhouse gases. The debate focusses specifically on whether the ocean surface temperature will more closely resemble El Niño, or La Niña condition (Vecchi *et al* 2008). This distinction is very important because conditions in the tropical Pacific affect a whole range of weather phenomena: tropical cyclone activity, drought and flood patterns at a global scale. Observational data compared with climate models have demonstrated that SST based models give a more accurate representation of climate change than the coupled GCM models (Vecchi *et al.* 2008). However, GCM models still form the basis of predictions from Intergovernmental Panel on Climate Change (IPCC). The response of the tropical Pacific to increasing greenhouse gases represents a fascinating intersection of theory, observation and modelling.

Table 1. Details of the global climate models and emission scenarios used for future climate projections. All projections are based on simulations conducted for the IPCC AR4 (Cherkauer and Sinha 2010).

Global climate model		
Model name	Description	Sensitivity to GHGs
GFDL	NOAA Geophysical Fluid Dynamics Laboratory (GFDL) version CM2.1.1 (Stouffer et al., 2006; Delworth et al., 2006)	High
HadCM3	U.K. Met Office Hadley Center Climate Model, version 3.1 (Gordon et al., 2000; Pope et al., 2000)	Medium
Emission scenarios		
Scenario	Description	Maximum CO_2
B	• global population peaks in mid-century before declining, • rapid changes in economic structures towards service and information economy, and • rapid introduction of clean and resources-efficient technologies.	550 ppm
A1B	• very rapid economic growth, • same global population pattern as B1, and • rapid introduction of new and more efficient technologies.	720 ppm
A2	• gradual continuous increase in global population, • regionally oriented economic growth, and • fragmented technological development.	850 ppm

Table 2. Global climate models and scenarios of greenhouse gas concentration used to generate climate scenarios (Cherkauer and Sinha 2010).

GCM	Research center and country	Resolution (lat × long)	SGHG
CSIRO-Mk2	Australia's Commonwealth Scientific and Industrial Research Organization, Australia	3.2° × 5.6°	A2 and B2
ECHAM4	Max Planck Institute for Meteorology, Germany	2.8° × 2.8°	A2 and B2
HadCM3	UKMO United Kingdom Meteorological Office, United Kingdom	2.25° × 3.75°	A2b and B2b

Greenhouse gas emissions by anthropogenic sources began with the advent of agriculture in human civilization, however it was the industrial revolution of the mid-1700s which began the emission of large amounts of carbon dioxide and methane into the atmosphere. Over the last 300 years CO_2 has increased by roughly one-third as a result of burning fossil fuels and deforestation (IPCC 2007). Smaller amounts of other (in some cases more powerful) greenhouse gases have been released in the most recent century, including sulphur hexafluoride and perfluoropentane. Predicted change in global temperatures is a complex relationship based on incoming radiation, long term sea temperature gradients, albedo effects and greenhouse gases, thus there is great variation in forward projections from the wide selection of available climate models. However, perhaps one of the greatest uncertainties is the course of action future human generations will take to curb greenhouse gas emissions. In response, the IPCC developed 40 scenarios of human behaviour based on assumptions on future economic and regulatory conditions (Figure 1). These scenarios can be inputted directly into climate models such as the HadCM3 and often scientists will use multiple scenarios to offer a range of probable outcomes and predictions (Levy *et al* 2004). Common scenarios include the extreme case A2 where the global dependence on fossil fuels and population growth remains high and the optimistic case B2 where fossil fuel use and population growth is curtailed and public policy focusses on environmental protection.

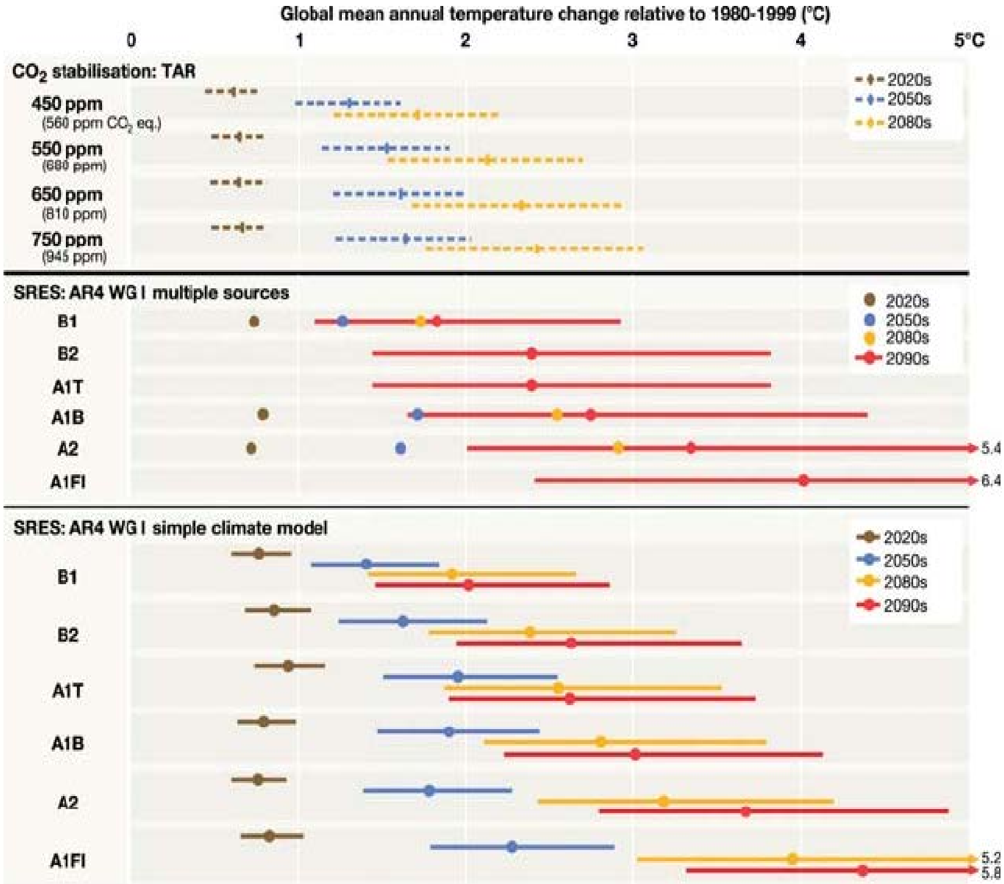

Figure 1. Global mean temperature change projected for various emission scenarios (IPCC 2007).

There is a large consensus among the experts that global climate will continue to change significantly during the next century. In the IPCC (2007) report, it was concluded that it is very likely that fossil fuel burning will be the dominant influence on atmospheric CO_2 concentrations during the 21st century. Model projections of atmospheric CO_2 concentrations estimated that by the end of the century, they could range from 490 to 1260 ppm, equivalent to between 75% and 350% above estimated levels of CO_2 in 1750. According to the same IPCC (2007) report, the global air temperatures estimated by the models are expected to increase during the 21st century in a range from 1.4 to 5.8 °C, relative to 1990 temperatures (Table 3). This projected increase is considerably larger than what was observed during the 20th century and is very likely to exceed any century-long trend experienced during the past 10 000 years.

Table 3. Climate change and greenhouse gas (GHG) concentration projections for the 21st century, if no climate policy interventions are made (modified from IPCC 2001).

Indicators	2025	2050	2100
CO_2 Concentration	415–460 ppm	460–625 ppm	475–1100 ppm
Global Mean Temperature Change from 1990	0.4–1.1°C	0.8–2.6°C	1.4–5.8°C
Global Mean Sea-Level Rise from 1990	2–15 cm	5–30 cm	10–90 cm

1.5 GREAT LAKES CLIMATE CHANGE

Observations in the Great Lakes region (Figure 2) have shown that climate change is already affecting the area. Winters are getting shorter, while extreme events like heavy precipitation and high temperature have been increasing since the 1990s (Wuebbles and Hayhoe 2004). Significant changes have been observed in cold season processes (e.g. snow fall, snow melt, freezing and thawing of soil) in the 20th century including a significant reduction in mean snow cover area and earlier spring thaw from 1972 to 2000 in the Northern Hemisphere (Lemke and Ren 2007; Cherkauer and Sinha 2010). Furthermore, in the Great Lakes region the occurrence of soil frost has been decreasing since the mid-1960s indicating warmer temperatures (Cherkauer and Sinha 2010). While observations of past climate demonstrate these warming trends, the prediction of future climate for the Great Lakes basin bears a higher degree of uncertainty than global projections, mainly because modeling regional-scale phenomena is more difficult (Jones *et al*. 2006). Therefore most model-based forecasts of future conditions are viewed as plausible scenarios rather than confident forecasts (Jones *et al*. 2006). It is thus useful to compare multiple studies of climate projections in the area and look for common predictions.

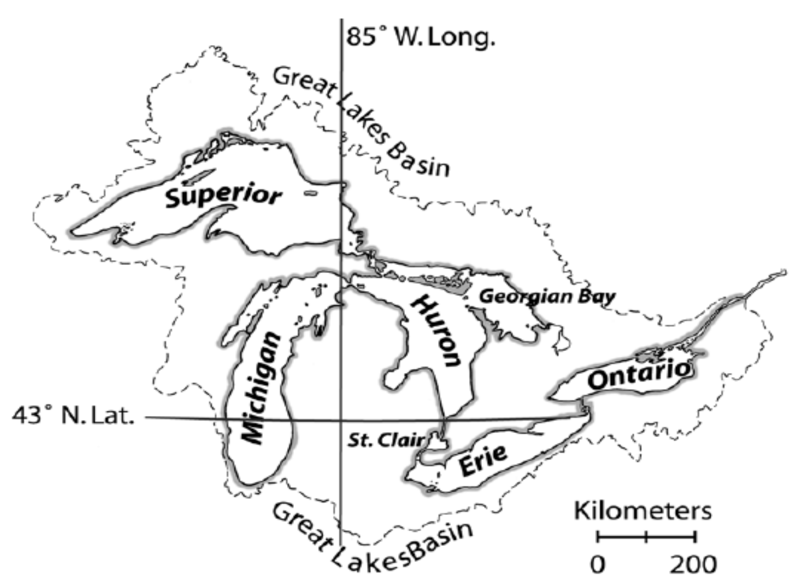

Figure 2. Laurentian great Lakes and Basin (Croley 2005)

The Great Lakes region could experience substantial increases in annual and seasonal temperatures and extreme heat events, particularly under the higher emissions scenario. Wuebbles *et al*. (2010) studied the effects of climate change over Chicago and neighbouring areas using data from a few coupled atmosphere-ocean GCMs: GFDL CM2.1, HadCM3 and U.S. NCAR - (National Center for Atmospheric Research) Parallel Climate Model (PCM). They found that over the next few decades (2010–2039) the annual-averaged temperatures were likely to increase in the order of 0.6–0.8 °C. The prediction for the end of the century (2070–2099) under lower emissions was that the annual-averaged temperatures could increase by 1.7–2.2 °C and under the higher emissions scenario by 4–4.5 °C (Figure 3). In addition, it appears that the greatest increases would occur over the summer with increases up to 6 °C. This is similar to the average of 21 models using the A1B scenario which found increases of 3–5 °C in the winter and 3.5–5 °C in the summer (Christensen and Hewitson 2007). However, a previous study by Wuebbles and Hayhoe (2004) found a larger range of increases in regional temperatures from 1 to 7 °C in the winter and 3 to 11 °C in the summer by the end of the 21st century. These predictions are similar to those reported by Jones *et al*. (2006) using two GCMs which projected air temperatures in the Great Lakes region to increase by 3 to 8 °C in the winter and 3 to 9 °C in the summer over the same time period. They expected increases to be smaller in the center of the Great Lakes region due to the buffering effect of the lakes, and thus higher in the south and north. The spatial heterogeneity of temperature increases has been examined in other studies including Mortsch and Quinn (1996), who predicted, using four GCMs, that temperatures would increase most in the southwestern part of the basin (Ohio, Indiana). Last, this is consistent with air temperatures in the Midwest United States which are generally expected to increase and contribute to a longer growing season (Cherkauer and Sinha 2010). From these studies, a common prediction is that over the next century the air temperature in the Great Lakes region will increase substantially. Because of Canada's northern latitudes, the rates of warming may be greater in Ontario, southern and central prairies and the Arctic than many other regions of the world (Lemmen and Warren 2004; Erwin 2009). These predictions feedback into some of the long term trends that have been observed in the Great Lakes region including the length of the frost-free season. By the end of the century, the date of the last frost will move earlier in the year by about 30 days, under the higher CO_2 concentration scenario, and 20 days, under the lower concentration scenario.

While over time the average temperature will increase, it is the variability of the climate that is emerging as an important prediction. Year-to-year variability in temperature is likely to increase because a higher frequency of very hot summers is expected, rather than a gradual rise in temperatures over time (Sousounis and Grover 2002; Wuebbles *et al*. 2010). The frequency and intensity of extreme cold days and cold spells are likely to decline considerably (Wuebbles *et al*. 2010).

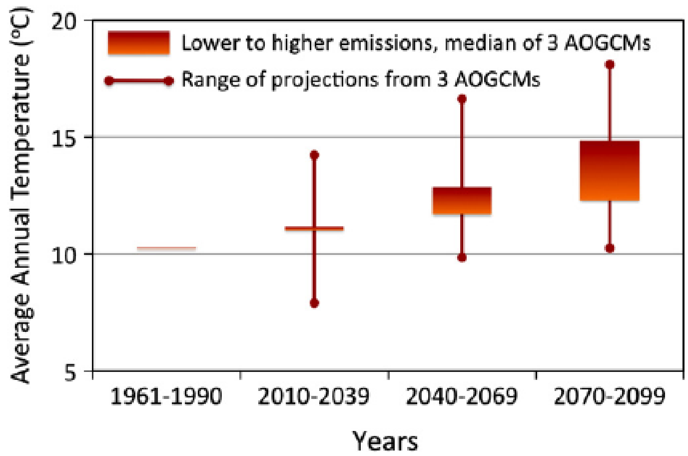

Figure 3. Average annual temperature changes in degrees C for the Chicago area from the IPCC range of scenarios and downscaled results from the three climate models over selected future time periods in comparison to the historical reference period 1961–1990 (Wuebbles *et al*. 2010).

As demonstrated in the fundamental models, the relationship between precipitation and temperature change is non-linear and thus climate change predictions of rainfall are not always intuitive. For example, although much of the conterminous United States experienced increased temperatures in the early 21st century, the North American continent was divided in terms of changes in precipitation. From 2001 to 2009 almost all the regions of the conterminous United States experienced elevated annual temperatures (Figure 4A) and in particular temperatures in the Southwest were exceptionally high (>1 to >2 SD above 20th-century means). However, the difference in annual precipitation between the 20th and early 21st century demonstrates the strong geographic contrast between the East and West. Many areas of eastern North America, including the Great Lakes basin, experienced precipitation >0.15 SD above the 1895–2000 mean, while much of the West experienced lower than average precipitation (Figure 4B). Seager and Vecchi (2010) explained this division across the country mathematically which can be paraphrased as: within the atmosphere, precipitation and evaporation is balanced by the divergence of a time-averaged, column-integrated moisture flux. The conclusion of the model is that wet areas will generally become wetter while dry areas will further become drier. This model was further developed to include the influence of topology and wind which led to a useful explanation of precipitation patterns: precipitation in one season would be highly influenced by the moisture content left behind from the previous season (Seager and Vecchi 2010). Thus, in general terms, shorter and drier winters could contribute to drier summers.

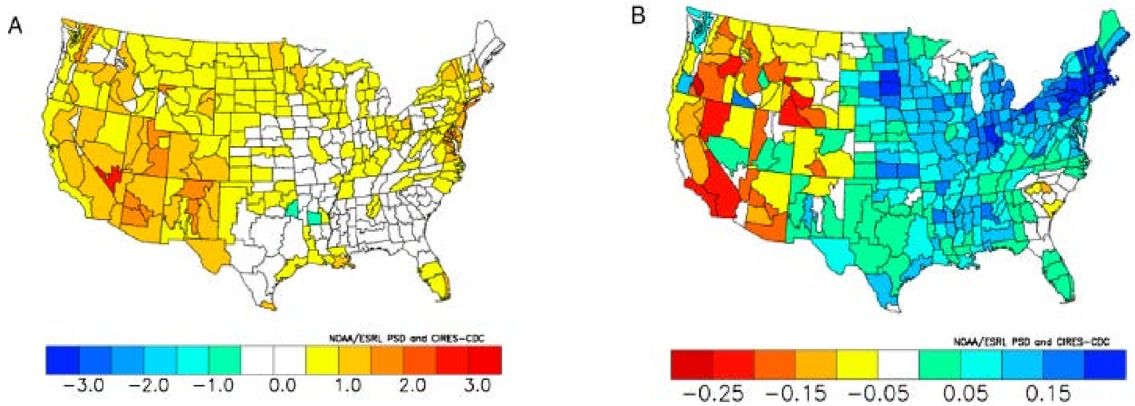

Figure 4. A) Composite standardized temperature anomalies for 2001–2009 relative to 1895–2000. B) Composite standardized precipitation anomalies for 2001–2009 relative to 1895–2000. Data are from MacDonald (2010) and mapped by US state climate divisions.

Wuebbles and Hayhoe (2004) and Cherkauer and Sinha (2010; Table 2) used GCMs like HadCM3 and PCM to predict precipitation under climate change for all emission scenarios. They found that both 24-h and 7-day heavy rainfall events will double by the end of the century, while thunderstorm frequency is likely to increase by the end of the 21st century in the Great Lakes area leading to higher runoff and increased risk of flooding (Trapp *et al*. 2007). In addition, increased regional temperatures will increase evaporation and transpiration (Wuebbles and Hayhoe 2004). Over the year, the average precipitation is expected to have only minor changes with a projected increase between 0 and 10%, however, the seasonal distribution will shift towards increased precipitation in the winter and less in the summer (Wuebbles and Hayhoe 2004; Christensen and Hewitson 2007). Spatially, precipitation will decline most in the southwestern part of the basin and increase in the more northerly areas (Mortsch and Quinn 1996).

Hydrologic forecast is tightly related to weather forecast and many studies (e.g. Sousounis and Grover 2002; Polderman and Pryor 2004) have examined outputs from climate models like the Canadian Coupled Climate Model (CGCM1) and HadCM2 to evaluate potential changes in large scale weather patterns (i.e. synoptic) over the Great Lakes region toward the end of this century. Although both models indicate that there will be fewer cold air intrusions in winter and more heat waves in summer by the end of this century, CGCM1 suggests a warmer climate scenario than HadCM2. Extremely cold winter days will be milder as defined by an increased thickness of air mass of 10 to 20 decametres (dam) and slightly weaker winds, while extremely hot summer events will be characterized by an increased air thickness of 10 dam and stronger winds. Both CGCM1 and HadCM2 models show the influence of the Atlantic Bermuda High to the east with a slight difference that HadCM2 predicts more moisture (southerly flow) at the surface while the CGCM1 predicts drier (more westerly) and shorter flow (Sousounis and Grover 2002). Both models predict future increases in precipitation but CGCM1 shows a smaller magnitude mostly coming during the first half of the year, while the HadCM2 predicts higher precipitation in the second half of the year (Sousounis and Grover 2002; Polderman and Pryor 2004). There is a good agreement between the two models with a predicted increase in the frequency and intensity of warm fronts and decreases in surface wind speeds with more frequent easterly winds (Figure 5). However, both models show a decrease in weak cyclone numbers, a slight increase in strong cyclone numbers and a significant decrease in days with southeasterly winds, but differ in the prediction of easterly winds. The CGCM1 predicts an increase in days with northeasterly winds, while the HadCM2 predicts an increase in days with southeasterly winds, and significant decreases in days with southwesterly winds, especially during the winter (Sousounis and Grover 2002).

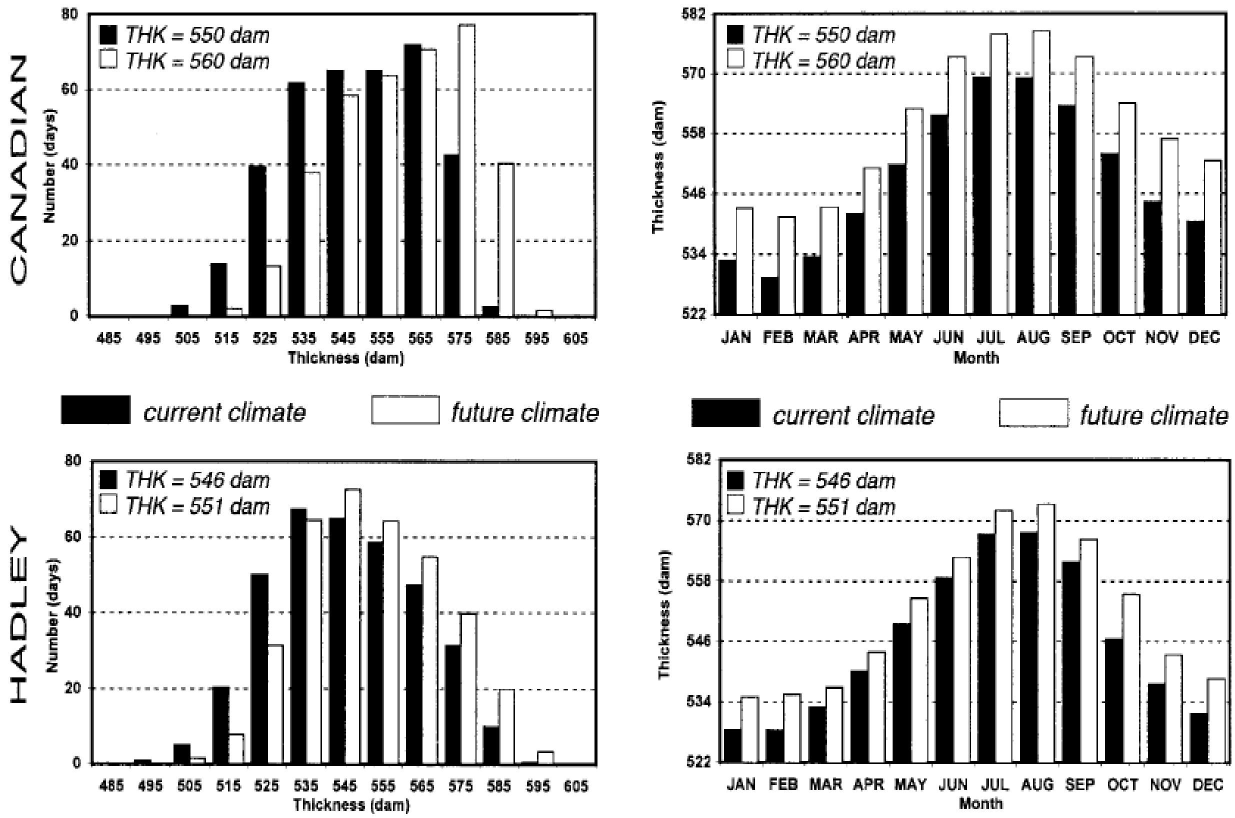

Figure 5. Potential and future weather patterns over the Great Lakes region (Sousounis and Grover 2002)

2. AQUATIC PROCESS AND PREDICTIONS

2.1 WATER TEMPERATURE

Changes to the air temperatures directly influence the thermal regime of lakes causing warmer surface temperatures, shorter duration of ice-cover, earlier onset of stratification, and an increase in the length of the stratified period (Dobiesz and Lester 2009). Although surface heating is partly offset by increased evaporation rates, a strong trend of increasing water surface temperature has continued for the past decades (Vincent 2009). In addition, for north temperate lakes the air temperature determines the duration of ice-free conditions, which in turn allows increased warming of the surface waters by sensible heat transfer (conduction and convection) and radiative transfer into the water column. The heating of the surface water causes changes in the density structure of lakes creating stratification. The lighter water at the surface prevents the transport of heat via turbulent mixing to deeper parts of the lake therefore acting as a positive feedback mechanism that further strengthens the thermal stratification and creates a system even more resistant to wind-induced mixing. One counterintuitive effect of climate warming is that the trapping of more heat in the surface-mixed layer will allow less heat to transfer to the lower column, and deep waters could become cooler (Vincent 2009).

Changes in the thermal regimes of water have already been observed in most lakes in North America. For example, using vertical temperature profiles of Lake Simcoe during the open-water period from 1980 to 2008, Stainsby *et al*. (2011) analyzed the trends in water column stability, the onset of stratification and the timing of fall turnover. It was observed that the water stratified earlier in the spring and remained stratified a month longer in 2008 compared to 1980. These changes were correlated with increases in air temperature over the same time period. The impact that these changes have on the water quality and biota of Lake Simcoe is the subject of current and future research (Winter *et al*. 2011).

In Lake Ontario there is evidence of increasing open-water temperatures in the Bay of Quinte. A steady increase in lake water temperatures have been observed in the summer (1950 to 2000) and the winter (1980 to 2000; Casselman 2002). Recent research from Huang *et al*. (2012) show that the surface air and water temperatures increased at all seasonal and annual time scales during the last 40 years in Lake Ontario. The increase for annual mean air temperature was 1.43±0.39℃ and the surface water temperatures increased by 1.26±0.32℃ from 1970-2009. The increase rate was higher for the air temperature than for surface water temperature in winter and autumn. By contrast in spring and summer the surface water temperature warmed faster than air temperature. They also found that the length of summer stratified season has increased by 12±2 days since early 1970s, most likely due to the increase in water temperature. Climate warming had also an effect on the wind speed over Lake Ontario, which declined and thus further enhanced the summer thermal stratification (Figure 6).

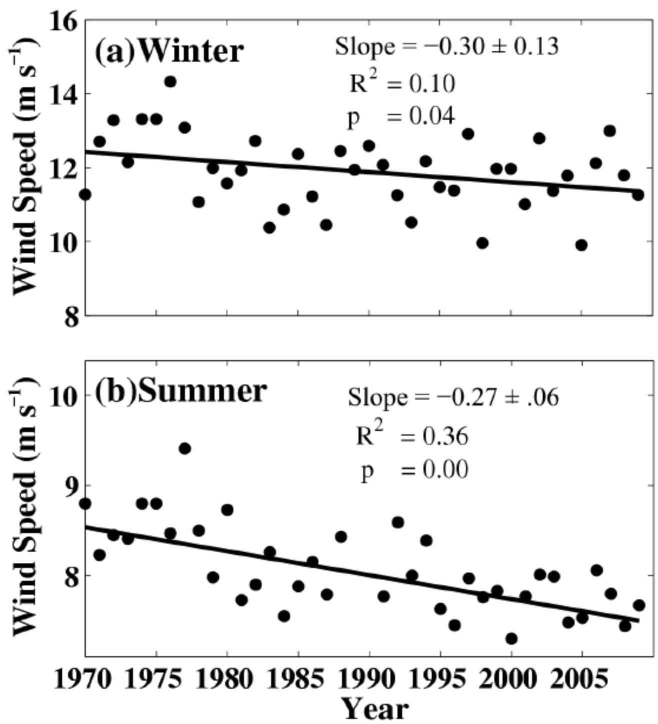

Figure 6. Regional averaged winter mean (a) and summer mean (b) of NCEP/NCAR reanalysis wind speed at 850 hPa level over Lake Ontario during 1970 to 2009 (slope in unit of m s^{-1} decadal^{-1}) (Huang *et al*. 2012).

McCormick and Fahnenstiel (1999) examined long-term (25–87 years) observations of water temperatures at seven locations throughout the Great Lakes: Sault Ste. Marie (Ontario), Green Bay (Wisconsin), St. Joseph (Michigan), Bay City (Michigan), Sandusky (Ohio), Put-in-Bay (Ohio), and Erie (Ohio). It was found that there are strong trends towards increasing temperature at two sites (Sault Ste Marie and Put-In-Bay) and weak trends at two other sites (Bay City and St. Joseph). The strong increasing temperature trends showed a 4 and 6 hr/year rate of increase in the maximum potential duration of summer stratification (14 and 18 days, respectively over the time period; Figure 7). The rate of increase in the duration data was mostly skewed towards earlier transitions to spring-like conditions. However, the data does not extend far enough back in time to distinguish between an unresolvable natural cycle, or anthropogenic activity forcing. The duration of the period in each year for which temperatures exceeded 4°C was also found to significantly increase at four sites. Significant long-term monotonic trends in the timing of the onset of thermal stratification, duration of stratification and the onset of fall mixing were observed throughout the whole historical data set. These trends resulted from changes in water column density, which are strongly correlated with increasing average air temperatures over time (Vincent 2009; Stainsby *et al*. 2011; Huang *et al*. 2012). The duration of summer stratification had increased nearly by 12±2 days (Figure 8) since 1970. This increasing rate is comparable to that of the duration of summer stratification season of Lake Superior, which extended from 145 to 170 days over the last century (Austin and Colman 2007). In a similar study Shimoda *et al*. (2011) show that the primary response to external meteorological forcing has been the increase in overall lake and (especially) epilimnetic temperatures, the increase in thermal stability, the lengthening of stratification period and shortening of the ice cover period of several well-studied north temperate deep lakes, including the major Great Lakes (Table 4).

Lake thermal regimes respond to climate change because they are controlled by solar radiation, wind velocity, air temperature and humidity. Expected changes in the thermal regime of air and water temperatures and their influence on the physical processes in lakes and streams and biological and biogeochemical processes can be summarized as follows:

Lacustrine Systems

Increasing lake surface temperature will have an influence on the start and end dates of summer stratification, and will further affect the length of summer stratified season in the lake (Huang *et al* 2012). Stratification would also alter the mixing regimes of lakes. In the southern part of the region, lakes switching from ice covered to open water in the winter would become monomictic (i.e. they would mix in autumn, winter and spring, and stratify in summer). In the northern part, some lakes that are presently monomictic and mix only during summer, would stratify in summer and become dimictic, mixing in spring and autumn. Some large deep lakes, like Lake Michigan, that are dimictic would be less likely to mix completely (McCormick 1990). Shimoda *et al*.'s (2011) analysis on water warming concluded that if current trends persist, we could expect that: 1) strictly dimictic deep lakes will migrate toward ice-free monomictic systems; and 2) monomictic lakes are likely to switch to meromictic hydrodynamic regimes due to the increasing suppression of deeply penetrative mixing during mild winters. An interesting finding was that the lakes as physical systems demonstrate a remarkable spatial coherence. Similar conclusions have been reached by Magnuson *et al*. (1997).

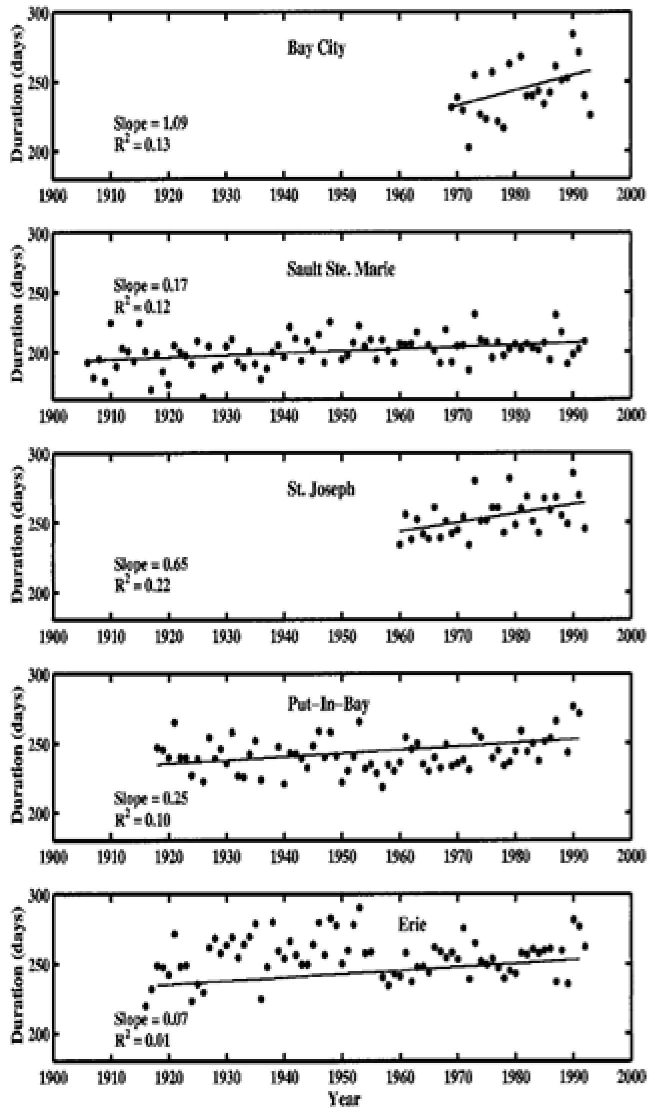

Figure 7. Plot of the duration of summer stratification from water monitoring sites that showed a significant trend over their entire data set (McCormick and Fahnenstiel 1999).

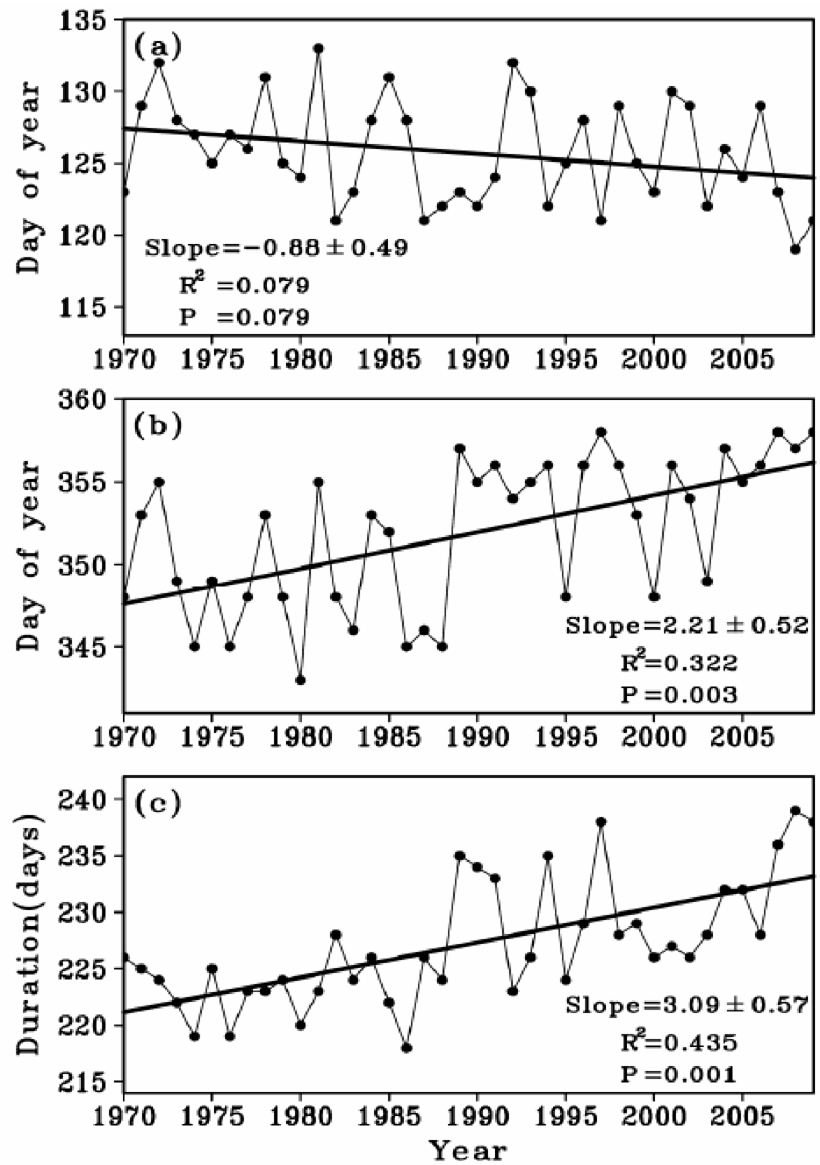

Figure 8. The start and end dates of summer thermal stratification (a and b), and the length of summer thermal stratification season in Lake Ontario (c; Huang *et al*. 2012).

Changes in temperature and stratification would be expected to alter the availability of dissolved oxygen in lakes. Longer summer stratification would increase the likelihood that deep hypolimnetic waters would be depleted of oxygen. Simulations with doubling CO_2 scenarios for Lake Erie predict summer oxygen declines of 1 mg/l in upper layers and up to 3 mg/l in deeper layers (although there is also a potential for an increase in 1 mg/l), and the development of more extensive areas of anoxia (Magnuson *et al*. 1997). Warmer temperatures would also increase bacterial activity in deep waters and sediments (Shimoda *et al*. 2011). Similar responses were obtained for smaller Minnesota lakes in model simulations by Stefan *et al*. (1996). Oxygen concentrations declined by 2 mg/l in surface waters and by as much as 8 mg/l in deep hypolimnetic waters, while summer oxygen depletion lasted up to two months longer compared with base climate scenarios. These oxygen declines occurred more rapidly and were longer lasting in eutrophic, compared with oligotrophic lakes, which offers some insight to the effect of climate on prairie systems.

Table 4. Summary of climate-induced changes in the thermal structure of the Great Lakes. (Modified from Shimoda *et al*. 2011)

Lake	Observed change	Time period	Observed change	Time period
	Increase in lake temperature (°C/yr)		*Increase in ice free season (d/10 yr)*	
Lake Superior	0.01 (near-shore)	1906–1992	13	1973–2002
	0.110 (epilimnion)	1979–2006		
Lake Michigan	0.065 (epilimnion)	1979–2006	8.5	1973–2002
Lake Huron	0.086 (epilimnion)	1979–2006	2.3	1973–2002
Lake Erie	0.01 (near-shore)	1918–1992	5.9	1973–2002
Lake Ontario	NA	NA	10	1973–2002

Fluvial Systems

There are other factors beside the air temperature that can influence stream temperatures, such as solar radiation, relative humidity, wind speed, water depth, groundwater inflow, artificial heat inputs and the thermal conductivity of the sediments. Of these, radiation is the most important therefore shading from riparian vegetation is very important (Stefan *et al*. 1996). Deterministic models including shading and wind sheltering can simulate water temperatures with a standard deviation of about 1°C (Magnuson *et al*. 1997). For example a modified version of the MNSTREM model was used to simulate the potential effects of doubling atmospheric CO_2 for five Minnesota streams with scenario inputs from four GCMs (GISS, GFDL, UKMO and OSU; Stefan and Sinokrot 1993). Stream temperatures were projected to increase in a range from 2.4 ± 4.7ºC. In the absence of riparian shading additional increases up to 6ºC were projected. Climate warming is expected to affect groundwater temperatures with a similar increase in magnitude as that was predicted for mean annual air temperatures (Magnuson *et al*. 1997). Therefore, the cooling effect of groundwater on streams is expected to be reduced. Studies by Meisner (1990a; 1990b) showed in a simulation that for stream waters in south-central Ontario, an increase in groundwater temperature of 4.8ºC combined with the increased air temperatures, decreased the length of headwater trout streams that remained below 24ºC during July and August by 30 and 40%, respectively. For one stream, the increase in water temperature was almost equally attributable to groundwater inputs and to air temperatures, while in another stream all of the increase in temperature could be attributed to groundwater temperature increase. For dammed streams the effect of climate change on stream temperatures flowing below dams will depend on whether the water is released from the reservoir epilimnion rather than the hypolimnion. Sinokrot *et al*. (1995) reported that cold hypolimnetic water release is felt as far as 48 km downstream in small, shaded Minnesota streams. Under a doubling of CO_2 concentration, this distance is projected to be shortened by up to 50%.

2.2 ICE COVER

In the fall, lake water cools along with the ambient atmosphere. After the surface water temperatures drop under 3.98ºC a phenomenon known as the inverse thermocline develops where the water warms at greater depths. As the air temperature declines, ice will begin to form on the surface, which can start as thin crystal platelets and needles (under calm conditions) or small frazil crystals (under windy conditions). Frazil ice forms typically in rivers in rapid streams and may accumulate downstream to form ice sheets, or attach to the stream substrate and form anchor ice. Frazil ice has not been reported in lakes, but its formation is possible in persistent open water areas. The thin ice layer formed first is called primary ice. Subsequent ice growth may occur beneath the primary ice layer as secondary ice, or in the form of a superimposed ice layer on top (Gow and Govoni 1983; Leppäranta and Kosloff 2000). Secondary ice consists of large ice crystals growing downwards from the primary ice. Secondary congelation ice crystals grow down from the ice–water interface with the same orientation as the primary ice layer crystals. Crystal size increases with depth, but its growth rate is limited by the insulating effect of the ice. Growth is ensured as long as the conductive heat flux through the ice (i.e. cooling from the atmosphere) is greater than the heat flux from water to ice. Therefore ice growth will also slow as the ice thickness increases. Superimposed ice is generated by snow and liquid water provided through flooding, rain or snow melt. Snow weight may also force the primary ice sheet below the water level causing flooding which requires a snow thickness of at least one-third the primary ice thickness. Snow-ice growth is thus often limited by the presence of snow and the availability of liquid water.

The melting season begins after the temperature of the ice-sheet reaches 0ºC and is uniform across its thickness. Melting begins at the boundaries and through the absorption of solar radiation penetrates inside the ice sheet. Once the porosity of the ice reaches 0.3–0.4 due to internal melting the ice cannot bear its own weight and the rate of melting increases dramatically. In spring, solar radiation will also provide a strong downward flux of heat starting up convection initiating ice melting.

The growth and melting of lake ice are vertical processes and can be expressed by:

$$\frac{\partial \rho c T}{\partial t} = \frac{\partial \left(K \frac{\partial T}{\partial z} - Q_s\right)}{\partial z} \qquad \text{Eq. 4}$$

where c is specific heat of ice, T is temperature, K is thermal conductivity, and Q_s is the net heat flux at the upper surface.

Lake ice climatology

The sensitivity of ice phenology to climate change has been investigated using observations from ground and remote sensing. Many studies have been conducted for North American lakes (Vavrus *et al*. 1996; Stefan and Fang 1997; Magnuson *et al*. 2000) with long time-series of field observations for the Great Lakes region (Stefan and Fang 1997; Ménard *et al*. 2002). The field observational data has been complemented with data from aerial surveys and microwave satellite images to allow the study of lake ice phenology (Kouraev *et al*. 2008; Leppäranta and Wang 2008). In addition, simulation data from computer models and regression models have been produced (Jeffries *et al*. 2005). Statistical analysis for single and multiple variables were used to develop regression models that require observed ice data and a few correlated input data to predict ice phenology and ice thickness (Palecki and Barry 1986; Livingstone 1997; Gao and Stefan 1999). A few physical models have been developed to simulate lake ice (e.g., Liston and Hall 1995; Giorgi *et al.* 1997; Stefan and Fang 1997; Thompson *et al.* 2005). These models are applicable to a broad range of lakes and are more accurate in forecasting lake ice than regression models, but their application is limited by the lack of reliable information from weather stations, which are often too far from lakes (Patterson and Hamblin 1988; Gu and Stefan 1990; Fang and Stefan 1996). As differences among lakes are typically larger than inter-annual differences in one lake, multivariate statistics are used to simultaneously analyze data on many lakes, and determines the effects of geographic location, morphometry and climate changes through simple empirical relationships (Palecki and Barry 1986; Williams *et al*. 2004; Williams and Stefan 2006). However, the results of most of these studies generally show that the duration of the ice-covered period in the mid-latitudes lakes depends mostly on climate conditions and limnology. The timing, presence and duration of lake ice cover are strongly related to the local air temperature and wind speed, as well as water temperature and lake stratification. Other spatial statistical analysis shows that physical responses of lakes to meteorological forcing are correlational over large spatial scales, indicating that lakes respond to local weather, but also to large-scale climate influences like El Niño/La Niña Southern Oscillation (Blenckner *et al*. 2007; Livingstone 2008).

The most pronounced changes in climate that can affect the ice regime of lakes will take place in winter and spring (IPCC 2001; IPCC 2007). The relationship is strong enough that ice phenology is considered a good indicator for regional climate variability and change (Kouraev *et al*. 2008). Significant changes in the phenology of ice cover have already been observed in both lakes and rivers over recent trends in climate (Lemke and Ren 2007). The Global Lake and River Ice Phenology Database contains freeze-up and break-up dates and other ice cover descriptive data for 750 lakes and rivers (Benson and Magnusson 2000). From the 287 lakes that are in North America, historical trends show evidence of later freezing and earlier break-up, a reduction in ice cover and a lower frequency of ice coverage due to increasing air temperatures (Assel and Robertson 1995; Magnuson *et al*. 2000). Another cross lake study conducted by Assel *et al*. (2003) reported declines in the annual maximum extent of ice cover in each of the five Great Lakes for data from 1983 to 2001 versus historical data from 1977 to 1982. Lofgren *et al*. (2002) also found that two climate models yielded predictions of substantially reduced ice-cover duration in Lake Erie and Lake Superior by the end of the 21st century.

In addition, changes in ice phenology observed during the last decades of the 20th century are more rapid than trends exhibited over longer time periods. Average rates of change in freeze-up and break-up dates for 65 water bodies across the Great Lakes region (observed during 1975–2004) were 5.8 times and 3.3 times respectively, more rapid than the average historical 1846–1995 rates (Jensen *et al* 2007). In their study of lake and river ice evolution in the northern hemisphere, Magnuson *et al*. (2000) showed that freeze-ups have a delay of up to 5.8 days and break-ups have been up to 6.5 days earlier, compared to the average 1846–1995 period.

Relatively little is known about the limnological processes that occur in lakes over winter, however, recent interest in ice formation over temperate lakes has arisen partly out of questions on the response of mid- and high-latitude lakes to global warming. Notwithstanding the paucity in research, it has long been suspected that ice cover has a very important effect on limnological processes. For example, at a basic level, ice formation may reduce the volume of liquid water in the lake substantially and increase the salt content in the adjoining water (Adrian *et al*. 1999). Furthermore, the balance between cooling from the atmosphere and the heat capacity of the lake sediments and the water can create convection currents during the winter. These simple changes can have indirect effects on other limnological processes. Here we summarize some of these processes:

Nutrient fluxes

The supply of nutrients in open water conditions is partly driven by sediment re-suspension and convective mixing and is a function of mixing intensity (Kristensen *et al*. 1992; Hamilton and Mitchell 1996). In winter, the sediment is isolated from the wind energy which create currents that promote mixing. Thus, the low mixing conditions not only reduce the resuspension of particulate and dissolved nutrients into the water column but they may even impede it by allowing the long term retention of nutrients in the sediment to occur through the gluing effect (Håkanson and Bryhn 2008). Furthermore, a less consolidated sediment is more prone to wind and wave-induced bottom shear stresses which demonstrates that longer ice-cover can lead to less nutrient release during the summer as well. There is little research done on the release of nutrients in water from the ice sheet.

Oxygen transport and consumption

Lakes covered with ice have almost no exchange with atmospheric oxygen and in the absence of photosynthesis anoxic conditions can arise. The eutrophication of lakes has increased over recent decades as water quality has deteriorated (Liu *et al* 2010). Oxygen depletion in ice covered lakes is driven by biochemical oxygen demand (BOD) and by the sediment oxygen demand (SOD; Ellis and Stefan 1989). Both BOD and SOD are strongly affected by physical conditions such as temperature stratification, near-bottom currents and thermal exchange with the sediment layer. Turbulence increases the flux of dissolved oxygen (DO) to the sediment. It was shown recently that at low temperatures, the SOD is extremely sensitive to temperature variations due to bacterial activity (Golosov *et al*. 2007). Even a fraction of a degree Celsius increase of water temperature near the bottom can essentially enhance oxygen consumption in the upper sediment layer and lead to increased anoxic conditions in the hypolimnion.

Release of methane

It is estimated that methane released from lakes accounts for about 20% of the global emissions of greenhouse gases (Bastviken *et al*. 2004). Isolation of lakes from the atmosphere by ice cover can result in accumulation of methane in the water column with a subsequent increase of emissions after the ice break-up. Schmidt *et al*. (2007) demonstrated that most of the methane produced under ice is dissolved and oxidized in the deep water column and thus its values do not significantly exceed the atmospheric concentrations. However, the methane fluxes can vary widely from micrograms to several grams of carbon per square meter per year depending on the type of the lake. Upper limit methane fluxes are found in eutrophic lakes, with the majority of methane production occurring in anoxic sediment layers (Bartlett *et al*. 1988). Global warming may affect increased occurrence of winter anoxia, typical for such lakes and significantly affect the methane production. Quantitative estimations of the effect of changed methane emission are subjects of ongoing research.

Light conditions under ice

Euphotic depth, H_e, is normally defined as the depth where solar radiation level has reduced to 1% from the surface level (Arst 2003). In the case of congelation ice, the albedo cuts much of the euphotic depth as compared with open water. In the presence of snow and snow-ice, euphotic depth is zero or very limited. The influence of snow and ice cover causes radiation to be highly diffuse just under the ice. In ice-free, clear day conditions, the asymptotic state of the angular structure of light is usually attained at deeper layers, but in ice-covered waters the radiation field is already in asymptotic state right beneath the ice. Therefore, apparent optical properties, which depend also on directional characteristics of radiation, need careful concern when examining the water body under ice cover.

2.3 PRECIPITATION

In Canada and the Midwestern United States, the Great Lakes are an important source of fresh water, recreational resources and transportation corridors, as well as a climate regulator. The supply of freshwater to the lakes comes from direct precipitation and runoff within the watershed. Half of the supply is derived from runoff and thus land surface processes, including regularization of stream flow within the basin, have a significant potential to impact lake levels and water quality. In order to understand past and future changes in the hydrologic cycle, many global and regional studies have focused on changes to floods and drought frequencies (e.g. Christensen *et al*. 2004; Milly *et al*. 2005; Sheffield and Wood 2008) and daily streamflow variability (e.g. Baker *et al*. 2004; Konrad and Booth 2005) under climate change scenarios. There are few Canadian studies on the effects of precipitation on lake hydrology, however, studies involving the Great Lakes areas in the United States can likely be extended into Canada.

Studies of Lake Superior water levels from 1948–1999 indicate that the seasonal cycle has decreased by 20% in amplitude from 40 cm to 32 cm (Lenters 2004). Lake Superior's summer and autumn water levels experienced a downward trend while there was almost no change in winter and spring levels. The decreased seasonal rates of the rise and fall in lake level reflects a decrease of the net influx of water (up to –1,360 m^3/s) in late spring and an increase in net influx during late autumn (up to +1,100 m^3/s; Lenters 2004). A steady decrease in outflow through the St. Mary's River was evident during July-December which reflected the lower water levels. Further analysis of the Lake Superior water budget indicates that seasonal water level changes are the result of changes in runoff and over-lake precipitation but not evaporation over the lake. For example, while a moderate shift in the seasonal patterns of lake evaporation were observed, the mean evaporation rates over the year were unchanged (Blanken *et al*. 2011). On the other hand, evapotranspiration rates on land would have an important effect on lake levels by modifying levels of run-off as well as water storage processes in snow pack and groundwater (Figure 9 and 10; Lenters 2004).

A large scale study of the influence of climate change on the Great Lakes area was conducted by the Great Lakes Environmental Research Laboratory (GLERL) through its Great Lakes Advanced Hydrologic Prediction System (AHPS; Croley 2005). The system took a new approach through its probabilistic meteorological outlooks in making hydrological predictions for the Great Lakes. Lake level fluctuations were categorized in three distinct types: long-term lake levels (annual), seasonal lake levels (following water source variation trends), and short-period lake level changes (mostly due to wind and storm surges).

Annual fluctuations accounted for most of the variability of the high and low lake levels. The overall range of the annual levels for most lakes was about 2 m, with precipitation influencing the major portions of long-term variations. Annual precipitation ranged from about 82 cm for Superior to 93 cm for Ontario, and was found to correlate very well with annual lake levels with a delay of one year. In addition, air temperature variations influenced lake level fluctuations in multiple ways: 1) plants tended to use more water in higher temperatures, 2) higher rates of evaporation from the lake and ground surface were found, and 3) greater humidity depletion in soils caused less runoff for the same amount of precipitation (Polderman and Pryor 2004; Croley 2005; Blanken *et al.* 2011).

Seasonal variation in lake level magnitude depends upon the individual water supplies (Figure 11). The seasonal range is about 30 cm on the upper lakes and about 38 cm on the lower lakes. When the net basin supplies diminish in the summer and fall, the lakes begin their seasonal decline. Although the monthly precipitation is fairly uniformly distributed throughout the year, the runoff has a peak during the spring from the spring snow melt and a minimum in the late summer from higher evaporation rates. The higher evaporation period is due to colder dry air passing over warm lake surfaces (Croley 2005; Blanken *et al.* 2011).

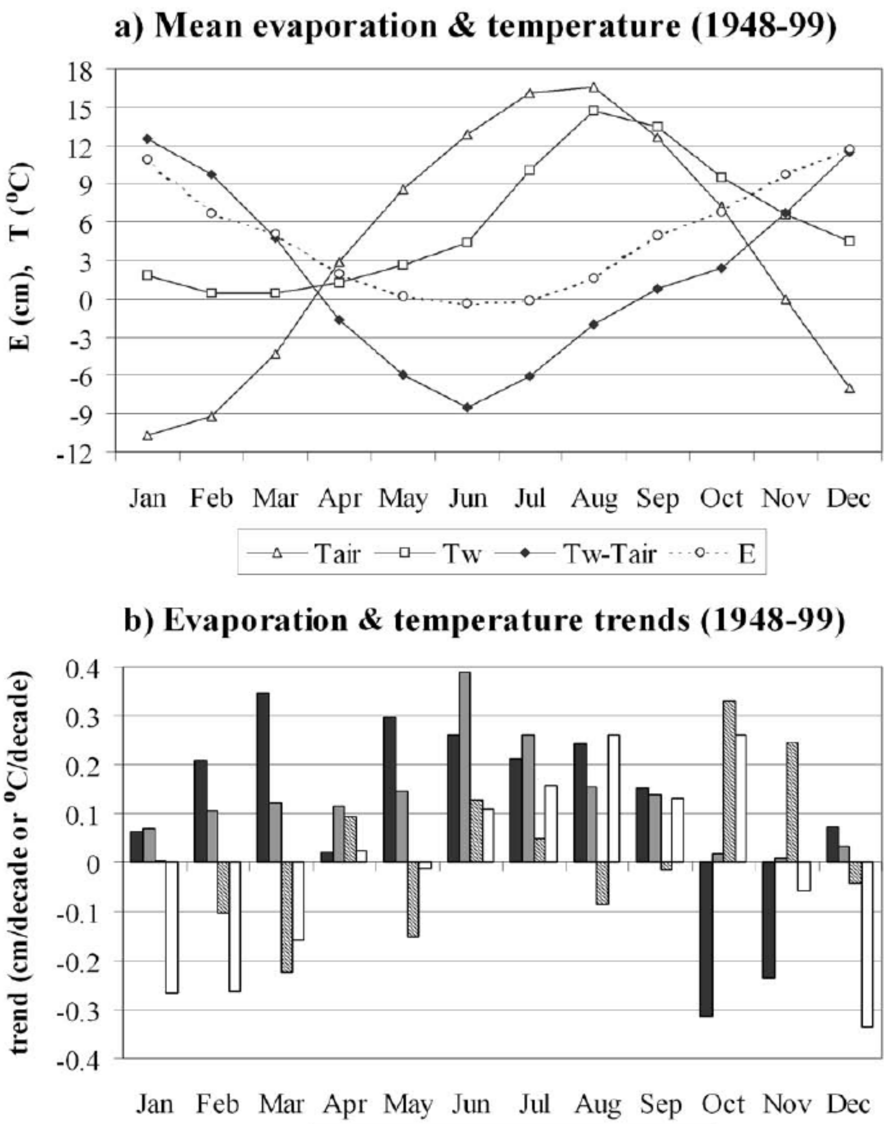

Figure 9. a) Long-term monthly mean over-lake air temperature (Tair), water surface temperature (Tw), water-air temperature difference (Tw-T air), and lake evaporation (E) and b) trends in Tair (black), Tw (grey), Tw-Tair (hatched), and E (white) based on linear regression of the individual monthly values, both for the period 1948–1999 (Lenters 2004).

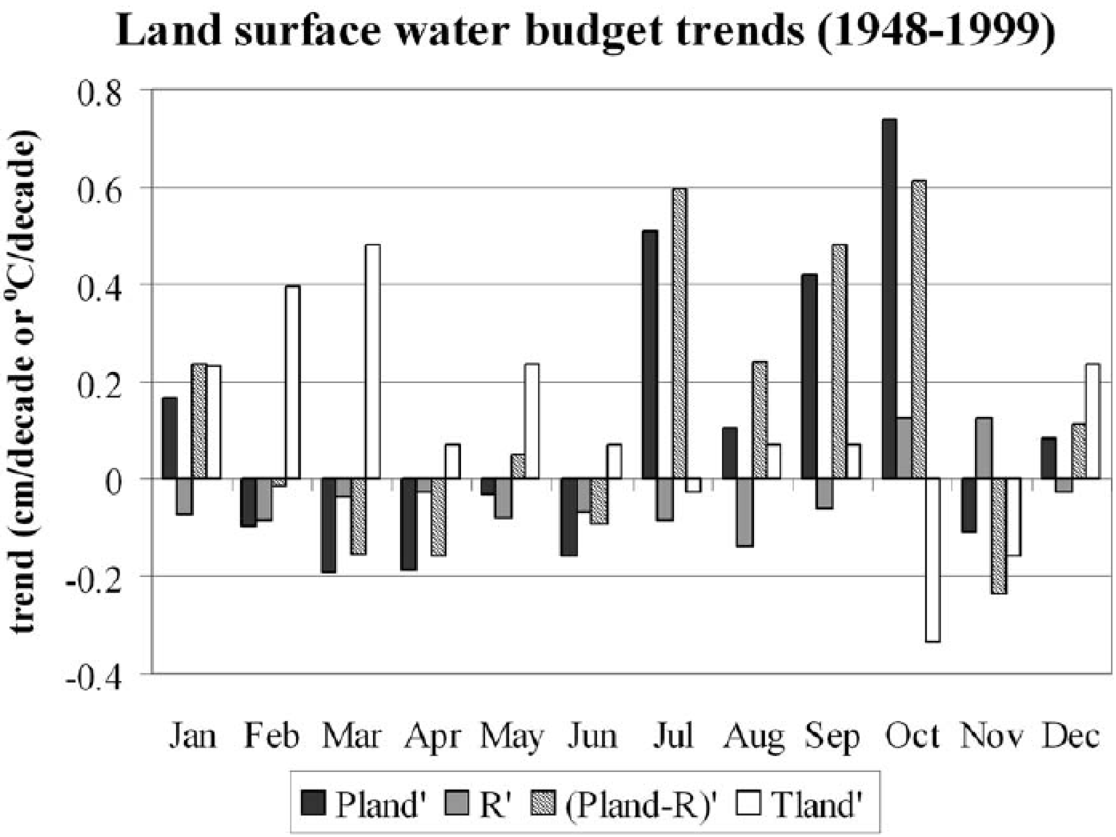

Figure 10. Trends in the monthly land surface water budget and air temperature of the Lake Superior basin for 1948-1999 (Pland′ - over-land precipitation, R' - runoff, Pland-R′ - equivalent to ET + ΔSland′, and Tland' - over-land air temperature). (Lenters 2004)

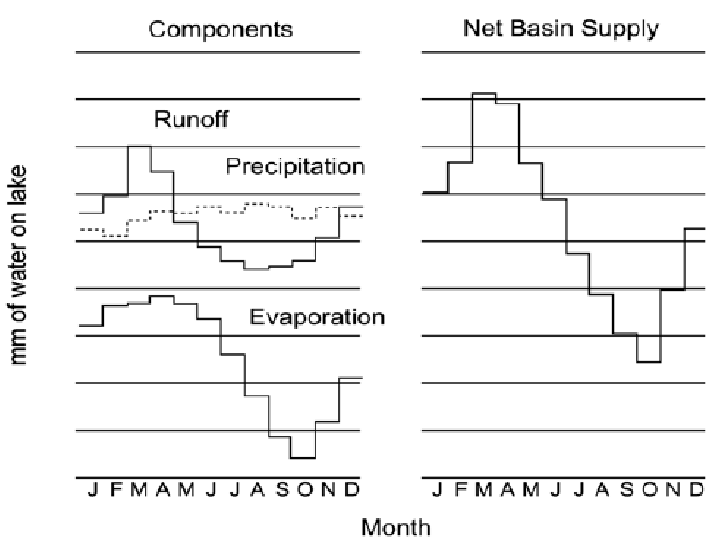

Figure 11. Seasonal Erie Basin Supplies (Croley 2005)

The net basin supply (NBS) is depicted in Figure 11 on the right panel and integrates the precipitation, the runoff and the evaporation.

$$NBS = P + R - E \qquad \text{Eq. 5}$$

where *P* is the volume of water from direct precipitation, *R* is the volume from runoff and *E* the evaporated volume (Polderman and Pryor 2004). As seen in Table 5, these three components of net basin supply are all of the same order of magnitude for each lake and range from about 62 cm for Lake Superior to 169 cm for Lake Ontario, with a maximum around the month of April and minimum in fall. Evaporation ranges from about 56 cm for Lake Superior to 90 cm for Lake Erie.

Table 5. Partial Great Lakes Annual Water Balance (1951-1988) (Croley, 2005)

Component	Superior		Michigan		Huron		Erie		Ontario	
	(cm)	(in)	(cm)	(in)	(cm)	(in)	(cm)	(in)	(cm)	(in)
Lake Precipitation[a]	82	32	83	32	87	34	81	36	93	37
Lake Runoff[a]	62	24	64	25	84	33	80	32	169	67
Lake Evaporation[a]	56	22	65	25	63	25	90	35	67	26

[a]Equivalent depth over the lake area.

Short period fluctuations are common along the shallow areas of the Great Lakes in particular in Lake Erie and are caused by storm surges and wind. Short term fluctuations are more prominent when the wind is blowing along the long axis of a shallow lake. A classical example is the storm of December 2, 1985 in Lake Erie, when the difference across the basin was as large as 5 m. Although they are short term conditions, they cause most of the shoreline damage on the Great Lakes (Croley 2005). Polderman and Pryor (2004) developed relationships between lake level and atmospheric conditions that allow interpretation of historical lake-level variability in terms of prevailing modes of larger-scale climate patterns (i.e. synoptic scale). In their analysis of synoptic-scale circulation patterns from 1956–1999 they found that inter-annual variability of NBS parameters is largely controlled by synoptic-scale variability during the fall and winter seasons. It was shown that inter-annual variability of precipitation is most strongly associated with increased frequency of open cyclone conditions over the basin and frontal cyclones south of the Great lakes. Years that have a positive change in lake level are likely to be associated with anomalies like these. Analysis of extended periods of lake-level transition indicates changes in winter synoptic-type climatology were consistent with changes in lake-level on time-scales in excess of decades. For example, negative lake-level changes during 1986–1999 were characterized by a greater frequency of mild, relatively dry weather patterns, which signified a northward shift in the polar jet and more frequent advection of dry continental air from the southwest. This recent rapid drop of lake level also appears to be strongly linked to anomalous late-summer and early-fall evaporation, which in turn seems to be more strongly reflective of increased lake surface temperature and the delay in the onset of ice cover than to variability in the relative frequency of summer synoptic types (Blanken *et al*. 2011). The trends in evapotranspiration and water budget for the last 50 years of the last century are shown in Figure 9 and 10 respectively.

A crucial question in climate change research concentrates on distinguishing whether the majority of the observed changes in synoptic-scale conditions are perturbations within existing synoptic types or new synoptic types evolving from old ones. Between 1956 and 1999 the regional climate of the Great Lakes became both warmer and wetter on average (temperatures increased by 0.33°C per decade; Polderman and Pryor 2004). Karl and Knight (1998) demonstrated that significant positive trends in precipitation (Table 6) for the Upper

Midwest and Great Lakes states could be attributed to changes in the frequency and intensity of extreme events, particularly during the spring and fall seasons. The analysis of meteorological parameters indicates that the trend toward warmer, wetter surface conditions were due both to an increase in the relative frequency of synoptic types associated with the advection of warm, moist air masses and to changes in the surface or intensity of individual parameter types. These changes illustrate an important feedback in that warmer late-fall through early-winter conditions could alter the intensity of synoptic scale circulations through decreased ice cover and an enhancement of mesoscale instability (Polderman and Pryor 2004). However, in order to have a robust climate prognosis for the Great Lakes basin, warmer lake surface temperatures and increased evaporation rates needed to be accurately represented within the models (Blanken et al. 2011).

Table 6. Summary of surface meteorology and average annual frequency for the set of observation days (1956–1999) in each summer and winter synoptic type. Daily means are derived from historical data averaged over the Lake Michigan-Huron basin. Precipitation and evaporation trends are decadal values (mm/10 yr) and in bold-face if statistically significant below the 0.1 level. Pacific-North American Pattern (PNA) and North Atlantic Oscillation (NAO) values represent the mean of the daily indices for each winter synoptic type (Polderman and Pryor 2004).

ST	Character	Avg FREQ (%)	Max FREQ	PREC (mm)	PREC Trend	EVAP (mm)	EVAP Trend	TMAX (°C)	TMIN (°C)	PNA	NAO
1	warm, wet	15	mid-July	4.08	–1.28	0.64	1.11	23.77	12.37	—	—
2	very warm	26	late-July	2.12	3.30	0.64	**3.52**	24.81	12.18	—	—
3	cool, dry	13	late-Sep	1.35	**2.83**	2.26	1.68	16.65	4.91	—	—
4	mild, wet	13	late-Sep	4.39	3.04	1.39	0.91	20.29	9.66	—	—
5	cool, dry	9	mid-Apr	1.18	1.33	0.62	**1.51**	15.53	2.94	—	—
6	warm, wet	14	late-May	3.97	–2.73	0.43	1.21	22.89	11.35	—	—
7	cool, dry	12	late-Apr	1.24	0.48	1.23	0.15	18.54	5.55	—	—
WT											
1	mild, wet	15	late-Oct	2.54	0.38	1.37	2.70	7.67	–2.10	–0.02	0.03
2	mild, dry	19	late-Nov	1.15	0.39	2.13	1.09	4.29	–5.92	0.06	0.17
3	cold, wet	17	early-Apr	2.42	**7.31**	2.58	**4.91**	0.30	–9.07	–0.13	–0.11
4	cold, dry	17	late-Mar	0.95	–1.60	2.66	**–9.47**	–0.45	–9.76	0.43	–0.50
5	cold, wet	15	early-Jan	2.12	1.44	2.68	–1.05	1.64	–7.56	–0.40	–0.10
6	cold, wet	18	late-Nov	2.57	**5.34**	3.26	–1.29	1.63	–6.61	–0.19	–0.05

Significant uncertainties are present in the calculated NBS, with the main source of error in the measured precipitation and especially runoff. A number of variables can contribute to errors in estimating the budget components and must be taken in consideration when assessing projection and hopefully addressed in future studies (Lenters 2004):

1. Errors in the hydrologic dataset and contributions from neglected water budget components.
2. Errors in evaporation rates, which are small during April–June but may contribute errors during January and March (Blanken *et al*. 2011).
3. Errors in measured precipitation and runoff, which would also have important implications for conclusions regarding the land surface water budget. Long-term mean spring runoff is underestimated in most studies. Some of the Great Lakes watersheds are not gauged, therefore, in the 3 months of highest runoff into the lake (April, May, and June) runoff errors are likely the primary source of uncertainty. Such errors might even

reflect a “large stream bias” as a result of the tendency for smaller streams to be not gauged.

4. Projections of regional climate change which are not quantified in most analyses.
5. The methodology for producing the daily time series of climate projections preserves the occurrence frequency of daily precipitation events from the historic record. If those frequencies change (for example, they become less frequent, but more intense), then the changes in daily streamflow metrics provided in studies will not reflect future conditions accurately.
6. Vegetation parameters in the watershed models are static, therefore, they do not adjust to projected changes in the growing season, or changes due to the effects of increased atmospheric Carbon. Numerous studies (e.g. Li *et al*. 2004, Wang *et al*., 2005) evaluating the effects of excess Carbon on plant transpiration have yielded mixed results with some plant types more sensitive to temperature than carbon and others being more balanced in their response.
7. Analysis of historic river runoff records by Gedney *et al*. (2006) indicate that observed increases in river discharge cannot be completely attributed to changes in climate, but are consistent with the suppression of evapotranspiration related to the increase in atmospheric Carbon. By contrast, Piao *et al*. (2007), suggest that observed increases in global streamflow are the result of climate change and deforestation and that increased CO_2 has actually contributed to a small decrease in streamflow.
8. Changes in plant physiology in response to a changing climate are important, however, such effects were largely neglected in most studies, therefore changes in evapotranspiration were directly attributed to changes in available soil moisture and the energy available to drive evapotranspiration.
9. The effects of lakes and wetlands, urban areas and the sub-grid variability in precipitation from summer convective storms were not explicitly studied, even though in some cases they may have a significant impact on aspects of these results like on the magnitude and timing of peak-flow events.
10. More large-scale analyses are needed to understand the similarities and differences in the climate models synoptic scale features.
11. More sensitivity studies through model simulations are needed to understand some of the large scale differences between the different climate models

Expected changes in the Great Lakes region due to climate warming to hydrologic cycle and its dependencies can be summarized as follows: Changes to the Hydraulic Cycle and the Effects on Lacustrine Systems

Precipitation will increase significantly in the winter and spring including an increase in extreme events such as heavy precipitation and periods of drought (Kling *et al*. 2003; Cherkauer and Sinha 2010). In the summer months, precipitation will generally decrease, however, each storm event will be larger and thus produce more runoff but less soil moisture and aquifer recharge. Total runoff is projected to increase in the winter and spring, with the distribution of daily total runoff to been shifted towards higher daily flows due to more frequent storm events. For end of the summer and fall, the pattern is expected to be reversed due to lower precipitation (e.g under the A2 scenario; Huang *et al*. 2012). Regions with projected decreases in summer flows for all three climate change scenarios (such as southeastern areas) will experience drier summers and lower water levels (Polderman and Pryor 2004; Cherkauer and Sinha 2010).

Positive trends in precipitation associated with the Colorado low pressure and frontal cyclones to the southeast of the Great Lakes suggest that late-fall to mid-winter is an important period for precipitation anomalies and also implies some degree of modification of the individual types which may reflect the role of reduced ice cover (Assel *et al*. 2003). Therefore increased evaporation from the Great Lakes is expected together with changes in frequency and surface manifestations of synoptic circulation patterns that reveal the important coupling of synoptic-scale phenomena to net basin supply anomalies and lake levels (Polderman and Pryor 2004; Blanken *et al*. 2011; Huang *et al*. 2012).

Change in influxes in spring and fall appear to compensate each other and lead to relatively stable water levels in all the Great Lakes (Argyilan and Forman 2003; Lenters 2004). Understanding the future long-term changes in Great Lakes water levels will require determining if the current compensation in seasonal trends will continue or change in magnitude (positive or negative) (Lenters 2004).

There is an important statistical significance in some of the observed trends, therefore it appears that the recent changes are not pure natural variations, but rather are part of a systematic shift (Lenters 2004). As such trends cannot continue indefinitely due to hydrologic variable constraints, it would be useful to investigate better the underlying climatic mechanisms responsible for the observed shifts in precipitation, evaporation and runoff, to help in understanding and predicting future variations. Although some potential factors contributing to climate change have already been suggested (such as shifting storm tracks), more work is needed to understand the mechanisms and causes driving the change. Beside direct lake and stream processes, it important that studies better approach land surface processes, which are related to water sources (e.g. runoff; Lenters 2004).

Changes to the Hydraulic Cycle and the Effects on Fluvial Systems

Changes in temperature and precipitation projected for the next century will induce important modifications into the hydrological regimes of the Great Lakes and St. Lawrence tributaries. Dedicated studies about the influence of climate change on streams in Great Lakes area are few, but from scattered information found in climate change papers, there is agreement that air temperature will increases in winter and spring which will affect precipitation (snow or rain) and the water volume stored in snow cover.

An important source of information about Laurentian streams is provided by a study conducted by Boyer *et al*. (2010). They present projections over the next century of stream flows using the hydrological model HSAMI coupled with three General Circulation Models (HadCM3, CSIRO-Mk2 and ECHAM4) and two greenhouse gas emissions scenarios (A2 and B2). The base flow was established from historical data (1961–1990) with a perturbation factor equivalent to the monthly mean difference for temperature and precipitation. Good correlation between winter-spring peak volume dates and mean air temperatures can be observed in historical data (1942–2000) for rivers in North-Eastern and Western North America (Stewart *et al*. 2004; Hodgkins and Dudley 2006). The mean difference was calculated between the reference period values and the future GCM projected values for three future 30 year periods (2010–2039, 2040–2069; 2070–2099; Figure 12). Although the climate estimates were variable due to the different GCMs used, they all projected an increase in winter discharges and a decrease in spring discharges. Depending on the latitude of the watershed, the center-volume date is expected to shift 22–34 days earlier.

For most rivers and for all 30 year periods, the projected changes in mean annual discharge, when compared to the reference period, were generally lower than a 15% increase.

This demonstrates that the greatest changes will be felt on a seasonal basis rather than across the century. The predictions in mean annual discharge per model were as follows:

- HadCM3: +6.6 to +17.7%
- CSIRO-Mk2: +1% to + 10 %
- ECHAM4: -4% to -12%

Therefore, it is the simulated seasonal discharges that indicate that mean winter and mean spring discharges will be most altered by changes in climatic variables (Minville *et al*. 2008; Quilbé *et al*. 2008). Winter discharge is expected to increase by an average of 52 % for the 2020s and by 133% for 2080s compared to the reference period in two Quebec rivers (Figure 13).

It is expected that projected hydrological changes for the Great Lakes and St. Lawrence tributaries will have significant impacts on the frequency and magnitude of sediment transport processes. An expected reduction of up to 32% of the maximum spring mean flow combined with a decrease of the frequency of higher than mean discharges will reduce the size of particles and the sediment volumes that can be transported during that season (Boyer *et al*. 2009). In contrast, higher winter flows will increase the potential of events capable of stronger sediment transport. This may lead to geomorphological changes, especially in ice covered rivers where the tunnel effect can induce higher water velocities in the confined stream (Boyer *et al*. 2009). The combination of these two stream flow regimes could lead to greater overall sedimentation in tributaries, at the confluences with the St. Lawrence River and even stronger sedimentation in the lakes.

Rare events are defined as discharges that are larger than three times the standard deviation of the reference periods. The magnitude of such events has great importance for channel stability. Rare events during winter are projected to be generally lower than for the reference period spring value, but their frequency depends on latitude and stream size (Boyer *et al*. 2009). Compared to the reference period, the frequency of rare events during winter would increase at higher latitude rivers and decrease for lower latitude rivers.

A large part of the error in hydrological projections in climate change studies is represented by the uncertainty in modeling precipitation. Most of uncertainties derive from the difficulty of an accurate evaluation of evapotranspiration and climate variability (Bates *et al*. 2008). Therefore, projected changes by models for river hydrology have to be carefully gauged (Boyer *et al*. 2009). Compared to the observations during the reference period, HadCM3 and ECHAM4 offer a better potential for the simulation of the variables of interest in Southern Great Lakes watershed. Different outcomes from HadCM3 and CSIRO-Mk2 models, which predict an increase in precipitation, versus ECHAM4 which projects a small decrease in median flow only adds to the uncertainty of model outcomes. Therefore, all the projected values for changes in the mean annual discharge are within the uncertainty zone (±19%) associated with HSAMI calibration process (Boyer *et al*. 2009).

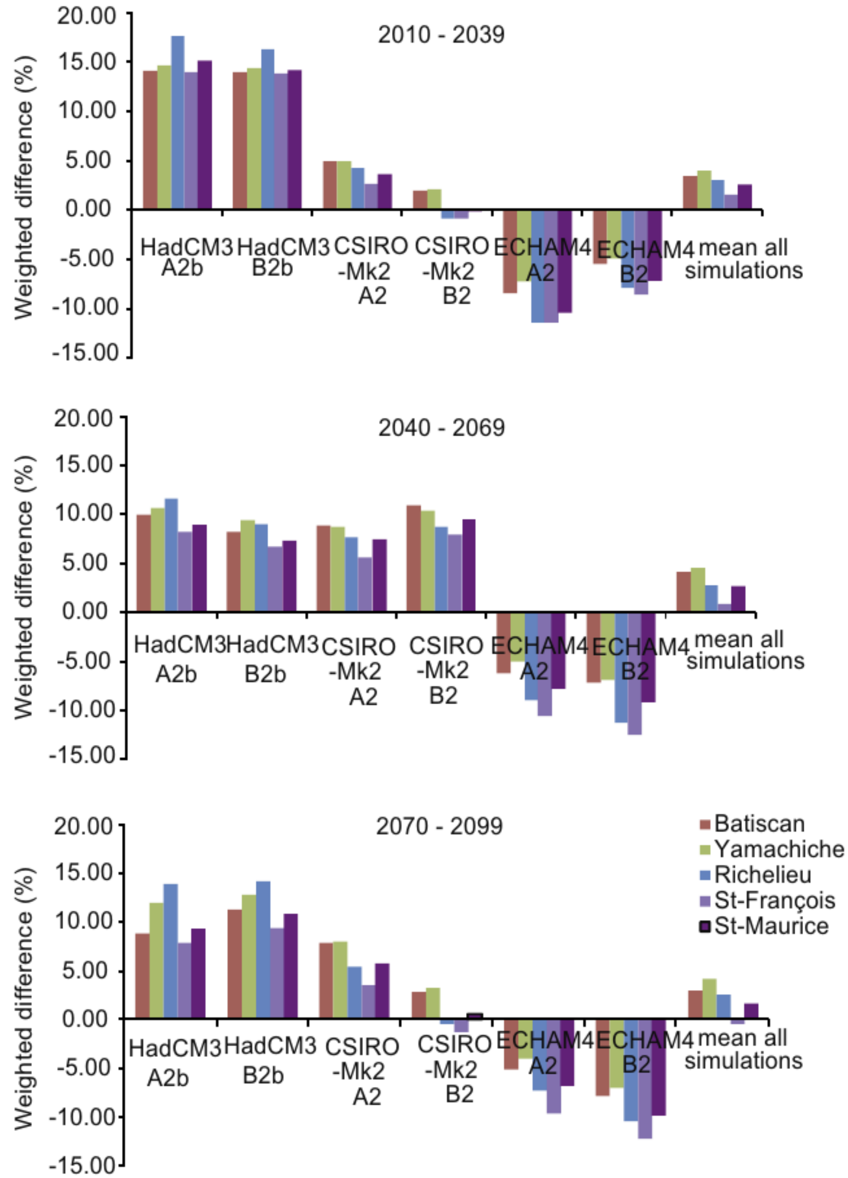

Figure 12. Relative mean annual discharges of each horizon in relation to the reference period (weighted difference (%) = (Qmean annual future-Qmean annual reference period)/Qmean annual reference period*100). (Boyer *et al*. 2010)

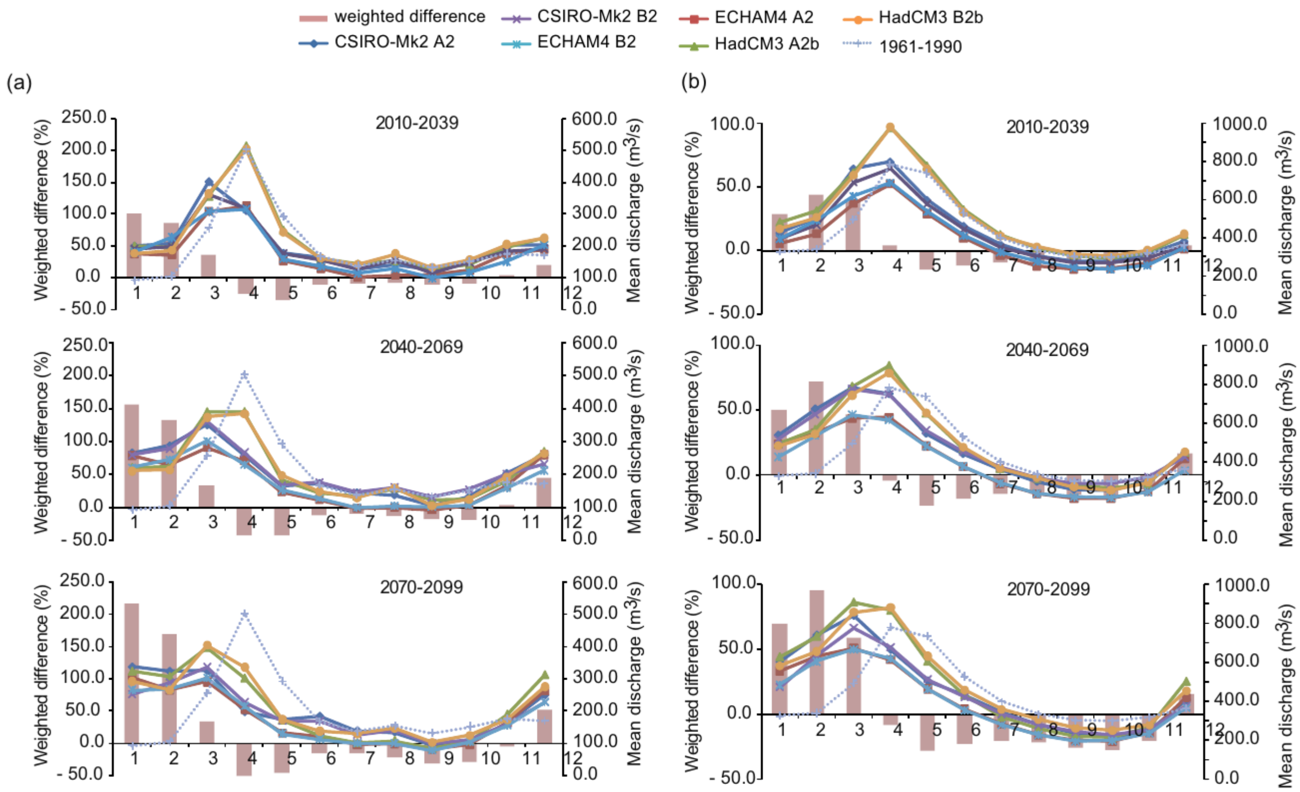

Figure 13. Example of mean monthly discharges and relative mean monthly discharges in relation to the reference period in two rivers in Quebec. (a) St-François; (b) Richelieu. (Boyer *et al*. 2010)

2.4 WIND

The effect of climate change on wind speed is not well understood and the few models that have attempted to project future conditions do not offer any robust conclusions (Breslow and Sailor 2002; Pryor and Barthelmie 2010; Pryor and Ledolter 2010). Looking back, Huang *et al*. (2012) demonstrated that the 10m wind speed over Lake Ontario has significantly decreased over the last 4 decades ranging from -0.20 to -0.33 m s^{-1} $decade^{-1}$. This was consistent with the studies of Wan *et al*. (2010), who also found a decreasing trend in wind speed over Ontario from 1953 to 2006. On the other hand, the frequency of extreme storms is expected to increase by 2 to 4 times over the next, which could be accompanied by tornadoes and high winds (Zwiers and Kharin 1998; Kharin and Zwiers 2000, 2005).

Changes in wind speed could play an important role in the depth of the epilimnion in lakes (Huang *et al*. 2012). Huang *et al*. (2010) used three dimensional models of Lake Ontario and determined that the thermocline would be shallower as a result of weaker wind speed. In addition, the summer mean water temperatures in the thermocline area would have a larger variability than those layers above and below the thermocline. This indicates that the variability of temperature in the thermocline region is sensitive to surface wind forcing, which results in stronger summer stratification with much warmer shallow surface mixed layers and cooler sharp thermocline in the lakes. The effects of wind speed on thermocline depth are likely to be more important in large lakes where wind has a longer fetch, whereas for the small lakes water clarity may have the stronger contribution.

2.5 WATER QUALITY

Water clarity is a variable being recommended for the detection and monitoring of ecosystem change under anthropomorphic and climate change in Canada (Gunn *et al.* 2001). In oligotrophic lakes, water clarity is primarily controlled by the concentration of coloured organic matter such as dissolved organic carbon (DOC; Scully and Lean 1994; Fee *et al*. 1996; Gunn *et al.* 2001). Decreased DOC concentrations related to lower DOC export rates from catchments during warmer and drier conditions could thus result in higher transparencies (Figure 14). A wide range of chemical, physical and biological processes in lakes can be influenced by water clarity including the thermal profile, attenuation of all light spectrums, the vertical distribution of plants and animals, as well as the form and availability of toxic metals (Schindler *et al*. 1997).

A long-term monitoring study by Gunn *et al*. (2001) of Secchi depth transparency in several lakes in Killarney Provincial Park demonstrated changes in the light environment of the park lakes over the past 25 years. Although the lakes are in close proximity, many individual lakes exhibited widely different rates and directions of change (Figure 15). In recent decades, the clear and acidic lakes responded to the effect of climatic variability and thus could be good indicators of freshwater ecosystem change. Very small changes in the DOC concentration in ultraclear lakes can have dramatic effects on habitat availability, water pH, transparency and water quality for many freshwater biota under changes in climate. In addition, in lakes with low DOC, the steep thermal and density gradient between the epilimnion and the metalimnion can break down, leading to a broad transition zone between the surface and bottom water habitats (Gunn *et al.* 2001). However it is the change in the depth and thickness of the thermocline which is most likely to be the result of increased temperatures and changes in water clarity in oligotrophic lakes. Fee *et al*. (1996) suggested that the expected magnitude of thermocline deepening related to changes in transparency was the same as those predicted by warming temperatures under CO_2 scenarios. Long term monitoring at the Experimental Lakes Area in Northern Ontario indicated that the thermocline deepened in a small lakes over a 20-year period when epilimnion temperatures rose by more than +2 ºC and DOC concentrations declined (Magnuson *et al*. 1997).

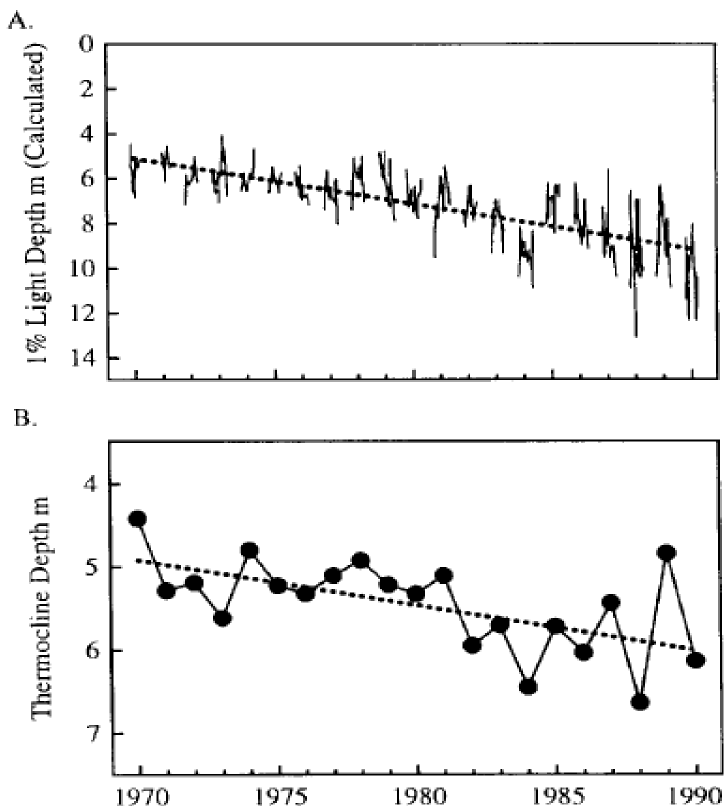

Figure 14. (a) Changes in penetration of photosynthetically active radiation (PAR) in Lake 239 as the depth of the isopleth representing 1% of surface light (equivalent to photic zone depth) (b) changes in thermocline depth in Lake 239 (Magnuson *et al*. 1997)

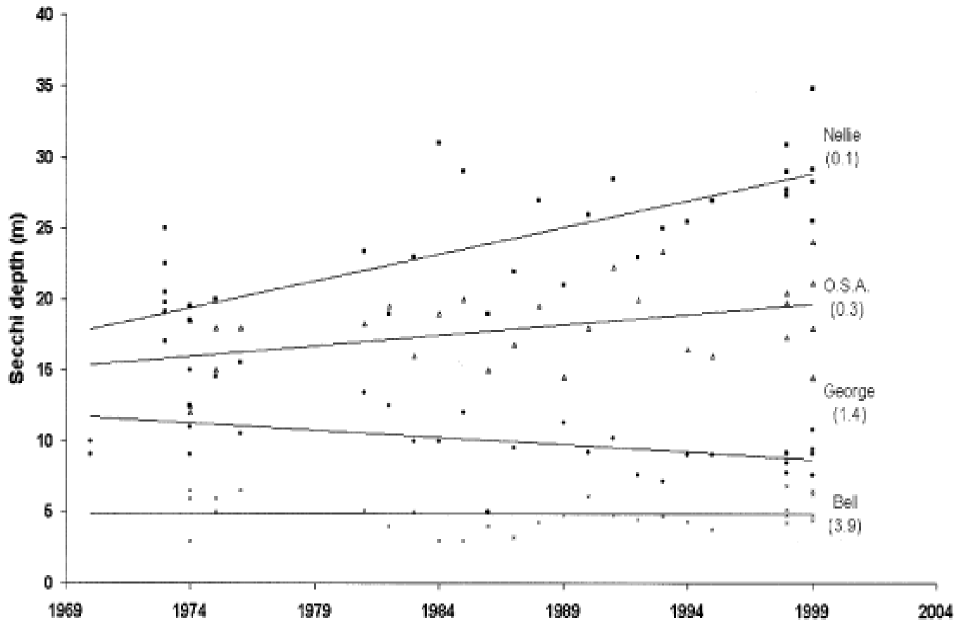

Figure 15. Changes in Secchi depth transparency of study lakes in Killarney Park Ontario. The fall 1998 DOC concentrations (mg/L) for the four study lakes are indicated in parentheses (Gunn *et al.* 2001).

Changes to the hydrology of rivers can alter the physico-chemical characteristics and quality of the water. For example, where drier spring and summer seasons are projected in the Great Lakes region, concentrations of dissolved organic matter from soils will decrease, increasing the water clarity and resulting in a range of associated effects (e.g. changes to primary production). Earlier ice cover break-up in the Great Lakes has led to earlier spring algal blooms and altered the dynamics of nutrient cycling processes. Lower stream flows and lake levels will also serve to concentrate nutrients and chemical contaminants, further deteriorating water quality. Projected reductions of up to 50% in outflow from Lake Ontario may result in the saltwater wedge in the St. Lawrence River intruding further upstream (Ramsar 2002). An increase in the incidence of severe rainfall events, as projected for the southeast, may increase the load of suspended sediment and associated non-point source pollutants (e.g. nitrogen) in rivers and lakes. Many of the above conditions will also favour the outbreak of water-borne diseases such as Giardia and Cryptosporidium (Ramsar 2002).

3. CONSEQUENCES TO BIOTIC COMMUNITIES

3.1 PLANTS AND WETLANDS

Temperature

In the Great Lakes basin there are two types of wetlands: inland wetlands and coastal wetlands. Coastal wetlands are located along the dynamic land-water interface where wetland ecosystems are exposed to changing water levels, and are therefore arguably more sensitive to climate change. They are dependent on hydrologic variability to maintain diversity and ecosystem functioning. Wetland area in continental North America is estimated to be around 191 million ha with roughly 41 million ha in the USA and 150 million ha in Canada (Figure 16; Ramsar 2002). There is evidence that climate change has a wide range of general impacts expected to affect both types of wetlands including: change in base flows; altered hydrology in depth and period; increased heat stress on wildlife; extended range and activity of some pest and disease vectors; increased flooding, landslide, avalanche, and mudslide damage; increased soil erosion; increased flood runoff resulting in a decrease in recharge of some floodplain aquifers; decreased water resource quantity and quality; increased risk of fires; and increased coastal erosion (Ramsar 2002).

Climate change in the Great Lakes wetlands will be mostly felt as water levels changes due to warmer temperatures, increasing evaporation, and altered precipitation and snow cover patterns. These changes are likely to affect the hydrology of their adjacent water bodies altering the current distribution and abundance of coastal wetland communities (Mortsch *et al*. 2006).

Inland wetlands are also vulnerable to climate change. The extent of semi-permanent and seasonal wetlands may be reduced by general increases in evapotranspiration and reduced summer soil moisture, particularly in the prairie regions of North America. Estimates based on a CO_2 concentration doubling scenario project that the southern limit of peatlands in Canada could retreat 200-300 km northwards (Anisimov and Fitzharris 2001). Furthermore, a major reduction in northern peatlands may transform the area from a net sink to a net source of carbon dioxide for the tundra region, while methane emissions may decrease due to drying and increased oxidation at the surface (Ramsar 2002). Mid-continental wetlands that depend on precipitation as a primary water source will be especially vulnerable to climate variation and change (Winter 2000). Within the Lake Simcoe watershed in Ontario, 89% of wetlands are considered vulnerable to drying and shrinkage due to the combined effect of a decrease in precipitation and an increase in air temperatures anticipated with climate change (Chu 2010). Climate warming will also reduce the extent of alpine tundra in North America, potentially causing species loss and ecosystem degradation through increased fragmentation.

Climate warming induced changes are not well understood at present but could alter the riparian vegetation and ecosystem dynamics, (Crowder *et al*.1996). Higher winter flows with an increase of 50–200% of the mean winter flow may extend bed and banks damaging plants and prevent germination of seeds. The river bed alteration through enhanced erosion may also modify fish habitat affecting fish migratory behavior and remove fish eggs and larvae of winter spawning species through enhanced flow transport of fish eggs and larvae of winter spawning species (Bergeron *et al*. 1998).

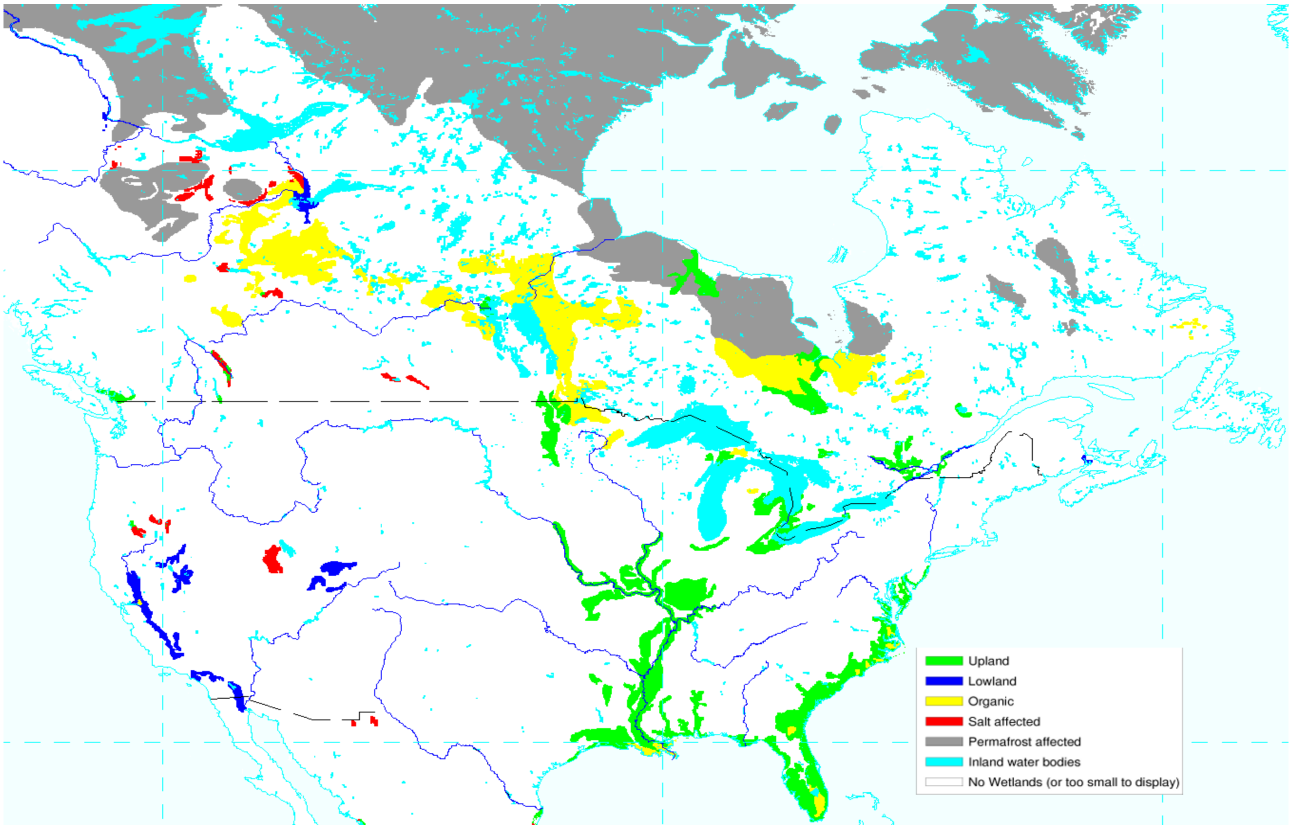

Figure 16. Wetlands in North America (United States Department of Agriculture 2012)

Ice Cover

There are several factors related to ice cover that affect the physical and chemical characteristics of a lake. Ice cover duration, timing of ice formation and break up, ice thickness and snow cover on ice can all affect the functioning of lake ecosystems (Kouraev *et al*. 2008). Changes in ice phenology due to global warming may have important consequences for phytoplankton, zooplankton, and fish communities (Shuter *et al*. 2012). Congelation ice does not provide an appropriate environment for living organisms, but algae can grow in the slush layer on top of ice, or in a pocket between snow and congelation ice. The timing of ice break-up influences the initial growth conditions for diatoms and the timing of the spring phytoplankton bloom (Blenckner *et al*. 2007).

3.2 AQUATIC INVERTEBRATES

Temperature

The direct impact of increasing temperatures on the physiology, population structure and community structure of aquatic invertebrates has been examined by a number of studies. The relationship between water temperature and zooplankton body size has been well established, where warmer waters result in smaller individuals (Moore and Folt 1993). This has also been found in larger invertebrates, where *Chaoborus* sp., living in deep, cold lakes, are larger than others of the same developmental maturity living in warmer waters (N. Yan, unpublished data). Thus, climate warming is generally expected to favour the smaller taxa of lower trophic levels, as well as smaller individuals within populations. Under climate change scenarios, this relationship could potentially have important impacts on aquatic ecosystems. On a population level, smaller females would produce fewer and smaller eggs, resulting in a lower population growth, and smaller body size would increase the predation risk from invertebrate predators. This relationship also has implications for other trophic levels, as well as the environmental characteristics of the system. For example, large zooplankton consume more algae and a broader array of algal species than small zooplankton. If zooplankton became smaller due to increased water temperatures, this could result in a reduction in grazing activity, leading to greater phytoplankton density and reduced water clarity. In addition, a preponderance of small zooplankton in a lake can shift a system from phosphorus to nitrogen limitation in nutrient-poor lakes, as well as indirectly influence the heat content in small, wind-sheltered lakes. In a study in Mouse and Ranger Lakes in south-central Ontario, Panov and McQueen (1998) observed a negative relationship between maximum *Hyalla azteca* size and temperature, with a stronger impact on growth in small individuals. At high summer temperatures, the largest individuals showed a net release of energy – under climate change, this would lead to the disappearance of the largest individuals from summer populations, and the exclusion of larger individuals from warmer habitats.

Several studies have investigated the direct impacts of increasing temperatures on invertebrate populations and communities through in situ warming experiments or observations over anomolously warm years. Results from these studies are mixed. An early study by Ferguson and Fox (1978) links declines in certain macroinvertebrate taxa (e.g. Ephemeroptera, Hemiptera, Odonata and Trichoptera) with increased temperatures, while a later study shows increased abundances of Ostracoda and Gastropoda in warmed ponds (McKee *et al*. 2003). However, one common pattern from several studies is that the response of various invertebrate taxa to increased temperatures is likely to be subtle. For example, a study by Hogg and Williams (1996) suggests that changes in invertebrate life history parameters (e.g. size at maturity, timing of emergence and adult sex ratios) may be more sensitive indicators of small, gradual shifts in temperature compared to measures such as taxonomic composition, species richness, community biomass or densities of particular taxa. From an experimentally heated, permanent, first-order stream outside Toronto, Hogg and Williams (1996) observed reductions in total species densities, increased growth rates, earlier emergence of adult insects and altered sex ratios with a relatively small increase in temperature (2.1-2.4°C mean annual increase). Changes were not always consistent among all observed species, and the authors suggest that responses to small shifts in temperature are not universal, but may be more prevalent within particular phylogenetic groups. Mesocosm experiments by Feuchtmayr *et al*. (2007) did not show a strong temperature effect on many macroinvertebrate taxa, as only gastropods increased in abundance in heated tanks. They suggest that overall abundances of most macroinvertebrates will not be much affected by predicted temperature increases, although the authors acknowledge that certain taxa were not well-sampled and thus may not have captured any potentially existing temperature effect for mites, *Coleoptera* or *Diptera*. In a groundwater system, Tixier *et al*. (2009) demonstrated that experimentally-controlled temperature increases influenced chironomid abundance and composition, but not taxonomic richness. In this case, it is suggested that the manipulated temperatures may have come close to the upper thermal tolerance for some chironomid species, leading to a reduction in abundance, but not necessarily loss of species. Further, while there were compositional differences between treatment and control, the functional differences (i.e. cold stenothermal species versus species with a wider thermal tolerance) were not consistent with warming.

Similarly, a two-year microcosm warming experiment conducted by McKee *et al*. (2002) suggested that the effects of small temperature increases on zooplankton communities in shallow lakes and ponds will be subtle – neither cladoceran diversity nor size structure was influenced by warming, but there was a tendency towards greater community evenness. Lastly, a Canadian study by Baulch *et al*. (2005) investigated the effects of artificial warming on epilithon communities of differing successional stages, and found that the response to increased water temperatures varied by community type. For example, there was no effect of warming on well-developed communities on artificial substrate, but there was an increase in biovolume for early successional communities. Bacterial density also increased in warmed enclosures, but there were no changes in the total density of macroinvertebrates or microcrustaceans, and there was no change in taxonomic composition.

Aside from overall warming temperatures, the response of aquatic communities is also thought to be dependent on the seasonal timing and magnitude of warming, as well as the sensitivity of the specific life-history forms of a species present in different seasons. For example, results from several European studies suggest that there will be strong seasonality in any effect of warming (e.g. George and Harris 1985; George *et al*. 1990; Straile 2000; McKee *et al*. 2000). For organisms which overwinter in resting stages, temperature is a cue that stimulates the production of overwintering stages and/or the release from dormancy. As climate models generally predict disproportionate warming in the fall and winter relative to summer in the temperate zone, Chen and Folt (1996) investigated the importance of fall-specific warming of two species of zooplankton in a lake in Vermont, United States. In-situ warming experiments revealed that the overwintering strategies of both species could be compromised by fall-specific warming. In *E. lacustris*, there was diminished survival and reproduction at fall temperatures >15°C, leading to a greatly reduced number of eggs in the sediment egg bank. Further, elevated fall temperatures induced premature hatching of eggs. In this scenario, individuals would be unable to reach reproductive age before the onset of winter, and potentially could lead to the failure of the entire cohort. In *D. catawba*, elevated fall temperatures initiated a switch from sexual to asexual reproduction, which the authors project would diminish the number of new ephibbia added to the egg bank, and ultimately a reduction in the recruitment of future spring populations. Examining the seasonality of climate change effects on lentic biota is still a nascent facet of climate change research, and has been suggested by numerous researchers is an area for future work (e.g., Baulch *et al*. 2005).

It should be noted that a full understanding of species thermal limits and the effects of thermal stress is obviously necessary for predicting the effects of increasing temperatures on aquatic organisms. Recent lab experiments by Ashforth and Yan (2008) showed that there is a reduction in survival of *Daphnia pulex* at temperatures >18°C, as well as a reduced time to maturity and overall fewer offspring. However, a more comprehensive review of temperature thresholds for all aquatic organisms is needed at this stage in climate change research (N. Yan, *personal communication*).

Paleolimnological studies are useful for highlighting changes to invertebrate populations in lakes. These studies illuminate effects of past environmental changes on lentic biota through analysis of sediment cores, and provide further insight in how aquatic systems might be expected to change under future climate change scenarios. A meta-analysis of Northern Hemisphere diatom-based paleolimnological studies by Rühland *et al*. (2008) highlights the main observation that lakes in both circum-Arctic and temperate regions have experienced very similar warming-induced taxon-specific shifts since the late 19th century. This shift is characterized by abrupt increases in planktonic *Cyclotella* with concomitant decreases in the heavily silicified *Aulacoseira* and/or small, benthic *Fragilaria* species. The timing of *Cyclotella* shifts in temperate lakes is consistent across the geographic area encompassed by this meta-analysis, with the shift occurring post-1940. The abrupt nature of these taxon shifts in the paleolimnoligical record suggests that an ecological threshold was exceeded, resulting in transformation of habitat availability and quality. The nature and timing of this type of taxonomic shift is consistent with warming and its associated effects on aquatic systems – namely, a short ice-cover period, longer growing season, changes in the light regime, increased nutrient cycling, and/or change to thermal and mixing properties of lakes. Changes such as these favor small, fast-growing *Cyclotella* species, and tend to be the dominant taxa in these types of conditions.

Rühland *et al*. (2008) also highlight the fact that temperate systems will take longer or require a greater increase in temperature before passing through such an ecological threshold. In the paleolimnological record, the onset of this shift occurred earlier in Arctic lakes, followed by high altitude lakes and then temperate lakes. Overall, this study confirms that previously reported ecological changes expressed in the paleolimnological record are widespread, and have occurred with increases in mean annual temperatures that are lower than those projected by climate models for both high- and mid-latitude regions of the Northern Hemisphere.

Environmental monitoring approaches over the past several decades or over a set of years including an anomalously warm summer have also been used to assess the potential impacts of climate change in the Great Lakes and Prairie regions of Canada. For example, Arnott *et al*. (2003) used a long-term data set to evaluate how physical, chemical and biotic variables in Boreal Shield lakes have responded to past fluctuations in climate over a period of two decades, and whether lakes in different regions respond to climate changes in a similar manner through time. This study showed that in Boreal Shield lakes, regional-level drivers are important in determining community dynamics, but the response to such drivers may be modified by individual lake characteristics. Generally, there was high temporal coherence in physical variables such as air and water temperatures, indicating strong regional controls on these variables, while there was generally less coherence among biotic variables, suggesting a strong influence of local controls. However, some local biotic characteristics did appear to be influenced by climate signals, suggesting that similar biotic responses across regions may arise when local controlling factors respond to climate in a similar way.

Locations in Scandinavia are similar to Boreal Shield regions in Canada in some respects, and studies there have shown significant changes in lentic invertebrate species composition with shifts in mean temperatures over time (Burgmer *et al*. 2007). Nyman *et al*. (2005) also determined that environmental factors most affecting chironomid populations, such as sediment organic content, total organic carbon, pH and mean July air temperatures, will be altered as a result of future climate change. It is suggested that limnological changes under climate change scenarios in this region will favor species associated with lakes higher in total organic carbon. In Canada, a study by MacLennan *et al*. (2012) conducted in 20 boreal lakes within Killarney Provincial Park showed that higher trophic levels of zooplankton had larger responses to warm summer temperatures during an anomalously warm, dry summer in 2005. It is suggested that warmer epilimnetic temperatures, higher zooplankton biomass and smaller body lengths of individuals within zooplankton populations may serve as indicators of climate warming effects in boreal lakes.

In the Canadian Prairies, temperature can play a large role in phyto- and zooplankton dynamics. For example, in Lake Winnipeg, midsummer epilimnion temperature is the single best parameter in predicting crustacean abundance (Patalas and Salki 1992). Jackson *et al*. (2007) predicted that in light of predictions for warmer winters and shorter ice cover periods, Canadian Prairie lakes will experience increased survivorship of planktivorous species, and thus stronger control of zooplankton. This may then decrease zooplankton control on phytoplankton, and result in increased phytoplankton abundance. In a study of 76 lakes in the Boreal Plain of Alberta, Sass *et al*. (2008) found that higher spring temperatures were positively related to end-of-summer chlorophyll *a* concentrations (estimated from Landsat images). Dupuis and Hann (2009) examined the effect of warmer water temperatures on phyto- and zooplankton abundance in three eutrophic lakes of the Canadian Prairies, and found that warmer temperatures resulting in decreased water transparency, increased phytoplankton biomass, increased relative abundance of cyanobacteria and a shift from abundant *Daphnia* to increased abundance of rotifers.

A few studies have taken advantage of GCMs to predict how climate change may impact lentic biota in the Great Lakes region. De Stasio *et al*. (1996) simulated the effects of climate change on four small north temperate lakes in the Great Lakes region, under four different climate scenarios; Brooks and Zastrow (2002) used two GCMs (Canadian Global Coupled Model 1; Hadley Centre Coupled Model v2) to assess impacts of climate change on primary production in Lake Michigan, and Lehman (2002) built on earlier climate projection studies by using second generation GCMs to assess impacts of climate change on all five Great Lakes. Predictions from these three studies are not entirely consistent, but do highlight some potentially important impacts of temperature increases on invertebrate biota.

In small lakes in the Great Lakes region, zooplankton productivity could either increase or decrease in response to warming, but that decreased productivity would be expected if zooplankton became more restricted to colder waters (De Stasio *et al*. 1996). In addition, the diel vertical migration of *Daphnia* sp. will be more constrained and focused into a narrower zone in order to minimize predation pressure. However, these migration patterns are likely to vary among different populations, based on differences in predation patterns among lakes.

Within Lake Michigan, climate change will negatively impact primary production via the predicted extension of lake stratification with increasing temperatures (Brooks and Zastrow 2002). Most algal biomass in Lake Michigan and other lakes is produced during the spring bloom, when the waters are well-lit, vertically mixed and nutrient-rich. Extended stratification will lead to a reduction in the duration of spring bloom conditions, and thus a reduction in the production of primary biomass. Extended lake stratification was also predicted by Lehman (2002) in all five Great Lakes, as well as elevated water and sediment temperatures. In this study, a number of potential invertebrate responses are predicted in light of these potential habitat changes – some due directly to increasing temperatures, and additional secondary effects such as the reduction in dissolved oxygen in deeper waters. For example, warmer temperatures will likely increase metabolism and rates of development in invertebrates, leading to shortened generation times. In addition, other developmental responses could be affected, such as premature hatching of resting eggs, or changes in body shape which could ultimately affect predator-prey interactions. Lehman (2002) notes that changes in community composition will be difficult to predict, given that different trophic levels may react in different ways, but as the four deepest Great Lakes will still have cold water refugia, it unlikely that any unique taxa will be lost due to temperature changes alone.

Ice Cover

Changes in ice phenology due to global warming may have important consequences for zooplankton (Shuter *et al*. 2012). For example, it has been found that earlier ice breakup was associated with higher summer *Daphnia* sp. densities and higher growth rates of juvenile sockeye salmon (Schindler *et al*. 2005). According to studies done in Lake Washington, earlier ice breakup and stratification creates a temporal mismatch between the peak spring phytoplankton bloom, which is closely tied to water stratification, and the growth timing of some species of zooplankton (Winder and Schindler 2004). The decrease in the dissolved oxygen (DO) in the hypolimnion can lead to a loss of benthic organisms, activation of anaerobic processes with accumulation of dangerous compounds such as methane (CH_4) and hydrogen sulfide (H_2S; Diaz and Rosenberg 1995). The smaller the lake, the more dangerous anaerobic conditions develop unless there is deep mixing that releases the gases.

Precipitation

Precipitation has been identified as a potentially important climatic driver in Canadian Boreal Shield lakes, as variation in precipitation can influence nutrient loading and inputs of dissolved organic carbon, which then influence productivity and water clarity and thus species richness and biomass. Within the Boreal Shield, Arnott *et al*. (2003) found that different subregions in Ontario had different biological responses to variation in precipitation. In the Experimental Lakes Area, increased phytoplankton richness and biomass were observed during a dry decade, despite decreased nutrient inputs. This increased richness was due largely to an increase in mixotrophic species, which are able to migrate into deeper waters with less light and higher nutrients. In contrast, drought cycles had a negative impact on phytoplankton richness in otherwise similar systems in the Sudbury and Dorset areas, due to interactions with other environmental stressors like acidification.

Lakes in the Canadian Prairies are particularly sensitive to changes in precipiation:evaporation ratios, and in recent years, the area has become increasingly more arid. Further, GCM predictions suggest that future growing seasons will be less productive as a result of declining precipitation (Covich *et al*. 1997). Limnological studies in this region concerning the impacts of climate change on invertebrate biota have highlighted the role of precipitation, and by proxy, salinity, on these organisms. Increases in conductivity in six Alberta lakes have been correlated with decreases in chlorophyll *a* concentration, as well as an association with a shift from cyanophyte species to chlorophytes, cryptophyes and chrysophytes (Evans and Prepas 1996). In study of 76 lakes on the Boreal Plain of Alberta, precipitation during the growing season was found to be negatively correlated to algal chlorophyll *a* concentration, suggesting that chlorophyll *a* and possibly phosphorus concentrations were diluted during wetter years (Sass *et al*. 2008)

Water Quality

Salinity

In the Canadian Prairies, recent studies have focused on the impact of changing lake salinity as a result of climate change as a potentially important structuring variable for biotic populations and assemblages. Sereda *et al*. (2011) examined the effects of climate on limnological and biotic characteristics of two lakes (Jackfish and Murray Lakes) in the interior plains of Canada, using historical and current data. Using the relationship between total dissolved solids and littoral macroinvertebrate diversity, the authors suggest that Jackfish Lake may have lost ~30% of its macroinvertebrate diversity between 1930-2004, when salinity increased from 1170 to ~3500 g/L TDS, and that similar losses are expected for other groups of taxa, such as phyto- and zooplankton. Planktonic biomass has not responded to increases in phosphorus concentrations over time, and generally is much lower than would be predicted by freshwater nutrient models – further climate-driven salinity increases in these lakes may result in large reductions in algal primary productivity.

A study of 70 lakes in the Saskatchewan prairies by Wissel *et al*. (2011) found that pelagic invertebrate communities of saline lakes in this region are resistant to interannual variability in climate, as the community composition is under hierarchical control at large spatial scales, which mimic the degree of environmental variation that is expected to arise from climate change over centuries. Thus, while pelagic invertebrate composition is stable with sub-decadal variation in climate, it may be a sensitive model to forecast the effects of climate variability on longer time scales. In these systems, salinity was the principle variable regulating pelagic invertebrate composition, as well as water depth, nutrient content and calcium concentrations.

As prolonged warming continues, habitat availability and extreme osmotic stress will determine final species combination.

Nutrients

In other systems, particularly in the Boreal Shield region, the effects of climate change on nutrients and consequently biota in lakes are tied not to salinity, but dissolved organic carbon dynamics. For example, littoral carbon is an important resource for higher trophic levels in lake ecosystems, and Baulch *et al*. (2005) has speculated that as littoral carbon increases with climate warming, the effect of warmer temperatures could thus lead to large-scale impacts on lake ecosystems in Ontario. This study also showed that carbon accrual was higher in experimentally warmed enclosures, and that even established communities are likely to show changes if there are concurrent effects on nutrient availability and light with prolonged warming. Other studies have more directly linked the influence of climate change on lake nutrients, and associated changes in biota. In Scandinavia, which is climatically and physically similar to the Boreal Shield areas of Canada, climate change is expected to favor invertebrate species associated with colored lakes, which are high in total organic carbon (Nyman *et al*. 2005).

Water Clarity

Some climate change studies have focused on the impacts of changing water clarity, and its interaction with temperature and nutrients. It appears that this factor can be of equal or more importance than air temperatures in influencing the physical and chemical environment of lakes in the Great Lakes and Prairie regions. The influence of changing nutrient concentrations as well as changes in DOC/lake clarity are predicted to impact invertebrate biota in the form of UV light damage. Underwater UV radiation is expected to change in a variety of ways in response to climate change, depending on concurrent changes in nutrients, the timing of ice cover and thermal regimes, and particularly DOC (Williamson *et al*. 1996; Williamson *et al*. 2002; Xenopoulos and Frost 2003). For example, an empirical DOC-UV radiation model developed from 65 glacial lakes in North and South America showed that changes in DOC are more likely to alter the UV environment in lakes than changes in the stratospheric ozone (Williamson *et al*. 1996). Further, small changes in DOC have the ability to produce large changes in UV penetration in lakes, particularly in low DOC systems (Williamson *et al*. 1996). As decreases in DOC and increases in water clarity have been observed during recent climate changes in Boreal Shield lakes (Schindler *et al*. 1990; 1996), UV radiation could potentially have a large impact on lentic communities in this region.

The direct effects of UV radiation on different freshwater taxa have been investigated in a number of studies. UV radiation can inhibit phytoplankton photosynthetic and growth rates, reduce biomass accrual and carbon assimilation in benthic algae, induce changes in periphyton species composition, reduce inorganic nutrient uptake in algae, damage algal DNA and disrupt electron transport chain and photosystem II pathways, and reduce protein synthesis and fatty acid production in algae (see references in Watkins *et al*. 2001). As increased exposure to UV radiation as a result of climate change is expected to influence different taxa in different ways, it may be difficult to predict specific population- or community-level changes (Williamson *et al*. 1996). Earlier studies have shown that invertebrate grazers, such as chironomids, tend to sustain more damage than primary producers, and that UV may preferentially damage zooplankton grazers that remain in surface waters during the day (Williamson *et al*. 1996). However, primary producer biomass may increase over long-term UV increases.

Xenopoulos and Frost (2003) showed that within phytoplankton communities in Ontario lakes, there is variable sensitivity among taxa to UV radiation. This variable sensitivity may thus induce taxonomic shifts in phytoplankton communities in the face of changes to UV radiation associated with climate change, which is supported by mesocosm experiments by Watkins *et al*. (2001). Williamson *et al*. (2002) also reported that organisms will have different responses to UV as temperature varies seasonally, and that UV even plays a role in observed seasonal patterns in body size and fecundity.

Watkins *et al*. (2001) experimentally manipulated UV radiation in lake mesocosms in the Experimental Lakes Area of northwestern Ontario. Results from three different UV treatments – photosynthetically active radiation (PAR) only (400-700 nm), PAR+UVA (320-700 nm) and PAR+UVA+UVB (280-700 nm) – showed that epilithon exposed to UV radiation had lower primary production than UV-blocked treatments, and that varying UV regimes induced taxonomic shifts in epilithic algae. Given that the UV levels were not experimentally increased for this study, this shows that algae are affected even at current levels of UV radiation. Further, the results from this study provide further evidence that algal communities are most susceptible to UV radiation during the early stages of colonization. Diatoms were the most UV-sensitive group, while chlorophytes made up a larger proportion of algal assemblages in UV treatments. However, species richness and diversity was unchanged across treatments.

Some studies have also shown that the effects of UV radiation can be influenced by nutrient levels. In experiments by Xenopoulos and Frost (2003), the previously described effects of UV radiation on phytoplankton were more pronounced (but not significantly) at high phosphorus levels. Further, results from Watkins *et al*. (2001) indicated that when UV radiation is blocked, there is lower primary productivity, and epilithic C:N:P ratios are also affected. Future work is needed to determine the effect of UV radiation on the elemental composition of epilithic biofilms, and the consequences on food quality for benthic grazers.

Environmental Contaminants

Environmental contaminants are currently still a major concern for the health of aquatic populations as well as the humans who consume them. Climate change is expected to impact various aspects of contaminant dynamics within aquatic ecosystems, although much about this topic remains to be uncovered. Schiedek *et al*. (2007) reviewed the predicted effects of climate change on environmental contaminants in aquatic biota, on a global scale with emphasis on marine systems. However, there are clear patterns and relationships which may be relevant to freshwater systems in Canada. For example, some organisms have decreased upper temperature thresholds in the presence of certain chemicals, and it has been suggested that reduced fitness will occur in the face of climate change, as biota experiencing stress as a result of the effects of climate change will likely be less capable of dealing with existing contaminants. Further, climate-related changes to food web structure will likely modify the transfer of contaminants, and predicted hypoxic conditions and increased UV radiation will also have negative interaction effects.

In the Arctic, atmospheric concentrations of various contaminants have declined or remained stable since mid-1990s (Carrie *et al*. 2010). Likewise, many of the first-generation pesticides and PCBs have been controlled, and declines in contaminant concentrations have been observed in many northern organisms (Schindler and Smol 2006). However, there is still concern over how climate change may impact contaminant concentrations, particularly in the north. Glaciers currently hold contaminants released during the 1960s and 70s, and melting will release high levels of contaminants to water bodies and their biota. Further, under warmer climates, contaminants will also be in vapor form for longer periods each year, allowing travel to higher latitudes and altitudes (Schindler 2009). It is also possible that release of some contaminants like mercury may be further accelerated by indirect effects of climate change, such as forest fires, which are expected to increase with warming (Schindler and Smol 2006).

Several studies have linked climate change to temporal patterns in fish contaminant concentrations within Canadian lakes. Rennie *et al*. (2010) concluded that patterns of long-term fish condition and mercury concentrations across several regions in Ontario are consistent with regional differences in climate change. In this study, warming trends are associated with declining mercury burdens, which supports previous studies suggesting that fish mercury concentrations may decline in warming climates in lakes where nutrients, carbon and mercury are supplied by allochthonous inputs, and in large, oligotrophic lakes where thermal stratification occurs. In the Prairies, Carrie *et al*. (2010) showed that algal-derived organic matter influences mercury burdens in Burbot. The authors speculate the climate change would lead to variation in algal productivity, and thus drive the pathway for mercury accumulation and methylation in these systems, ultimately leading to greater mercury burdens in Burbot.

3.3 FRESHWATER FISH

Temperature

Two main avenues are used to assess the impact of climate change on species' ranges: 1) model future shifts in bioclimatic envelopes based on climate change scenarios and apply them to correlations between species' distributions and current climatic conditions, or 2) compare changes between historical and current species distributions (Heino *et al*. 2009). The ladder approach is often more difficult due to the lack of availability of historical distributions of freshwater fish species. The distributional patterns of freshwater fish in North America are best predicted by a combination of environmental variables (climate and topography), phylogenetic constraints and postglacial dispersal routes (Knouft and Page 2011). Fish are ectothermic, so their growth, reproduction, and survival are temperature-dependent (Ficke *et al*. 2007) and their northern and southern distributional boundaries are often predicted by temperature (Shuter and Post 1990; Rahel 2002; Lyons *et al*. 2010). Therefore, changing thermal regimes are expected to lead to shifts in species' geographic distributions as populations migrate along isotherms to track suitable thermal envelopes (Rahel 2002; Ficke *et al*. 2007; N. Mandrak and C. K. Minns, *personal communication*). Distributions may also change at the local scale with shifts in the spatial distribution of individuals, for example, within a single lake due to increases or decreases in thermal habitat availability (Shuter *et al*. 2002). Each species will respond to climate change differently so predicting how entire communities or ecosystems change is a difficult task (Ficke *et al*. 2007; Heino *et al*. 2009). Furthermore, as ranges undergo spatial changes, new sets of species distributions will generate novel patterns of overlap, resulting in non-analogous species assemblages (Williams and Jackson 2007).

Temperate fish species are typically assigned to one of three thermal guilds (Magnuson *et al*. 1997; Jansen and Hesslein 2004): warmwater (niche centered around 28°C; e.g., most centrarchids), coolwater (niche centered around 24°C; e.g., most percids) and coldwater (niche centered around 15°C; e.g., most salmonids). However, fish thermal preferences occur along a continuum of temperatures, and a coldwater species' optimal thermal envelope may lie at either extreme of the thermal guild.

Past, present, and future fish distributions are often modelled based on species thermal limits or thermal guilds (Shuter and Post 1990; Lyons *et al*. 2010). These distributional models use air temperature, surface water temperature, groundwater temperature, or correlates of thermal regime (e.g., growing season, accumulation of degree-days, elevation, ice-in and ice-out dates) to make regional assessments of the impacts of climate change on species distributions (Meisner 1990*a;* Meisner 1990*b;* Jackson and Mandrak 2002; Shuter *et al*. 2002; Chu *et al*. 2005). While water temperatures are better predictors of the thermal conditions experienced by fish than air temperatures, the data is often unavailable, so in consequence, air temperatures are often used in place of water temperatures in predictive modelling (Jansen and Hesslein 2004). Some models use a variety of climate-related variables, for example, Chu *et al*. (2005) measured the impact of climate change on freshwater fish distributions in Canada using climatic variables describing both growing season and air temperatures. In a similar example, Lyons *et al*. (2010) modeled the distribution of stream fishes in Wisconsin using a combination of 38 environmental variables, 8 of which described growing season, air temperature and water temperature.

Temperature predictions from a variety of climate models, mostly global circulation models, and scenarios have been applied to predict future species distributions (Table A1). Studies focusing on Canadian freshwaters have used the CGCM2 model with emission scenarios ranging from “business-as-usual” and “ecologically friendly” (Jackson and Mandrak 2002; Chu *et al*. 2005; Sharma *et al*. 2007). Other GCM models have also been applied using the various IPCC (2007) emission scenarios and a 2 x CO_2 scenario (Minns and Moore 1992; Stefan *et al*. 1995; Shuter *et al*. 2002; Lyons *et al*. 2010). However, Peterson and Kwak (1999) and Jansen and Hesslein (2004) used warming estimates from local climate studies arguing that these values are well within the expected temperature increases generally anticipated for their study area by 2100. Species distributions have been modeled until at least 2020, and often until mid-century and 2100, but never beyond. A few studies have incorporated more than one climate model and many use more than one climate scenario in their predictions. Using a range of scenarios can provide a range of possibilities of how species could be affected and could be viewed as a kind of ‘uncertainty analysis’ (S. Sharma, *personal communication*).

Changes to species’ distributions, both at the edges and centre of their range, have been inferred using a variety of models and quantitative and qualitative measures (Table A1). For example, Chu *et al*. (2005) used regressive models based on fish-presence absence data coupled with climate predictions to infer future patterns of occurrence across the study area. Classification tree models have been also used to estimate probability of fish presence (Lyons *et al*. 2010 ; Steen *et al*. 2011). Regressive models coupled with presence/absence data have been used to quantify changes in fish yield across distributions (Minns and Moore 1992). Shuter *et al*. (2002) estimated relative changes in maximum sustained yield with climate change using a series of calculations based on environmental variables and species sensitivity to those variables. Others still have estimated species’ distributions by modeling thermal habitat availability using general linear models and complex simulation models (Stefan *et al*. 1995; Sharma *et al*. 2007). Jansen and Hesslein (2004) used a thermal model linking interactions at the air–water interface with heat distribution throughout the water column to estimate future thermal fish habitat in a single lake. Therefore, evaluations of the response of species’ distributions to climate change have varied from broad regional predictions of future range contraction, expansion, and shifts to estimates of changes in regional fish abundance to measures of future habitat availability in representative lakes. Although some distributional models perform better than others, a lot of models perform reasonably well and the choice of model often depends on what kind of data is available (Elith *et al*. 2006; S. Sharma, *personal communication*)

Lacustrine Systems

In lacustrine systems, water temperature is considered to be the most important environmental variable determining fish species distributions at the regional scale (Rahel 2002). Temperature directly affects fish physiology and an increase in temperature beyond the thermal preference of a species can cause metabolic stress, resulting in reduced fecundity and recruitment, and increased mortality (Magnuson *et al*. 1997). On a larger spatial and temporal scale, these year to year impacts on individual populations of a species can manifest in significant changes in the distribution of populations across its range. Changes to species distributions will be most detectable at range limits, where the abiotic and biotic factors that previously prevented further spread become more or less favourable to it (Gaston 2009).

The following studies outline some of changes that are expected in the Great Lakes Basin and surrounding watersheds in lacustrine systems:

- The northern distributional boundary of Smallmouth Bass is limited by a short growing season that prevents young of year to acquire sufficient energy during the summer months to survive through the winter (Shuter and Post 1990). Predictions derived using a quantitative mechanistic model, estimate that for each degree Celsius of warming, the northern limit of Smallmouth Bass will advance 120 km north (Shuter and Post 1990).
- Minns and Moore (1992) estimated that if atmospheric CO_2 is doubled, Lake Whitefish will exhibit an 81% change to its current range in Eastern Canada, and Northern Pike and Walleye will exhibit changes of 88% and 87%, respectively. Overall fish yield capability will decline for all three species and those areas currently supporting highest fish yields will become areas with low or marginal yield. Higher fish yields are anticipated in the northern portions of the species' current ranges but will not compensate for declines in the south. Therefore, future climate change is likely to result in changes in species occurrence and abundance across the Great Lakes Basin.
- Suitable thermal habitat of Walleye is expected to shift from southern Ontario to central and northern Ontario over the next few decades (Shuter *et al*. 2002). In southern Ontario lakes, decreases in maximum sustainable yield will depend on lake morphology; in lakes that are not expected to stratify, an increase in surface water temperatures beyond the optimum performance range of Walleye results in a total loss of suitable habitat. In lakes that are expected to stratify, only a fraction of the lake will be available to individuals compared to present conditions. In central and northern Ontario lakes, warmer surface water temperatures will create new thermal habitat for the species.
- Jansen and Hesslein (2004) modeled the impact of temperature change (-2°C, 2°C, 4°C and 9°C) on the spatial and temporal extent of thermal fish habitat for Lake Trout, a coldwater species, and Yellow Perch, a coolwater species, in Lake 239 of the Experimental Lakes Area. Lake 239 is located in northwestern Ontario and is representative of small Canadian Shield lakes that the two species inhabit. The number of days that surface water was available for Lake Trout decreased from 121 days to 66 days (~50%) when thermal habitat was modeled using a 9°C warming. Further, all climate scenarios reduced the window of littoral feeding opportunities from 28 days to as little as 4 days. In such a case, Lake Trout would have to make feeding excursions into warmer water, which carries a high metabolic cost and could result in a decrease in fecundity. Lake Trout occurrence and abundance is, therefore, likely to decrease in Canadian shield lakes in response to the loss of suitable thermal habitat and populations will be limited to deep lakes that do not warm up as much (C. K. Minns, *personal communication*). These results can be extended to Cisco and Lake Whitefish, which have similar thermal niche preferences (Jansen and Hesslein 2004).
- Yellow Perch thermal habitat substantially increased with temperature increases of 2° and 4°C and decreased to below baseline levels when temperatures increased to 9°C (Jansen

and Hesslein 2004). However, young-of-the-year perch have a higher optimum temperature for consumption than adults and may benefit more from temperatures increases.

- Chu *et al*. (2005) predicted a 49% decrease in the Canadian distribution of Brook Trout by 2050. The species is predicted to be extirpated from the Prairies and to decrease in occurrence in the Great Lakes Basin and surrounding watersheds. Walleye will expand throughout much of its present range and occupy most of Saskatchewan by 2050. There is a high probability that Smallmouth Bass will expand its range throughout most of northwestern Ontario and eastern Manitoba by 2050. And by mid-century, the Pugnose Shiner is expected to expand its range in the Great Lakes Basin while Arctic Char will be completely extirpated from Ontario. More accurate predictions of range expansions would require the application of local filters such as lake morphology and biotic interactions; both factors can prevent or facilitate the establishment of new species (Chu *et al*. 2005).
- Sharma *et al*. (2007) predicted suitable summer thermal habitat for smallmouth bass across Canada in the year 2100 using three climate change scenarios – two representing a high increase in greenhouse gases each year and one representing a low annual increase. By July 2100, the majority of lakes in Ontario and the Prairies will contain suitable habitat for Smallmouth Bass and the potential extent of their distribution varies between the three climate change scenarios. As the abiotic and biotic conditions (e.g. light availability, availability of spawning substrate) of many northern lakes are unknown, however, there is uncertainty regarding the spatial pattern of Smallmouth Bass distribution in the north after range expansion.
- Stefan *et al*. (1995) used a simulation model to estimate the amount of suitable habitat (described as good growth habitat area – GGHA- and volume - GGHV) for coldwater, coolwater and warmwater species in Minnesota lakes assuming a doubling of CO_2. Coldwater species were affected the most; in southern lakes the already small amount of available habitat was reduced by 14% with climate change and in northern lakes, GGHV declined by 8% on average. Good growth conditions were expected to be present only in the 3 deep oligotrophic lakes in the south and absent from all well-mixed lakes in the north. Coolwater species will experience moderately reduced GGHA in 17% of Minnesota lakes; however, increases in GGHA will be twice as large in the north than in the south. Due to the extended growing season, GGHA will increase the most in well mixed lakes and reduction will only occur in small, medium-depth lakes and deep eutrophic lakes. Temperature increase associated with a doubling of CO2 will result in a GGHV gain of 27% in southern lakes and 76% in northern lakes. However, relative increases in GGHA and GGHV will depend on lake morphology (see Figure 17).

A strengthening in lake stratification will lead to decreases in the volume of suitable thermal habitat available for coldwater species and increases for warmwater species (Jansen and Hesslein 2004; Sharma *et al*. 2007). However, warming is also expected to impact species distributions via a lengthening of the stratification period and consequent loss of available dissolved oxygen in the hypolimnion (Ficke *et al*. 2007; Jaing *et al*. 2012; C. K. Minns, S. Sharma, and F. Rahel, *personal communication*). A longer stratification period can have especially negative impacts on populations inhabiting the hypolimnion of medium-depth lakes (e.g., Lake Erie) because there will be an increase in the intensity of “summer kill” due to anaerobic and anoxic conditions developing in some parts of the lake in certain years (D. Jackson, S. Sharma and B. Shuter, *personal communication*). Furthermore, as winter conditions become less severe due to delayed ice-in dates, the “winter kill” phenomenon currently observed in these systems will decrease in intensity, and they are likely to become susceptible to invasion by species that couldn’t survive there under current conditions (Rahel and Olden 2008; B. Shuter, *personal communication*). Under future climate scenarios, dissolved oxygen levels are not expected to significantly decline within the Great Lakes, with the exception of Lake Erie.

Many changes that will have a strong effect on fish distributions may not be a direct consequence of warming but will be mitigated by increasing temperatures (B. Shuter, *personal communication*). For example, warming will lead to range expansions and increase predation rates and competition between native and invading species for resources. In the Great Lakes Basin, aquatic invasive species are considered the primary threat to 13 of 82 rare fish species and a secondary threat to three other species (Mandrak and Cudmore 2010).

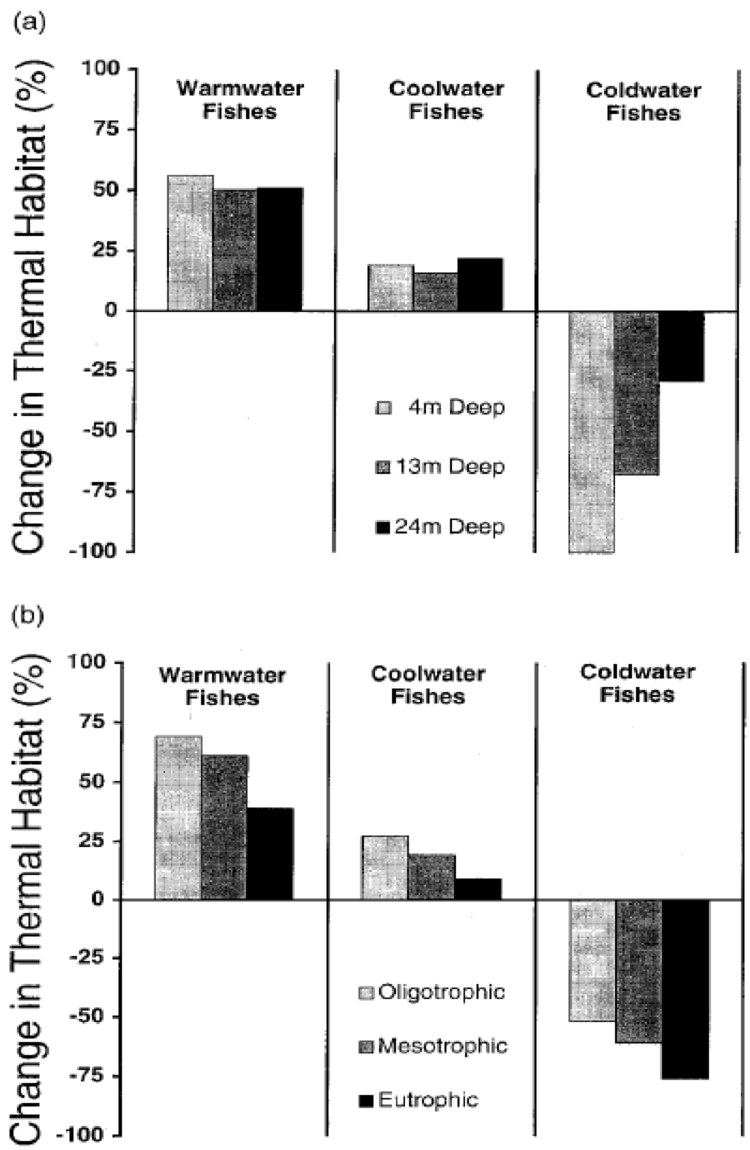

Figure 17. Changes in thermal habitat under 2 x CO2 scenarios for warm, cool and cold water fishes in (a) lakes of different depths and (b) lakes of different trophic status (data from Stefan *et al*. 1995 in Magnuson *et al*. 1997)

The following studies suggest how temperature change may indirectly impact species distributions in lacustrine systems (Table A1):

- Cyprinids in the Great Lakes Basin are threatened by range expansion of predatory fish such as Pike and Smallmouth Bass, occurring as a result of warming water temperatures (Jackson and Mandrak 2002). By modeling the future availability of thermal habitat for Smallmouth Bass using a “business as usual” climate change scenario, Jackson and Mandrak (2002) estimated that by 2050, two-thirds of Ontario will have suitable thermal conditions; by 2100, all but the most extreme parts of the province will have thermal habitat available for the species. Further, a shortened ice-cover period will reduce the probability of Pike and Smallmouth Bass winterkill, leading to increased recruitment and abundance and consequently, predation rates. At the end of the century, predation due to Pike and/or Smallmouth Bass is expected to result a loss of 7,991 populations of Fathead Minnow, 6,064 populations of Northern Redbelly Dace, 5,510 populations of Finescale Dace, and 5,260 populations of Pearl Dace. The spatial distribution of losses will not be uniform; watersheds to the north and northwest of Lake Superior will likely experience the greatest loss of the four cyprinid species.
- Lake Trout may be outcompeted by Northern Pike and Smallmouth Bass in lakes where the two species co-occur. Increasing temperatures will limit the window of littoral feeding available to Lake Trout and Northern Pike and Smallmouth Bass are more efficient littoral predators (Shuter *et al*. 2002; Jansen and Hesslein 2004). In a small boreal lake, Lake Trout reduced its use of littoral habitat by 55% after introduction of Yellow Perch (Wall and Blanchfield 2012). Even in those lakes where Lake Trout are able to take refuge in the hypolimnion during the warmest months and persist, competition from cool and warmwater species for littoral resources will result in lower annual energy intake for Lake Trout (Shuter *et al*. 2002; Vander Zanden *et al*. 2004). While Lake Trout may mitigate the negative impacts of climate change by adapting a strategy of intermittent reproduction in years when energy intake is insufficient, this will ultimately reduce the productivity and competitiveness of individuals (Jansen and Hesslein 2004). If Smallmouth Bass expands its Ontario range as predicted by Sharma *et al*. (2007), the number of vulnerable Lake Trout populations in the province will increase from 118 (~1%) to 1612 (~20%; Sharma *et al*. 2009).

Changes in temperature could also interact with Dissolved Organic Carbon (DOC) to affect the thermal stratification of lakes and consequently, the thermal habitat available for cold and coolwater species. High levels of DOC lead to a shallow thermocline and a larger hypolimnion that benefits cool and coldwater species, while low DOC levels will result in the opposite situation (D. Jackson, *personal communication*).

Competition between coldwater, coolwater and warmwater species can eventually lead to reduced fecundity and low recruitment rates in the least competitive species, a precursor to shifts in distributional boundaries. This is particularly relevant in lakes currently occupied by coldwater predators, since competition of cool and warmwater species adds to the physiological stress experienced from deteriorating thermal conditions (D. Jackson, *personal communication*). In fact, many native species could probably persist if their systems were closed to endemic southern species (B. Shuter, *personal communication*).

Fluvial Systems

In lotic systems, temperature and flow regime are the dominant physical factors driving species spatial distributions (Peterson and Kwak 1999). Fish species that inhabit headwater streams are more affected by groundwater temperature than air or water temperature (Meisner 1990b; Rahel 2002). In streams and rivers where temperatures increase quickly, cool groundwater seeps also serve as a refuge for coolwater species, and even for some warmwater species, sometimes for as long as a month(Ficke *et al*. 1997; D. Jackson, *personal communication*). For example, populations of redside dace, a coolwater species endangered in Ontario, are becoming increasingly physically stressed due to warming groundwater temperatures and urbanization, which is squeezing out its current habitat. An increase in groundwater temperature as a result of climate change could effectively eliminate thermal habitat for these species resulting in substantial range shifts.

The following studies suggest how temperature change may directly impact species distributions in rivers and streams:

- Meisner (1990*a*) estimated that an average summer air temperature increase of 4.1°C (groundwater temperature increase of 4.8°C) will reduce brook trout summer thermal habitat by 42% in the Humber River and 30% in the Rouge River in Ontario. These losses are expected to affect population size as well as habitat connectivity for the species.
- Lyons *et al*. (2010) modeled the impacts of limited warming (+0.8°C), moderate warming (+2.4°C) and warming (+4.0°C) on fish occurrence in all Wisconsin streams using a comprehensive set of environmental variables. With warming, 23 species declined in distribution, 23 species increased, and 4 had no change. Declining species lost more habitat than increasing species gained. The predicted total combined loss of stream length for declining species was 5,497 km per species under limited warming, 14,915 km per species under moderate warming, and 21,046 km per species for major warming. The predicted total combined gain in stream length for increasing species was 2,896 km per species under limited warming, 5,543 km per species under moderate warming, and 6,719 km per species for major warming. All three cold-water species declined substantially with increasing water and air temperatures and one species was extirpated from Wisconsin under the major warming scenario. All 16 cool-water species were expected to decline with warming with 3 species being extirpated from Wisconsin under warming scenarios. Among the 31 warm-water species modelled, 3 were expected to decline, 4 showed no change in distribution, and 23 increased in distribution. For species that decreased in distribution under the three warming scenarios, the density of streams containing fish decreased steadily with increasing temperatures. Two spatial patterns were observed for warm-water species: species increased their distributions northwards and the density of occupied streams increased.
- A temperature increase of 5°C by 2100 is expected to lead to declines in coldwater species across the Muskegon watershed in Michigan, while cool and warmwater species are expected to significantly increase their ranges (Steen *et al*. 2011). Brook, Brown and Rainbow Trout are expected to be virtually eradicated from the system while Chinook and Coho Salmon may be eradicated from some creeks and rivers but maintain populations in others. There will be gains in the ranges of Small and Largemouth Bass and Northern Pike across the system, the largest increase being a 276% increase in the probability that Northern Pike will occur in the Middle Branch River.

The effect of rising temperature on freshwater systems can also be modified by land-use patterns, especially around rivers and streams. In the Muskegon River watershed in Michigan, land-use change was predicted not to drive changes in species composition but to nevertheless cause large changes in the distributions of a few species, like Walleye and Chinook Salmon (Steen *et al*. 2011). . Heavy urbanization of the surrounding watershed generally leads to warmer groundwater and stream temperatures, partly because runoff passes over hot asphalt before reaching streams during storm and rain events (D. Jackson, *personal communication*).

Precipitation

Changes to the hydrological regime can result in changes to the magnitude, frequency, duration, and timing of annual precipitation as well as changes to evapotranspiration and runoff rates (Ficke *et al*. 2007). A general increase in precipitation in a region might come in the form of heavy summer rainstorms instead of frequent summer and fall rainfall, leading to a general drying up of watersheds (Kling *et al*. 2003). Within the Great Lakes Basin, increases in precipitation may be offset by higher evapotranspiration rates, resulting in a net decrease in lake water levels and stream flow (Magnuson *et al*. 1997). For freshwater fish the timing and nature of the precipitation may be just as important as the amount.

Lacustrine Systems

Changes in the precipitation regime due to climate change may result in substantial losses in fish habitat. A decline in water levels and low flow could negatively affect the spawning, nursery and feeding grounds of many species (e.g. Yellow Perch and Smallmouth Bass) in shallow regions of littoral zones and in wetlands (Ficke *et al*. 2007). Entire small lakes may disappear as a result of increased evaporation relative to precipitation resulting in dramatic losses in fish habitat (Magnuson *et al*. 1997).

Fluvial Systems

Generally, declining river flow rates threaten freshwater biodiversitythrough a loss of habitat and connectivity between watersheds (Xenopoulos *et al*. 2005; N. Mandrak, *personal communication*). In lotic systems, temperature and flow regime are the dominant physical factors influencing fish distribution (Peterson and Kwak 1999). Due to varying life history traits and habitat preferences, each species will respond differently to changes to hydrological patterns. A lack of winter snow cover generally leads to the absence of a “spring fresher”, which negatively impacts freshwater fish like Pike that depend on this increased seasonal water flow for spawning habitat (C. K. Minns, *personal communication*). On the other hand, if spring floods come earlier or are more severe, there will be impacts on the young of various Trout species that hatch in the spring and require slow-paced, gentle melting (B. Shuter, *personal communication*). Streams that are already characterized by extreme variability, like those of the Prairies, contain mostly environmental generalists but a greater frequency of extreme weather events may drive out whatever few specialists there are (Ficke *et al*. 1997).

The following studies suggest how changing hydrological regimes might impact fish distributions:

- Changes to thermal and hydrological regimes interacted to impact rainbow trout populations in the southern Appalachian mountains. Using an individual-based modelling approach, Clark *et al*. (2001) explored a variety of streamflow and climate change scenarios and found that any benefit that increased spring temperatures had on egg development was offset by flow alterations that had a negative effect on spawning and fry survival.

- Riverine Smallmouth Bass distribution in the Kankanee River, Indiana was modeled based on climate change projections for the Great Lakes region using a 2 x CO_2 scenario (Peterson and Kwak 1999). Results suggested that flow regimes during spawning/rearing had a greater influence on the density of Smallmouth Bass than either air temperature or winter discharge. A 25% increase or decrease in spawning/rearing discharge corresponded to a 42.2% decrease or 40.8% increase in mean adult density. However, a 25% increase in spawning/rearing air temperature corresponded to only a 6.0% increase in mean adult density.

Stream dwelling fish like pelagic-spawning cyprinids are threatened both by declining stream flow and stream fragmentation (Perkin *et al*. 2010). In the Great Plains of the U.S., recent extirpations of pelagic-spawning cyprinids were positively correlated with reductions in water discharge in stream fragments less than 100 km in length. Future climate change scenarios predict that stream fragments in the southern Great Plains may lose up to 12% in discharge while streams in the northern portion may gain only up to 5% in stream flow. These results are relevant to Canadian Prairie watersheds because similar physical processes govern these systems and a loss of stream habitat and connectivity in the U.S. will impact species' ability to shift ranges into the Prairies in response to climate change.

However, Perkin *et al*. (2010) also concluded that fragmentation explained 70% of the variation associated with declines of these species, emphasizing how important is it to consider land-use scenarios and fragmentation due to changes in stream flow when evaluating the impact of climate change on stream-dwelling fish. Land-use patterns can also strongly mitigate the effects of changing water temperatures and flow regimes on riverine species, either exacerbating or compensating for decreases depending on the nature of the land-use (Peterson and Kwak 1999).

Species habitat availability can also be indirectly impacted by altered hydrological regimes due to climate change. A change in precipitation regime that drives a vegetative shift in the terrestrial environment of watersheds (e.g., forest to grassland) will affect the thermal structure of lakes in that watershed, leading to changes in habitat availability for different fish species (D. Jackson, *personal communication*). A decrease in overall precipitation, coupled with higher rates of evapotranspiration due to increasing temperatures, can also lead to higher salinity in watersheds. A variety of fish species (e.g. Cyprinids) inhabiting the relatively more saline lakes of southern Saskatchewan and Manitoba could become vulnerable in the event of a significantly altered hydrological cycle and there could be a general shift towards species more tolerant of such conditions (Magnuson *et al* 1997; Rahel and Olden 2008; D. Jackson, *personal communication*). Finally, reduced ice cover due to warming can lead to increased rates of evapotranspiration over the winter period, which could offset any precipitation increases experienced in other seasons (D. Jackson, *personal communication*).

Precipitation and Connectivity

Changes to species distributions due to a loss of connectivity brought upon by alterations in flow regime can be considered an indirect consequence of climate change. Decreased or absent spring runoff coupled with a lack of heavy spring/summer rains will result in rivers and tributaries drying up in some parts of the Great Lakes Basin, leading to a loss in watershed connectivity (S. Sharma, personal communication). Perkin *et al*. (2010) demonstrated the importance of watershed connectivity on the persistence of Cyprinid species in the Great Plains although such evaluations have not really been carried out for fish species in the Great Lakes Basin (D. Jackson and K. Minns, *personal communication*).

Any loss of watershed connectivity due to changing precipitation regimes is a double-edged sword for freshwater diversity; on the one hand, less connected watersheds may slow down the dispersal of invasive species and pathogens while on the other hand, all species will be hindered in their abilities to track thermal envelopes (D. Jackson, *personal communication*). Unfortunately, many invasive species enter waterways as a result of deliberate human action despite efforts to educate the public about their threats to native ecosystems (D. Jackson and S. Sharma, *personal communication*).

Connectivity will change dramatically, especially for inland systems and tributaries into the Great Lakes, but the nature of this change is largely unknown because of the uncertainties associated with climate change and precipitation (D. Jackson, *personal communication*). It is possible that many inland lakes will be disconnected from the rest of the watershed if there is a significant decrease in precipitation coupled with increased evapotranspiration rates. The opposite is also true, and there are a few areas in Indiana that could serve as connections for species to invade from the south due to low-lying landscapes that can easily flood (D. Jackson, *personal communication*).

Wind, Waves and Current

Wind speeds are positively related to the degree of mixing that occurs between layers in lakes. Higher wind speeds lead to a deeper thermocline and consequently, a smaller hypolimnion space, affecting the persistence of coldwater species (D. Jackson, *personal communication*). Lower wind speeds would have the opposite effect. Unfortunately, little is known about how wind and cloud cover will changing with changing climate (C. K. Minns, *personal communication*).

Extreme weather effects can also result in increased turbidity due to more sediment flowing into lakes/rivers, which decreases the amount of light that makes it through the water column (D. Jackson, *personal communication*). Some fish, like Walleye, are sensitive to the amount of light getting through the water column. Although juveniles spend a lot of time in shallow water and high levels of light, the mature adults move into deeper, darker waters and become sensitive to U.V. levels. Other fish are visual predators, so an increase in light levels might result in more foraging opportunities to the benefit of predator populations but at a cost to prey (D. Jackson, *personal communication*). However, little is known about how changes in U.V. light penetration may affect the distribution of freshwater fish and it is certainly not a driving force in determining species' ranges, but perhaps another stressor on fish populations.

Lastly, there has been some speculation that recent observations of slowing declines in fish contaminant concentrations in the Great Lakes region may be linked to climate change. Ample evidence exists that contaminants such as PCBs should actually decrease under increasing air temperatures. Thus, while French *et al*. (2011) observed that slowing declines in fish PCBs in the Great Lakes region are coincident with shifts in increasing air temperatures (~1991) climate change is ultimately ruled out as a mechanism for slowing decline.

4. INFORMATION GAPS

4.1 Air temperature

Magnuson *et al*. (1997) identified five broad research needs regarding climate change effects in Great Lakes basin (taken from the paper):

- Long-term research and monitoring should be maintained and expanded at key locations. Often, responses to climate are complex and unpredictable from first principles.
- Models of aquatic system behaviour should be improved and tested against long-term data and manipulative field experiments.
- Climate models should be improved to include outputs of wind and clouds and at temporal and spatial scales more suitable for subregional analyses.
- The heterogeneity of potential responses should be recognized and a predictive understanding of this heterogeneity should be developed.
- A better understanding of the temperature responses of aquatic organisms and

communities is needed, especially for winter.

During the research of this literature review a few directions for future research have been identified:

1. There is a need to elucidate a wider array of in-lake processes that are likely to be affected by climate change.
2. Also, it is necessary to examine the heterogeneity in responses among different water bodies in order to understand the significance of dealing with the uncertainty that the climate signals impose to the lake ecosystems and shape abiotic variability or biotic responses (Shimoda *et al*. 2011). Because of the numerous variables that can be used to rapidly reflect various stressors, lakes are in a position to act as as potential sentinels of climate change (Wagner and Adrian 2009).
3. No studies have been found that investigated the effects of the more frequent short term temperature oscillations that may affect surface biota.
4. Based on an examination of syntheses such as those of Kling *et al*. (2003) and Mortsch and Quinn (1996), it appears that predicting the future climate on relevant spatial scales for a Great Lakes assessment remains very limited.
5. Future work planned for Lake Simcoe should include the assessment of climate change impacts on the long term seasonal dynamics of phytoplankton, on zooplankton abundance and community composition, and deep water dissolved oxygen (Shimoda *et al*. 2011).
6. Future analysis of climate change effects on physical processes in the Great Lakes must include an evaluation of the thermal layers of the lake to determine if the observed temperature and density changes are taking place in the surface layers or in the hypolimnion in connection with the observed increase in light penetration during the last decades (Eimers *et al*. 2005).
7. One last aspect identified in this study is that future research may need to focus on is the spatial coherence of processes among the lakes (Livingstone 2008; Shimoda *et al*. 2011). To be specific, more weight should be placed in improving our understanding of the small-scale aspects of lake mixing and consequently in describing the complex interactions among the mechanisms that most likely induce the changes in lake mixing regimes (Wuest and Lorke 2003).
8. Currently, although shifts in the physical processes of the deep lakes due to climate change is incontestable, the induced alterations in their chemical and biological properties are still less clear and quite often inappropriately researched (Shimoda *et al*. 2011).

4.2 Precipitation

1. There are not enough studies that correlate loss of vegetation due to human activity with changes in precipitation patterns and its influence on local climatology.
2. In the future, precipitation forecasts should be based on an objective multimodel ensemble prediction system to enhance their reliability and the types of information should be expanded to include soil moisture, runoff, and hydrological variables. More research is needed to improve existing knowledge and capabilities to forecast short and long-term precipitation trends and to make this information more useful and timely for decision making.

3. We need to improve our understanding of the causes of long-term changes in oceanic conditions, the atmospheric responses to these ocean conditions, and the role of soil moisture feedbacks. These are needed to advance in precipitation prediction capabilities. Ensemble precipitation prediction is needed to maximize forecast skill and downscaling is needed to bring coarse-resolution forecasts from General Circulation Models (GCM) down to the resolution of a watershed. In addition, it is vitally important to separate the effects of natural variability from anthropogenic induced climate change.
4. On longer time scales, significant land-cover changes have occurred in response to changes in precipitation and human intervention, and the role of land-cover changes in increasing or decreasing precipitation should be evaluated. Improved understanding of the difference between gradual changes in climate, critical environmental thresholds, and abrupt hydrologic changes is needed to enhance society's ability to plan and manage risks.
5. The relationship between climate changes and abrupt changes in water quality and bio-geochemical responses is not well understood and needs to be a priority area of study for modern process and paleoclimate research.
6. In order to reduce uncertainties in the response of floods to abrupt climate change, improvements in large-scale hydrological modeling, enhanced data sets for documenting past hydrological changes, and better understanding of the physical processes that generate flooding are all required.

4.3 Invertebrates

More information is needed regarding the physiological effects of increased temperatures on invertebrate taxa. For instance, there is little work which examines temperature-dependent sex determination in aquatic invertebrates, and it has been suggested that a comprehensive review on the temperature thresholds for physiological damage for all types of aquatic organisms would be useful (Hogg and Williams 1996; N. Yan, personal communication). Lehman (2002) also suggests that a review encompassing the magnitudes of variation in algae and zooplankton growth rates with water temperature would aid in predicting changes to these assemblages.

In order to further understand how climate change will influence lentic systems in Canada, Baulch *et al*. (2005) has suggested that future work should include long-term experiments encompassing broad spatial scales, in order to capture the range of natural variability within and among different habitats of a lake. Further, while seasonality of warming effects has been the focus of some studies (e.g., Chen and Folt 1996), this is an area in which more exploration is needed (Lehman 2002; Baulch *et al*. 2005). Lehman (2002) also suggests that incorporation of oxygen dynamics, lake morphology parameters, heat advection by river discharge, and ice dynamics into predictive modeling will aid in assessing impacts of climate change on production in the Great Lakes. Uncertainty about changes to cloud cover could also impact how biota respond to climate warming – at present, GCMs predict either increases *or* decreases in cloud cover in the Great Lakes region, and fluctuation either way will affect light intensity and thus photosynthesis rates of phytoplankton (Brooks and Zastrow 2002). Lastly, more work on the biophysical laws relating to temperature would be useful – for example, there is some evidence to suggest that the spread of *Bythotrephes* may be limited by climate change due to water temperature tolerances (N. Yan, personal communication). In addition, there could be important implications regarding the role of temperature and fatty acid profiles in aquatic organisms, such as omega-3 fatty acids, which could have health consequences on higher trophic levels (N. Yan, personal communication).

It is clear that the effects of climate change on invertebrate populations will likely involve the influence of various factors, including temperature, nutrients and light. For example, the effects of warming temperatures in a particular lentic system will be mediated by the baseline nutrient and light conditions in the system. Thus, many researchers have called for studies which examine effects along a resource gradient, or multi-factor experiments, in order to more fully understand (and predict) impacts of climate change on invertebrate organisms (e.g. Baulch *et al*. 2005).

A number of recent studies have suggested that the physical, chemical and biotic properties of lentic systems are likely to be concurrently influenced by additional environmental stressors, such as eutrophication, land use changes, acidification and drought events. Unfortunately, disentangling the effects different stressors have on biota has thus far proven to be difficult (Arnott *et al*. 2003; Desellas *et al*. 2011). Within the Great Lakes and Boreal Shield regions, drought events and widespread calcium decline are considered of particular importance in the context of climate change (N. Yan, personal communication). For example, experiments on the effects of increased temperature on *Daphnia* were exacerbated in low Ca conditions (Ashforth and Yan 2008). The authors suggest that the energetic costs of survival and reproduction are higher at low Ca concentrations, higher temperatures and decreased food availability.

Fish

We lack a concrete understanding of the biology of most species (D. Jackson, N. Mandrak, C. K. Minns, and B. Shuter, *personal communication*), even with respect to temperature. For example, predictions of the future distribution of Lake Trout based on changing thermal structure in lakes carry a certain degree of uncertainty because foraging patterns are not well understood; if foraging areas and suitable thermal habitat overlap less and less, distributions will be negatively affected. It is also unclear what features of thermal regime affect fish survival and reproduction and the relative importance of mean daily temperature, maximum daily temperature, and heat accumulation, which is relatively unknown for most species (Rahel 2002; N. Mandrak, *personal communication*). Isotherms are really just a correlate of fish distributional limits but it is certain that temperature is critically important to the underlying mechanisms (N. Mandrak, *personal communication*).

While absolute temperatures may affect species distributions, the seasonal pattern of temperature is also important and not often built into distributional models (B. Shuter, *personal communication*). For example, temporal shifting of spring warming and fall cooling can have an effect on fish reproduction and ultimately, recruitment. Many fish use both light and temperature as a cue to reproduce; warmwater species tend to be spring spawners and are more temperature-driven than light-driven, and coldwater species tend to be fall-spawners and are more light driven. As coldwater species expand their ranges' to more northern latitudes to track thermal envelopes, they will be additionally stressed because they may begin spawning when temperature conditions are not appropriate (i.e. too early in the season).

Changes to winter conditions are not given as much attention as summer conditions in species' range studies. Winter temperatures are an important determinant of distribution patterns in some warmwater species but this is rarely reflected in modelling approaches, which tend to model how changes in summer temperatures will drive species' ranges. Also, low overwintering temperatures are necessary for the spawning success of a number of Salmonids and White Sturgeon.

More importantly, perhaps, implications of increasing temperature on the presence/absence of ice cover during the winter months and the effects these changes will have on albedo has not been adequately discussed (C.K. Minns and D. Jackson, *personal communication*). Also, we have little understanding of the role of ice cover on biota under present conditions, let alone when considering climate change (K. Minns, *personal communication*). Ken Minns of the University of Toronto and the Great Lakes Laboratory for Fisheries and Aquatic Sciences (Department of Fisheries and Oceans, Canada) has a number of projects underway predicting various aspects of thermal regimes in lakes like ice-in and -out dates, ice thickness, and temperature modeling. He is currently in the stage of acquiring more data sets to broaden the applicability of the model.

Interactions between temperature and other abiotic and biotic factors are difficult to anticipate but could have a great impact on species distributions (F. Rahel, *personal communication*). For example, fish that are occupying waters at the upper limit of their thermal preference carry higher metabolic loads that they need to compensate for with greater food intake; whether that food is available will depend on a number of abiotic and biotic conditions, many of them also impacted by climate change (Ficke *et al*. 2007). Therefore, there are limitations to using only thermal tolerance to predict species distribution. Thermal envelopes do not take into account dispersal limits or competitive interactions between species, leading to predictions of theoretical distributions that are larger than realized distributions (Shuter and Post 1990; Sharma *et al*. 2009).

Generally, current distributional models have several shortcomings. While physical models of lake processes are quite advanced (C. K. Minns, *personal communication*), there is a relative absence of linkages between the physical modeling and the biological modeling that has been done (N. Mandrak and B. Shuter, *personal communication*). Most models do not integrate life history traits, despite their importance in determining fish distribution (Hayes *et al*. 2009; K. Minns, *personal communication*). For example, the juveniles of some fish species have different thermal preferences, limits, and foraging patterns than adults but often only the ecology of the adults is considered (Ficke *et al*. 2007). This type of modeling approach would require field-based data that relates birth, death and movement rates to habitat conditions (Hayes *et al*. 2009). There is also a lack of abundance data and even basic presence/absence data for many fish species, especially in the northern parts of the Great Lakes Basin and Prairie watersheds (C. K. Minns, *personal communication*).

Most models also do not account for local-scale variation in temperature that can result from surrounding land-use practices or groundwater inputs (Rahel 2002). GCMs have poor local resolution and provide global predictions at a spatial resolution that may not reflect the scales at which fish are impacted; a coupling of local models and GCMs is needed to better anticipate future changes in species distributions (Minns and Moore 1992; B. Shuter, *personal communication*). Also, since there are no standardized methods to model species distributions, in terms of the type of temperature variables or climate models used, it is difficult to compare between studies (Rahel 2002).

Considerable variation in precipitation regimes (i.e., amount, timing, intensity) is predicted for the future. Climate models are not very clear about how precipitation and runoff will change, although Nick Jones at the Ontario Ministry of Natural Resources is carrying out some relevant research that may clarify predictions for the Great Lakes Basin, and there needs to be greater effort applied to linking local hydrological models to species distributional models (D. Jackson, C. K. Minns, *personal communication*). Therefore, at this time, there is much that is still unknown about how fish species' ranges will shift in response to changes to the hydrological regime across the Canadian portions of the Great Lakes Basin and the Prairies.

5. CONCLUSION

Maintaining water levels in the Great Lakes and their connecting waterways is vital to supporting urban water supply, shipping lanes, a commercial and recreational fishery, and habitats for ecologically, economically and socially important fish and wildlife. Fisheries and Oceans Canada is conducting a risk assessment under the predicted impacts of climate change that will contribute to a socio-economic assessment of business risks and possible adaptation strategies under the Aquatic Climate Change Adaptation Services Program. This document has served as a review of the potential climate and limnological changes expected in the Great Lakes basin (with some insights into prairie systems when possible), as well as an opportunity to identify future research needs.

Climate is determined by the interaction between the radiation from the sun, the outgoing radiation from the earth, and the energy budget from the earth's surface up through the different altitudinal zones. Challenges in predicting future climate conditions typically arise from a lack of data within one of two altitudinal zones (e.g. stratosphere), or difficulties in modelling the interfaces between zones. Further, changes in solar radiation have non-linear effects on climate parameters experienced on earth, leading to strong negative feedbacks within the energy budget. However, studies into historical shifts in climate have demonstrated that large changes in Earth's climate is a combination of astronomical phenomena superimposed on longer planetary trends driven by ocean currents. Further, the Medieval Climate Anomaly period provides an indication of the role of greenhouses gases on climate warming and cooling. From this body of research the Global Circulation Models have been developed which provide predictions on future climate conditions across the planet. The greatest challenge is not determining the role of greenhouse gases in the atmosphere, but instead understanding how the ocean will react to them. Whether the tropical ocean resembles El Niño, or La Niña conditions remains a critical open question. The distinction is important because the tropical Pacific can affect global weather phenomena including tropical cyclone activity, drought and flood patterns. Last, a greater source of uncertainty in terms of future climate projections is how humans will respond to this impending challenge to cut greenhouse gas emissions. Regardless of the scenario of human behaviour, there is consensus among studies that the global climate will change significantly over the next 100 years due to the burning of fossil fuels. CO_2 concentrations are estimated to range between 75% and 350% above estimated 1750 levels of CO_2. And according to the same model, the global air temperatures is estimated increase during the 21st century in a range from 1.4 to 5.8 °C, relative to 1990 temperatures.

Observations in the Great Lakes region indicate that the climate is already changing including: shorter winters, heavier precipitation events, higher temperatures, reductions in mean snow areas, and earlier spring thaw. Predicting future conditions is even harder at smaller regional scales compared to global patterns, therefore it is recommended that common patterns observed over a wide range of models be used to characterize future conditions. Generally the Great Lakes region is expected to continue to see substantial increases in annual and seasonal temperatures, extreme heat events, much earlier spring thaw dates, a small change in overall precipitation but a doubling of heavy rainfall events (including stronger and more frequent thunderstorms), and a relatively small decrease in wind speeds by the end of the century. The prairies will also experience increases in temperatures and overall climate variability, however they are expected to receive less precipitation. The overall effect of these changes on lakes is warmer surface waters, stronger and earlier stratification, potentially cooler but less oxygen rich hypolimnia, and shorter periods of ice cover and thinner. The prediction of lake levels present a challenge and more work is recommended on understanding the land processes that lead to changes in runoff. Currently it appears that changes in influxes in spring and fall will compensate for each other and lead to relatively stable water levels in all the Great

Lakes. However, recent rapid drops in lake levels appear to be strongly linked to anomalous late-summer and early-fall evaporation, which in turn seems to be reflective of increased lake surface temperature and the delay in the onset of ice cover. Clearly it is important to gain a better understanding of the processes affecting the lake levels. Finally, increased water clarity is expected in oligotrophic lakes which can have linked effects on water quality and the depth of the thermocline. There are few studies that examine the influence of climate change on streams in Great Lakes, but from scattered information there is general agreement that air temperature will increases in winter and spring which will affect precipitation (snow or rain) and the water volume stored in snow cover. Changes in river discharge will likely be stronger on a seasonal basis than across the entire year. Winter discharge is expected to increase with a corresponding decrease in spring discharge which could influence sediment transportation and maintenance of river morphometry through erosion.

The effect of climate change on the Great Lakes biotic communities is the subject of other literature reviews under the Aquatic Climate Change Adaptation Services Program, however, this review briefly examined the links between physical changes and biotic responses by reviewing climate related research conducted on 1) wetlands plants, plankton and invertebrates, and 2) distributional shifts in fish communities related mainly to connectivity. A general conclusion of the review was that magnitude and direction of climate change impacts on biotic components of aquatic ecosystems is highly dependent on other factors including water quality, anthropogenic activity and habitat fragmentation. In most cases, climate change might best be evaluated as a factor which could alleviate or further complicate existing concerns in aquatic habitats.

Much of the impacts of climate change on coastal wetlands, or salt-water intrusion in the St. Lawrence, is contingent upon on the Great Lakes' discharge. However, even within inland wetlands a range of impacts are predicted including change in base flows, altered hydrology, extended range and activity of some pest and disease vectors, decreased water resource quantity and quality, and increased risk of fires. The extent of semi-permanent and seasonal wetlands may be greatly reduced in the prairie regions of North America. Estimates based on a CO_2 concentration doubling scenario project that the southern limit of peatlands in Canada could retreat 200-300 km northwards. For phytoplankton, paleolimnological studies have demonstrated that climate change could induce taxon-specific shifts through the combined influences of warmer water temperature, a short ice-cover period, longer growing season, changes in the light regime, increased nutrient cycling, and/or change to thermal and mixing properties of lakes. These changes would generally favour small, fast-growing species and occur earlier in Arctic lakes and high altitude lakes then temperate lakes. Some climate change studies have focused on the impacts of changing water clarity, and its interaction with temperature and nutrients. Changing nutrient concentrations with increased lake clarity are predicted to impact phytoplankton and invertebrate biota in the form of UV light damage leading to lower rates of photosynthesis and growth, changes in periphyton species composition, reductions in inorganic nutrient uptake, and damage to algal DNA and disruption of the electron transport chain.

In zooplankton and other invertebrates, the effects of water temperature on an animal's metabolism and growth are fairly well know, however, the population and community level impacts from climate change are less understood and likely strongly influenced by other environmental factors. Generally, warmer waters tend to favour smaller individuals in zooplankton in the epilimnion and as such, life history parameters will be more sensitive indicators of small, gradual shifts in temperature than other ecological measures including taxonomic composition, species richness, community biomass or densities of particular taxa. Even so, life history changes will likely also be taxon specific rather than a general impact across all invertebrates. Further, responses of aquatic invertebrates to climate change will depend strongly on the seasonal timing and magnitude of the limnological changes. The timing of ice-breakup could have a strong influence on the overall productivity of the zooplankton community, especially if it creates a temporal mismatch with the spring phytoplankton bloom. Larger shifts in the overall abundance of zooplankton are more likely if climate change parameters significantly increase the salinity or total dissolved solids concentrations in lakes, which is likely to occur in prairie lakes.

The distribution of fish in North America is influenced by multiple factors, however, for northern fish appropriate thermal conditions is a critical parameter to population viability. Overall the direct impacts of hydrological changes will be species specific as bad habitat conditions for one species are generally optimal for another. Within our brief review we note that the diversity of fish habitat requirements among Canada's fish assemblage will result in trade-offs in fish productivity across the country. Generally, changing thermal regimes are expected to cause shifts in fish distributions if landscape connectivity allows for migration. If fish can move, the local extirpation of old species and invasion of new species with different thermal preferences will cause significant changes to the trophic structure of the community which the thermal generalists that remain will need to adapt to. If fish cannot move, resident fish could be negatively affected by the increasing temperatures but would also not be pressured by competitive invaders. In many cases it isn't clear which of the two factors poses a greater threat. From our review of physical and limnological changes in lakes, the depth and strength of the thermocline will be a critical parameter for some coldwater species (e.g. Lake Trout) while water clarity will influence the forage ability of warm water species (e.g. Walleye and Northern Pike). If a lake containing all three species slowly warms while becoming clearer, it will be difficult to determine which fish species will be the most in danger of local extirpation. In river system the annual discharge and temperature of groundwater sources will both be highly influential on species assemblages. Like in lakes, changes in physical quality will benefit some species while hindering others. For example, lower winter snow cover could reduce the spring freshet and negatively impact Northern Pike who thrive in flooded backwaters, while helping Trout who require slower-paced spring flows in the main channel to spawn.

In the final section of this report we summarize some gaps in available information which would benefit from further research. The field of climate change science is greatly accelerated in the last couple decades, and so we suggest that literature reviews of this nature be conducted frequently as more insights become available.

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7. APPENDIX 1: EXPERT INTERVIEW SUMMARIES

7.1 DR. GEORGE ARHONDITSIS

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Research interests:

Aquatic biogeochemical modelling

Aquatic ecosystem responses to climatic variability

Plankton ecology/food web dynamics

Watershed-aquatic ecosystem interactions

Current Research Initiatives

Lakes and streams are particularly sensitive to the ecological impacts of climate forcing, and several long time-series have shown a close coupling between climate, lake thermal properties and individual organism physiology, population abundance, community structure, and food-web dynamics. Thus, understanding the complex interplay between meteorological forcing, hydrological variability, and ecosystem functioning is essential basic knowledge for assisting risk assessment and water resource/fisheries management. During the last three years, several colleagues and I have shown the effects of climate variability on the Lake Washington thermal structure, timing of the spring bloom, coupling of the trophic interactions between phytoplankton and zooplankton, inter-specific niche differentiation, and the sockeye salmon (*Oncorhynchus nerka*) behavioral patterns. I plan to continue this research and investigate the effects of climate variability on the North American lake ecosystem phenology. I hope to use for this study several of the most renowned Canadian freshwater monitoring programs with uniquely detailed records for weather conditions, hydrological flows and physical, chemical and biological variables. My plan is to develop novel modeling techniques (Bayesian Hierarchical/Dynamic Linear Models, Structural Equation Modeling) to detect spatiotemporal trends in the physical structure, water chemistry and the food-web dynamics of North American lake ecosystems. This combination of mechanistic and empirical approaches is often highlighted as the optimal modeling framework to study how climate signals cascade through natural ecosystems, and how they shape abiotic variability and/or biotic responses. Plankton communities will be a central component of this research due to the socioeconomic impacts of their potential structural shifts (e.g., bottom-up forcing on commercially exploited fish stocks) and their complex interactions with the atmospheric CO2. My research acknowledges the importance of two complementary directions of research: firstly, the need to elucidate the wide array of in-lake processes that are likely to be affected by the climate change; and, secondly, the need to examine the heterogeneity in responses between different waterbodies. The rational of this approach and its importance for dealing with uncertainty in ecological forecasts is advocated by several recent review papers.

Questions and Answers:

1. *Do you have any comments about any unpublished research you may conduct at this moment which can help this review?*

- Currently the work is focused on the upper part of the lakes, the euphotic zone. This is the place where most of the climate change effects are expected to take place.
- There is evidence that thermal stratification will get stronger and it will last longer. Therefore, even if the nutrient loading will remain the same, because of the longer and stronger stratification the upper euphotic zone will be isolated from the hypolimnetic layer, which is the main source of nutrients.
- In this new research the focus is on nutrient recycling. Because of higher temperatures the bio-chemical processes are more active and available nutrients from various sources like excretions from zooplankton are being reused for

phytoplankton growth. This increased reuse of existing nutrients will at least partially compensate for the nutrient limitation from the traditional sources.

- New scenarios are analyzed through biochemical modelling in order to understand how the microbial community will mediate between the effects of increased temperatures and a decrease in nutrient availability

2. *What are the main gaps in our knowledge related to the physical processes in the lakes and streams that may prevent us understanding the impact of climate change on the Great Lakes basin*?

- Much of our contemporary understanding has been based on empirical evidence from offshore areas, while the interactions with the nearshore zones have largely been neglected. In many large lakes, the most degraded areas are nearshore zones above the summer thermocline adjacent to the mouths of large rivers and enclosed embayments with restricted mixing with offshore water. These areas are intermediate zones in that they can receive polluted inland waters from watersheds with significant agricultural, urban and/or industrial activities while mixing with offshore waters having different biological and chemical characteristics. These are the areas that need increased attention in the future.
- The main climate-induced shifts are related to: air temperature, rainfall and wind forcing. They can potentially influence lake mixing and currents, because they determine both the rate and magnitude of warming/cooling and the magnitude and frequency of runoff.
- Runoff affects water level which in turn strongly drives nearshore dynamics. Winds produce coastal upwelling events forcing deeper, cooler water often with different water quality, up to depths where they can interact with shallow water intakes. Drastic changes in temperature can disturb biota and even reset the entire system. Surface waves can resuspend bottom sediments in the shallow zones of large lakes, and as sediments tend to be repositories of both nutrients and contaminants, resuspension events are highly important in predicting water quality.
- The classical two dimensional conceptualization (time and depth in an offshore site) has been sufficient until now to understand the issues required to be solved. However, any further advancements of our understanding of the climate-induced changes on lake phenology should be based on more integrative frameworks that consider as one of the focal points the interplay among watershed, nearshore and offshore lake areas.

3. *What processes are poorly understood and need more research and data?*

- Two main areas in lake phenology need more attention and more understanding:
    - the period of the spring bloom, especially the recession period (transition to stratification
    - the stratified period itself
- There is needed more research related to the microorganisms feedback loops
- More understanding of episodic events is required. Upwelling and downwelling events have the potential to disturb, or even reset entire systems. There is a need to understand these wide range of dynamics.

4. *What are the pathways from the climate drivers to the effects on the physical processes in Canadian freshwater?*

- Hydrodynamic processes, thermal structure, but also the direct impact of temperature on metabolic rates

5. *What changes have been already observed and what could be attributed to climate change and what should we expect to occur in the near future?*

- There is an increase in occurrences of extreme events. There are fewer precipitation events, but at a higher intensity. Therefore growth is disturbed, or even wiped out in certain circumstances and the system is reset.
- It has to be noted that there are, however, patterns that contradict each other in the physical processes, but it does not happen in the biologic processes.

6. *On the modelling side, are there any local hydrodynamic/thermal Great Lakes models coupled with global climatic models to ensure input for various climate change scenarios that would produce credible lake processes evolution results?*

- There are not too many modelling efforts trying to couple regional models to GCMs. The main reason is that they operate at different scales.
- When downscaling the methods will introduce additional uncertainties.
- Current methodologies take the predictions from GCMs and use them as inputs in the local models. However, bayesian approach is needed in order to assess the uncertainty introduced by the methodologies, the downscaling (if present), measurements, etc.
- His laboratory team is working to promote an integrated system model that allows the uncertainty due to errors to be promoted across the system. Most IPCC models do not take these errors in account.

7.2 DR. DON JACKSON

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Research interests:

- structure and composition of ecological communities in aquatic ecosystems
- comparing fish communities in lakes and streams to determine the relative importance of biotic, abiotic, spatial, and biogeographical factors in determining the species composition
- the colonization and extinction of fish species within lakes and their connecting waterways to quantify the role of environmental factors in determining fish community structure, the metapopulation aspects of the fish communities, and the potential for species invasions
- various aspects related to biodiversity and conservation biology (i.e. redside dace and crayfish)
- assessing and developing methods of multivariate statistical analysis
- developing models and approaches to predict the spatial distribution of species, their association to habitat conditions, and the resulting

Questions and Answers:

1. *How do we expect climate change drivers to impact the abiotic conditions of freshwater systems (e.g. temperature, flow, dissolved oxygen, water currents, light penetration) and influence fish species distributions, specifically? Pathways, mechanisms, etc.*

- increases in surface temperature will affect the length of thermal stratification, which will be more of an issue in Lake Erie where there may be anaerobic or anoxic conditions in some parts of the lake and in particular years
- changes to thermal structure will be less of an issue in the other Great Lakes because of their depth
- new thermal habitat due to increasing surface temperatures, primarily in the nearshore areas of lakes and connecting waters
- within main lakes, except for Lake Erie, does not anticipate huge changes in dissolved oxygen in the hypoliminion
- elevated surface water temperatures and resulting net reduction in dissolved oxygen will stress cool and coldwater species
- in areas where cool and coldwater species are trying to capitalize on surface water/hypolimnetic prey, this will be more of an issue especially if the lake is small

- if you don’t have a coolwater prey base, coldwater species such as lake trout may be forced to forage in the hypolimnion or nearshore areas where they take heavy metabolic loads for doing so
- if temperatures increase, those species will have less opportunity to do that
- unknown what will happen with precipitation, ice cover, evapotranspiration
- considerable variation in precipitation regimes predicted for the future, both in terms of how much precipitation there will be and when that precipitation will fall
- reduced ice cover will lead to increases evapotranspiration rates over the winter period, which could offset any increases that there are in precipitation
- groundwater could see an increase in temperature and a decrease in levels, which will have huge implications on coolwater species
- in streams and rivers where temperatures increase to above 20°C, cool groundwater seeps serve as a refuge for coolwater species, sometimes for as long as a month
- with increasing temperatures, those refugia might be lost and coolwater species will no longer survive in those waters
- DOC can affect the thermal stratification of lakes, which has implications for cool and coldwater species; the effect of DOC on species distribution is mediated by changes to temperature so it is an indirect effect
- high DOC leads to a shallow thermocline and lots of hypolimnion, which will benefit cool and coldwater species; low DOC will result in the opposite situation
- wind speeds also affects thermal structure of lakes – increased wind speeds lead to increased mixing in lakes, which leads to a deeper thermocline and consequently, a smaller hypolimnion space; once again, cool and coldwater species are affected
- another thing to consider is the link between forest cover and thermal stratification; a decrease or increase in forest cover will affect surface water wind speeds and thus, the thermal structure of lakes
- some work has been carried out at Laurentian University to map out the hypolimnion depth in lakes relative to the surrounding landcover
- if you have a change in precipitation regime that causes the surrounding land to shift from forest to grassland, you could see a change in the thermal structure of surrounding lakes, leading to changes in habitat availability for different fish species
- this shift in landcover types could also be mediated by forest fires, that may increase or decrease in frequency and intensity with climate change
- some fish, like walleye, are sensitive to the amount of light getting through the water column; juveniles spend a lot of time in shallow water but as they mature they move into deeper, darker waters and become sensitive to high light
- other fish are visual predators, so an increase in light levels might results in more foraging opportunities; that will have positive effects on predator populations, but negative effects on prey
- extreme weather effects can result in increased turbidity due to more sediment flowing into lakes/rivers, which decreases the amount of light that makes it through the water column and may aggravate fish gills

2. *What general changes do you anticipate to see in fish species' distributions? Which species are most likely to experience a (1) contraction or (2) expansion in their current geographical range? How will range boundaries shift?*

- the impacts of climate change on the distributions of recreationally and commercially important species such as walleye, lake trout and smallmouth bass have been adequately discussed
- the impact of climate change on small littoral or prey species (e.g. cyprinids), which aren't commercially as important, is often mediated through the impact of climate change on their predators
- for example, bass and pike have important impacts on their communities because they are dominant littoral predators; therefore, any changes in the distribution of bass and pike will have impacts on the broader fish community as well as zooplankton communities
- on the other hand, lake trout have a much more subtle effect on their communities
- threatened species may experience habitat loss and thus range contraction due to several factors like climate change and landscape conversion interacting
- e.g. populations of redside dace, a coolwater species endangered in Ontario, are becoming increasingly stressed due to warming groundwater temperatures and urbanization, which is squeezing out its current habitat
- in this case, the consequences of climate change becomes magnified – not only is there less and warmer groundwater getting in due to changes to the landscape, any runoff from storms and rains passes over hot asphalt and is warmed up before it reaches the streams that redside dace occupies
- species that are commonly used as baitfish are likely to expand their habitat because their dispersal is aided by human intervention

3. *What models are (1) most accurate and (2) frequently used in predicting changes in the biogeographical distributions of fish species?*

- no comment

4. *How does watershed connectivity between the Great Lakes Basin and surrounding watersheds moderate the potential of species to respond to climate change via range shifts at the rate of warming that we are anticipating?*

- connectivity will change dramatically, especially with inland lakes and tributaries into the Great Lakes, but the nature of this change is largely unknown because of the uncertainties associated with climate change and precipitation
- inland lakes could become disconnected because of lower precipitation
- many species native to the Mississippi River Basin but not the Great Lakes Basin will require human intervention to make the jump because there aren't necessarily enough direct connections between the two watersheds to facilitate species movement

- there are a few areas in Indiana that could serve as connections for species to invade from the south due to low-lying landscapes that can easily flood
- the continental divide between the Great Lakes Basin and the Hudson Bay Coast Basin is no longer a dispersal limit due to unchecked human intervention, and a variety of species have already made the jump
- we can't consider the impact of connectivity on species dispersal under climate change without also mentioning human-aided movement
- historically, fish movement would occur at a much slower rate but we are seeing unprecedented dispersal rates due to human-aided "spot" introductions
- diversions such as the one that sends water from North Dakota's Devil's Lake northwards into Manitoba via the Red River) increase connectivity and expose watersheds to possible invasive species and foreign pathogens

5. *Do you have any comments on any ongoing/unpublished research pertaining to this topic, conducted by yourself or colleagues, which may be relevant for this review?*

- most research on Prairie watersheds focuses on water quality issues because eutrophication in Lake Winnipeg is a current and pressing issue
- however, climate change may have even more severe impacts on Prairie watersheds than those of the Great Lakes Basin because they will be impacted strongly by a lack of water
- less water leads to higher salinity, which has negative consequences on cyprinid populations
- a variety of fish species inhabiting the relatively more saline lakes of southern Saskatchewan and Manitoba could be vulnerable in the event that climate change results in future reductions in precipitation and increases in evapotranspiration
- these effects would also result in increased fragmentation in watersheds
- however, some paleological work suggests that the Prairies have been in a "wet" phase in the past 80 years, so the conditions that are familiar to us right now are perhaps atypical
- if the Prairies revert back to a "dry" phase over the course of the next century, the effects of this natural variation in precipitation coupled with the effects of climate change could have even greater impacts on ecosystems than we currently anticipate

6. *In your opinion, what are the main gaps in our knowledge related to how anticipated changes in physical processes in lakes will influence species distributions that may prevent us from understanding the impact of climate change in the Great Lakes region? What processes remain poorly understood and need more research and/or data?*

- too many missing links and too much speculation based on a few case studies
- better models needed at a final spatial scale – regional models where the hydrological regime is built in
- implications of increasing temperature on the presence/absence of ice cover during the

winter months and the resulting effects on albedo

- need better biological monitoring data

7. *Are there any other aspects of the influence of climate change on freshwater systems of the Great Lakes region that you would like to mention that was not covered in the above questions?*

- no comment

8. *Can you recommend other experts in the field that should be interviewed for the purpose of this review?*

- John Magnuson
- Andrew Drake – fish movement

7.3 DR. BRENT M. LOFGREN

Physical Scientist, National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory (NOAA / GLERL)

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Research interests:

His research focuses on modeling of atmospheric systems and their coupling to terrestrial and water surfaces, with particular emphasis on interannual to interdecadal timescales in the Great Lakes basin.

Questions and Answers:

1. *Do you have any comments about any unpublished research you may conduct at this moment which can help this review?*

- Current work focuses on regional scale modelling of the climate that has better coupling between the atmosphere and the surface than ever before. Surface refers to water and land. This is very important as coupling was not considered in previous research and may have contributed to additional errors and uncertainties.

2. *What are the main gaps in our knowledge related to the physical processes in the lakes and streams that may prevent us understanding the impact of climate change on the Great Lakes basin*?

- Main gaps have their roots from the complexity of the systems. Each process that occurs in these systems adds a layer of uncertainty.
- Also, gaps in our knowledge relate to predicting precipitation, changes in temperature profiles in the lakes, estimating runoff and water quality. Each of these adds a certain degree of uncertainty.

3. *Do we have enough data to quantify the warming trend?*

- We have a paper that documented the serious decrease in ice-cover area and duration over the Great Lakes, which contains records for over the last 40 years. The expected result is to determine the timing of the onset of the stratification and the changes in surface temperature. For example, the increases in surface water temperature in Lake Superior are much larger than the increases in mean air temperature nearby.
- Recent monitoring past this summer has shown that surface temperatures of parts of southern Lake Michigan and all of Lake Ontario did not go below 4 ºC. Therefore, the summer stratification was maintined over the whole winter instead of developing the normal inverse stratification under a protective ice-cover.

4. *What processes are poorly understood and need more research and data?*

- We need to dispel the myth that air temperatures alone cause evapotranspiration, particularly on land. We should understand it as a part of the complex energy budget.
- The whole system is connected in complex ways rather than one way temperature-evapotranspiration. The basis for the connection air temperature-evapotranspiration was purely empirical and linked to the mean annual cycle, as both air temperatures and evapotranspiration are higher during the summer and lower in the winter. Therefore it was easier to make that connection and attribute the causes to greenhouse gases (GHG) instead.
- Aerosols provide a negative feedback. While GHG can linger around for decades and more, the aerosols can disappear from the atmosphere within weeks. If fossil fuel emission would stop and aerosols would disappear from the atmosphere it is possible that the effect of GHG would increase dramatically.

5. *What are the main physical processes influenced by climate change and how is that expected to affect the ecosystem?*

- Surface temperatures, change in timing of the overturn of the thermocline and even the absence of the overturn in some cases.
- The change of the onset of the stratification and overturn will affect two important processes and without overturning we can lose both:
    - nutrient loading form the bottom
    - oxygenation from the water surface

6. *What changes have been already observed and what could be attributed to climate change and what should we expect to occur in the near future?*

- Reduction in ice-cover, lack of overturning in some areas
- Stronger stratification during the summer
- Large increases in surface water temperatures compared to mean air temperatures, as documented for Lake Superior. This can be explained by the fact that the same or even more amount of heat is distributed to a shallower epiliminion.

7. *On the modelling side, are there any local hydrodynamic/thermal Great Lakes models coupled with global climatic models to ensure input for various climate change scenarios that would produce credible lake processes evolution results?*

- There a current efforts in GLERL laboratory to create a coupled system with an array of 1-D diffusion models.
- Also, at University of Wisconsin they are trying a similar approach, but using a different model package.

8. *What other aspects of climate change influence on the Great Lakes physical process and phenology I did not cover in my questions and you want to add ?*

- In order to understand the impact of climate change we need to avoid confusing the effect of long term temperature changes with the seasonal changes. This will make us differentiate between natural variability and climate change due to anthropogenic forcing.

7.4 DR. NICK MANDRAK

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Research interests:

Biodiversity & Systematics; Conservation Biology; Ecology of Populations, Communities & Ecosystems

Questions and Answers:

1. *How do we expect climate change drivers to impact the abiotic conditions of freshwater systems (e.g. temperature, flow, dissolved oxygen, water currents, light penetration) and influence fish species distributions, specifically? Pathways, mechanisms, etc.*

- temperature is the most obvious abiotic condition that affects distribution
- at a biogeographical scale there is a relationship between changes in temperature and distributional shifts
- Shuter (1990) – looked at overwinter survival of young-of-the-year smallmouth bass and found that juveniles needed to grow to a certain size to survive the winter
- Shuter took a very good mechanistic approach to the question and pointed out the underlying mechanism that likely drives the northern edge of most fish species in Canada
- we need to better understand why exactly temperature is important because how temperature shapes ranges is beyond just physiological maximum and minimum limits
- e.g. Asian carp – the time at which individuals are able to spawn is directly linked to accumulated growing degree days
- isotherms are really just a correlate of what is going on although temperature is critically important to the underlying mechanisms
- in parts of the basin there will be certainly be issues regarding water quantity and specifically, not enough water
- a direct effect on species' distributions is that a loss of water in tributaries will lead to a loss of aquatic habitat
- an indirect effect might be a loss of connectivity because in southwestern Ontario, the mitigation to water quantity issues will be to build damns, which fragment watersheds

2. *What general changes do you anticipate to see in fish species' distributions? Which species are most likely to experience a (1) contraction or (2) expansion in their current geographical range? How will range boundaries shift?*

- we should not only consider how the northern edge of species' ranges will change, but also what will happen at the southern range
- even warmwater species might be vulnerable to increasing temperatures because they may not be able to escape these conditions if there isn't sufficient connectivity between watersheds
- ranges might become smaller overall because species are unlikely to be able to disperse as freely as they have since the last ice age
- warmwater species might see contractions in the southern parts of their range but no expansion in the northern part due to lack of connectivity
- for reference, consider the round goby – it is an invasive species with no thermal limit in the Great Lakes, and while it quickly invaded the Great Lakes it has taken a very long time for the species to make it through the tributaries
- expansion is going to be difficult and the realized distributions of species will not match the theoretical distribution predicted by models
- over the longer term, not 20 or 30 years but 100+ years, it gets increasingly more difficult to predict how distributions might shift because at that time scale, the biotic conditions (i.e., vegetation and prey communities) in species' habitats are likely to change in addition to the abiotic (i.e. temperature)

3. *What models are (1) most accurate and (2) frequently used in predicting changes in the biogeographical distributions of fish species?*

- Mandrak (1989) model – discriminate function model
- no one model is clearly better than the rest
- Elith *et al*. (2005) – compared different distributional models that have been used to predict the distributions of aquatic invasive species and found that some models perform better than others but a lot of models perform reasonably well and the choice of model often depends on what kind of data is available
- even when a model hasn't been specifically designed to take climate change into account, as long as it has a temperature component it can be used to model distributions under climate change
- can't think of any cases where simulation modeling has been applied

4. *How does watershed connectivity between the Great Lakes Basin and surrounding watersheds moderate the potential of species to respond to climate change via range shifts at the rate of warming that we are anticipating?*

- a lot of climate change modeling going on in freshwater fishes does not address the issue of connectivity
- early research assumed that there are enough connections between the Great Lakes Basin and the Mississippi River Basin to facilitate dispersal
- U.S. Army Corps of Engineers found that there are 18 connections between the two basins (GLMRIS study)

- the presence and absence of connectivity moderates the potential of species to respond to climate change to a great extent
- human transfer of species needs to be measured, however, to better understand the rate at which species might colonize other watersheds
- canals are another mechanism that affect fish movement inland from the Great Lakes
- work in the Trent-Severn Waterway has shown that fish do move through the recreational locks (unpublished)

5. *Do you have any comments on any ongoing/unpublished research pertaining to this topic, conducted by yourself or colleagues, which may be relevant for this review?*

- Mandrak (1989) – redoing the paper using amore of a risk assessment point of view and incorporating the findings of the GLMRIS study
- new research will use a model and consider how leaky the connections might be between the two basins and how realistic it is that the species will use the connections
- model predicts the ecological interactions and identifies what traits make a successful invader rather than trying to predict species distributions

6. *In your opinion, what are the main gaps in our knowledge related to how anticipated changes in physical processes in lakes will influence species distributions that may prevent us from understanding the impact of climate change in the Great Lakes region? What processes remain poorly understood and need more research and/or data?*

- basic understanding of the biology of most freshwater fish species
- linking physical and biological models
- e.g. Asian carp – we don’t look at the cumulative effects of temperature on basic life processes of fish and that’s an area where we are lacking knowledge
- we have a poor understanding of how temperature affects life processes such as reproduction because there’s nothing to suggest that it is necessarily that particular temperature that’s important, it could be that the temperature is correlated to accumulated heat units and that’s what’s important to the fish

7. *Are there any other aspects of the influence of climate change on freshwater systems of the Great Lakes region that you would like to mention that was not covered in the above questions?*

- water level changes in the Great Lakes will affect wetlands, which are important both to fish life processes as well as connectivity

8. *Can you recommend other experts in the field that should be interviewed for the purpose of this review?*

- no comment

7.5 DR. KEN MINNS

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Research interests:

Links between the supply and quality of habitat, and the life history characteristics, population size, productivity, and dynamics of fish populations in lakes.

Formulation and implementation of regional models of large scale and cumulative impacts of anthropogenic stresses on freshwater resources, especially fisheries.

Development and application of practical fish habitat management tools for site assessment and ecosystem management.

Application of system analysis tools for resource management problems, particularly using GIS and simulation modelling

Questions and Answers:

1. *How do we expect climate change drivers to impact the abiotic conditions (e.g. changes in air/water temperature, humidity, precipitation, wind, GHG concentrations, solar irradiance/cloud cover) of freshwater systems and influence fish species distributions, specifically? Pathways, mechanisms, etc.*

- temperature is likely the most important variable to affect future species distributions
- temperature directly impacts fish thermal tolerances and thus the presence or absence of a species in a particular location
- some species are dependent on flow conditions and may be directly impacted by changes in precipitation, which impacts patterns of hydrology
- lack of snow cover means absence of a “spring freshet
- for example, pike spawn in small pocket wetlands that become connected to lakes in the spring by increased water flow from melting snow; therefore, no spring freshet may result in a loss of connectivity and decreased spawning habitat for pike
- indirect effects of climate change on species distribution include an increase in the duration of lake stratification, which can lead to anoxia in late summer in intermediate-sized lakes with moderate depth
- those species dependent on the hypolimnion (i.e. lake trout) will experience a decrease in habitat quality in those lakes
- don’t know enough about the role of ice cover on biota
- changes to ice cover are likely to be more important for stream fishes – changes to fish winter refugia

2. *What general changes do you anticipate to see in fish species' distributions? Which species are most likely to experience a (1) contraction or (2) expansion in their current geographical range? How will range boundaries shift?*

- coldwater species: ranges will contract and shift north, insofar as they can.
- for example, species like Arctic Char are as far north as they can be.
- coolwater species: there will be changes across distributions, both in terms of performance and presence/absence/abundance.
- walleye: currently at the centre of their distribution in Ontario, species may expand their range northwards and increase in productivity, but the southern edge of their range is likely to contract because conditions will get too warm
- walleye will not only experience a range shift but the performance of them will change as well
- lake trout: in deep lakes with a hypolimnion, distribution is not expected to change much because warming mainly affects the surface
- in the far north parts of their distribution, lake trout currently occupy all sorts of lakes because they are cold enough
- with increasing temperatures, they may experience a contraction because they will be pushed into deeper lakes that do not warm up in the summer as much (research that is unpublished).
- In the southern area of their range, indirect effects like anoxia may reduce their numbers as well
- warmwater species like smallmouth bass are expand their distributions
- hydrological networks won't change much so connectivity is likely to decrease rather than increase, which could alter patterns and rates of changes in species' distribution

3. *What models are (1) most accurate and (2) frequently used in predicting changes in the biogeographical distributions of fish species?*

- presence/absence modelling coupled with physical lake attributes
- main criticism of these models is that they don't take into account life history
- Shuter and Post (1992) used an interesting population model (smallmouth bass and yellow perch)
- not enough emphasis spatially explicit modeling but work on invasive species is opening up those avenues
- human-induced movement is still missing from modeling approach (except for studies involving exotic species)
- some assumptions can be made about this: the more common a species is and the more commercially/recreationally important it is, the more likely it is to be moved by humans

4. *How does watershed connectivity between the Great Lakes Basin and surrounding watersheds moderate the potential of species to respond to climate change via range shifts at the rate of warming that we are anticipating?*

- general impression is that species' abilities to move beyond the Great Lakes Basin is restricted because they would have to move past the continental divide
- there is greater potential for spread in the Prairie watersheds because of their configuration northward
- due to the dispersal abilities of exotic species (i.e. some species of carp), endangered and rare species are likely to become squeezed out because their historical capacity for

range shifts is low

5. *Do you have any comments on any ongoing/unpublished research pertaining to this topic, conducted by yourself or colleagues, which may be relevant for this review?*
- Dr. Minns is has a number of projects on the go that are relevant for the review;
- E.g. predicting various aspects of thermal regimes in lakes like ice in and out dates, ice thickness, temperature modelling.
- Dr. Minns is currently in the stage of acquiring more data sets to broaden the applicability of the model
- this will allow researchers to speak more confidently about how they expect climate effects to be manifested in lake attributes
- ice beak up model: the primary predictive variable for when ice break-up date is the day when running air temperature crosses 0C while the secondary predictor is the solar elevation at the time that this happens.
- the higher it is, the sooner ice breakup will come, but even though temperatures might warm up sooner, solar elevation will remain the same
- Dr. Minns also wants to look at the oxygen regime will be affected in lakes in a climate change scenario, and has ideas of how the possible effects in principle but lacks the model to confirm these ideas (relevant to Lake Trout and the indirect effects that climate change could have on the amount and quality of their habitat)
- Brian Shuter is working on an NSERC strategic project looking at the productivity of fish (i.e. walleye and lake trout)
- how do food webs change with lake and climate characteristics?

6. *In your opinion, what are the main gaps in our knowledge related to how anticipated changes in physical processes in lakes will influence species distributions that may prevent us from understanding the impact of climate change in the Great Lakes region? What processes remain poorly understood and need more research and/or data?*
- the modelling of physical processes in lakes is quite advanced
- ELCOM is one example of this and is used extensively in the Great Lakes; it is very accurate with temperature profiles
- what is lacking is an understanding of the biology of the organism, i.e. what environmental variables are most important to the species?
- for example, there is still little data about where Lake Trout get food; even though they like cold temperatures they will forage in more shallow inshore areas to find prey
- Trout may do much of their foraging in the spring and fall when temperatures in these inshore areas are suitable for trout and spend the summer hiding out in the hypolimnion; but what if the length of the summer season becomes significantly longer?
- climate models are not very clear about how precipitation and runoff will change, although Nick Jones (OMNR) is doing some work on this
- in the southern part of species' ranges, there is good data on distribution but the data becomes sketchier in the north
- the Great Lakes drainage is well covered in terms of species presence-absence but the northern half of the Nelson drainage is lacking in data, except where there are hydro projects
- there is improved species' abundance data for the Great Lakes in recent years, but abundance data is even more scarce in the north
- mining companies are required to fish out lakes before they use them for tailings and this

provides an opportunity for scientists to gather very accurate abundance data - Brian Shuter and Mike Rennie are looking into using this data to assess biomass estimates for remote lakes

- we know very little about how wind and cloud cover will change with changing climate

7. *Are there any other aspects of the influence of climate change on freshwater systems of the Great Lakes region that you would like to mention that was not covered in the above questions?*

- there needs to be more focus on smaller, inland systems in the drainage but there is usually a bias towards big lakes
- the Great Lakes will not change as dramatically because of their size
- inland systems with smaller lakes, streams, wetlands, will see bigger changes
- yet, we only know a reasonable amount about 20% of those lakes

8. *Can you recommend other experts in the field that should be interviewed for the purpose of this review?*

- John Gunn
- Matthew Wells (UTSC)
- Ying Ming Zhao (OMNR)
- Paul Blanchfield (DFO – Winnipeg)
- Mike Rennie (DFO – Winnipeg)

7.6 DR. LINDA MORTSCH

Researcher
Environment Canada
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Linda is a senior researcher with Environment Canada and an adjunct in Waterloo's Faculty of Environment. She has 20 years research experience in climate change impact assessment. Linda conducts research on the impact of climate change on water resources and wetlands in Canada as well as "effective" communication of climate change. She has contributed to the Intergovernmental Panel on Climate Change (IPCC), the world's leading forum for assessing climate change. From 1992 to 1997, Linda led a Canada-U.S. integrated climate change impact assessment in the Great Lakes-St. Lawrence Basin. She has provided expert advice to British, Canadian and US governments, as well as numerous international organizations. Her recent projects include developing a guidance document to incorporate climate change information into the Ontario's Source Water Protection program.

Research interests:

Climate vulnerability, impact and adaptation assessment for water resources and wetlands, climate change scenario development for water resources assessment, stakeholder engagement, "effective" communicate of climate change.

Questions and Answers:

1. *Do you have any comments about any unpublished research you may conduct at this moment which can help this review?*

- Currently the work is focused on a regional climate model that can be linked to model the hydrological cycle.
- Another project is looking at cities at risks regarding their water supply.
- The last project focuses on coastal wetland models, which could also be linked to climate change scenarios.

2. *What are the main gaps in our knowledge related to the physical processes in the lakes and streams that may prevent us understanding the impact of climate change on the Great Lakes basin*?

- Most studies today, when researching a certain process consider the climate as a constant. This lack of integration by taking the process out of context leads to false results, or considerable bias.

3. *What processes are poorly understood and need more research and data?*

- The link between the water temperature and air temperature is poorly understood. For example, a recent research in Lake Superior revealed that surface water temperature has increased twice as fast as the mean air temperature in the area.
- The connection between ice-cover and turbulent mixing. The thermocline development and evaporation from water surface and land.
- There is not enough research done to project changes in wind speed and direction and some of their consequences such as erosion.
- Also, more research is needed to fully understand the increased precipitation and its dependent processes: runoff and sediment and nutrient transport.

4. *What are the main physical processes influenced by climate change and how is that expected to affect the ecosystem?*

- Older, but still valid research done for Lake Michigan emphasizes the main physical processes affected by climate change: "... While the lakes repeatedly undergo seasonal transformations associated with their mid-latitude orientation, new long-term trends are likely to have significant impacts on this system. It has been established that the lake-level fluctuations prior to 1980 were predominately driven by changes in precipitation. However for the first time in our years of record, increasing evaporation, which is likely linked to anthropogenic climate change, has begun to significantly affect the lake-levels. Summertime evaporation rates have more than doubled since 1980 as a result of increasing water-surface temperatures and subsequent increases in over-lake wind speeds. The summertime water-surface temperatures are significantly correlated with decreasing wintertime ice cover, and are likely influenced by the cumulative effect of an increasing number of summertime warming days. In addition, recent evaporation increases are likely being underestimated due to an inadequate representation of increasing over-water wind speeds during the warm season, particularly during the fall."

5. *What are the pathways from the climate drivers to the effects on the physical processes in Canadian freshwater?*

- There are many processes that act as conduits to climate change: air temperature, wind, cloud cover, snow, ice, and storm tracks. The intensity of storms has increased especially in the winter and act as important drivers for change.
- More precipitation in form of rain in winter results in more runoff and corresponding higher water levels.
- The depth, duration, and onset of melting of the snow pack have huge implications for the erosion season, onset of stratification and other time sensitive processes.

- Storm tracks are important too as their poleward shift influences the precipitation and temperatures of the Great Lakes region.

6. *On the modelling side, are there any local hydrodynamic/thermal Great Lakes models coupled with global climatic models to ensure input for various climate change scenarios that would produce credible lake processes evolution results?*

- There are large differences between the resolutions used in the GCMs and regional models like the Regional Canadian Model (RCM). For example, on the GCM grid the Great Lakes are represented as only as two points. Therefore, the feedback which a coupled model could benefit from is not really useful. In addition, downscaling procedures introduce additional uncertainties that would reduce the usefulness of such procedure.
- However, there are efforts in certain laboratories such as that of Brent Lofgren, which are aiming to perfect such systems to attain a useful state and provide better local projections.

7. *What other aspects of climate change influence on the Great Lakes physical process and phenology I did not cover in my questions and you want to add?*

- There are not enough studies looking at some processes that are not receiving enough attention, but could be exacerbated by climate change, such as :
    - erosion
    - volatilization of chemicals
    - growth of organism (G. Arhonditsis has a recent article on this)
    - interconnection between offshore and nearshore processes
    - interconnection between physical and biogeochemical processes

7.7 DR. FRANK J. RAHEL

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Research interests:

Research involves fish ecology with a particular focus on streams, habitat relationships, and landscape ecology

Addressing issues of fish habitat use and movement patterns in regards to both large spatial scales and patchiness

Interested in what constitutes a habitat patch, how these patches are rearranged by disturbances such as floods, and what factors influence fish movement among patches

Homogenization of aquatic biota across the world through habitat alteration and species introductions

Much of the research involves species of conservation concern including native trout and nongame fishes such as native minnows in prairie streams."

Fish ecology, fisheries management, landscape ecology, climate change, invasive aquatic species

Questions and Answers:

1. *How do we expect climate change drivers to impact the abiotic conditions of freshwater systems (e.g. temperature, flow, dissolved oxygen, water currents, light penetration) and influence fish species distributions, specifically? Pathways, mechanisms, etc.*

- No comment

2. *What general changes do you anticipate to see in fish species' distributions? Which species are most likely to experience a (1) contraction or (2) expansion in their current geographical range? How will range boundaries shift?*

- No comment

3. *What models are (1) most accurate and (2) frequently used in predicting changes in the biogeographical distributions of fish species?*

- for coldwater fishes, mean July water temperature (and the more readily available and highly correlated mean July air temperature) has become a standard dependent variable for predicting the geographic ranges or altitudinal limits of fish species
- a commonly cited number is that coldwater fish (i.e. trout) will not be able to persist where mean July air temperatures exceed 22°C.

4. *How does watershed connectivity between the Great Lakes Basin and surrounding watersheds moderate the potential of species to respond to climate change via range shifts at the rate of warming that we are anticipating?*

- shallow water and riverine species will be able to respond to climate change by migrating northward in the Great Lakes Basin
- however, deepwater pelagic species such as lake trout and whitefish will likely not use connecting waters to a significant degree; these species will be most likely to suffer local extirpation with a warming climate

5. *Do you have any comments on any ongoing/unpublished research pertaining to this topic, conducted by yourself or colleagues, which may be relevant for this review?*

- interactions between temperature and other abiotic factors are difficult to anticipate but could have a great influence on fish species distributions
- for example, warmer summers will increase the likelihood of hypoxia in lakes that stratify, and which often harbor coldwater fishes at the southern limits of their ranges
- fish extirpations may, therefore, not be due to excessively warm temperatures, per se, but to the loss of oxygen that accompanies prolonged stratification and increased primary productivity that are the direct result of increased temperatures
- see Jiang *et al*. 2012. Oxythermal habitat parameters and identifying cisco refuge lakes in Minnesota under future climate scenarios using variable benchmark periods. Ecological Modeling 232:14-27.

6. *In your opinion, what are the main gaps in our knowledge related to how anticipated changes in physical processes in lakes will influence species distributions that may prevent us from understanding the impact of climate change in the Great Lakes region? What processes remain poorly understood and need more research and/or data?*

- No comment

7. *Are there any other aspects of the influence of climate change on freshwater systems of the Great Lakes region that you would like to mention that was not covered in the above questions?*

- the interaction between climate change and species invasions is an important question
- a general review of the issues was presented by Rahel and Olden (2008). Assessing the effects of climate change on aquatic invasive species (Conservation Biology 22:521-533).
- a recent example for lakes in the Great Lakes region is a paper by Sharma *et al*. (2011). Comparing climate change and species invasions as drivers of coldwater fish population extirpations. PLOS ONE 6(8)
- Sharma *et al*. (2011) concluded that climate warming will cause more extinctions of cisco populations than invasions by rainbow smelt

- on the other hand, Jackson and Mandrak (2002) predicted that invasion of a predatory fish species due to climate warming will cause more extirpations of minnow populations in Canadian Lakes than warming temperatures alone
- Jackson and Mandrak (2002). Changing fish biodiversity: predicting the loss of cyprinid biodiversity due to global climate change. Pages 89–98 in N.A. McGinn, editor. Fisheries in a changing climate. Symposium 32. American Fisheries Society, Bethesda, Maryland).

8. *Can you recommend other experts in the field that should be interviewed for the purpose of this review?*

- No comment

7.8 DR. SAPNA SHARMA

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Research interests:

Predicting the effects of environmental stressors on ecosystems and improving the use of quantitative approaches used to generate these predictions.

Research bridges the fields of community ecology, quantitative ecology, spatial ecology and time-series analysis.

Questions and Answers:

1. *How do we expect climate change drivers to impact the abiotic conditions of freshwater systems (e.g. temperature, flow, dissolved oxygen, water currents, light penetration) and influence fish species distributions, specifically? Pathways, mechanisms, etc.*
- increases in air temperatures will lead to increases in surface water temperatures, but either slight increases or no change in hypolimnetic temperatures
- dissolved oxygen levels: as surface water temperatures increase, the length of the stratification period is likely to increase and this could lead to low oxygen levels in the hypolimnion by the late summer, affecting coldwater species
- changes in secchi depth could affect species like walleye which are sensitive to light in the water column, but how this might happen is less clear

2. *What general changes do you anticipate to see in fish species' distributions? Which species are most likely to experience a (1) contraction or (2) expansion in their current geographical range? How will range boundaries shift?*
- at the southern extent of the range of smallmouth bass, distributions were not impacted as much, probably because those temperatures are not expected to increase as much in the north
- Dr. Sharma has worked on cisco populations: a coldwater forage species, cisco is experiencing major contractions at the southern extent of their range in Wisconsin
- she examined how climate change and invasion of rainbow smelt affect cisco populations
- Ontario analysis of cisco populations shows that because there is more coldwater fish habitat available, there are no contractions in their Ontario range; perhaps with greater increases in temperatures these Ontario populations would also experience contractions

3. *What models are (1) most accurate and (2) frequently used in predicting changes in the biogeographical distributions of fish species?*
- the best model to use very much depends on the data set
- artificial neural networks worked well for smallmouth bass while logistic regression

models worked well for cisco

- a variety of statistical models can be used to see which are the best at predicting species presence/absence
- different models have different merits and there likely isn't one that works great in all situations
- CGCM2 has three scenarios (A1, A2, B1) and produces a conservative estimate of climate change (no extreme changes in temperature or precipitation)
- however, in total there are 15 different climate change scenarios that can be used in GCM's and considering how the rate of climate change we are currently experiencing, some of these "extreme" changes might not be so extreme after all
- by using all scenarios, you can get a better idea of the range of possibilities of how species could be affected
- this can be viewed as an "uncertainty analysis"

4. *How does watershed connectivity between the Great Lakes Basin and surrounding watersheds moderate the potential of species to respond to climate change via range shifts at the rate of warming that we are anticipating?*

- it's difficult to predict how connectivity between freshwater systems will affect species distribution at larger scales
- Dr. Sharma would like to direct her research to quantifying connectivity because the link between climate change and connectivity is not well understood (there is a lot of uncertainty) but possibly very important
- no spring runoff, as seen in 2011-2012, will impact water levels in streams, lakes and rivers; unless there are heavy rains in the spring and summer, some rivers and more importantly tributaries (which many species use to disperse), may dry up
- if there is a lot of spring runoff, of if precipitation increases with climate change in the spring and summer, the opposite situation might be observed and species dispersal patterns will be affected accordingly
- smallmouth bass has now crossed the continental divide and will be able to disperse naturally northwards
- Dr. Sharma looked at some invasive and native species to get at how to differentiate between natural vs. human-aided dispersal but these methods are not well developed

5. *Do you have any comments on any ongoing/unpublished research pertaining to this topic, conducted by yourself or colleagues, which may be relevant for this review?*

- work by John Lyons in Wisconsin (climate change might impact coldwater species – brook trout and brown trout)
- work by Heinz Stefan in Minnesota

6. *In your opinion, what are the main gaps in our knowledge related to how anticipated changes in physical processes in lakes will influence species distributions that may prevent us from understanding the impact of climate change in the Great Lakes region? What processes remain poorly understood and need more research and/or data?*

- incorporating dispersal
- incorporating uncertainty of climate change models (different versions)
- incorporating multiple stressors

7. *Are there any other aspects of the influence of climate change on freshwater systems of the Great Lakes region that you would like to mention that was not covered in the above questions?*

- No

8. *Can you recommend other experts in the field that should be interviewed for the purpose of this review?* See question 5

7.9 DR. BRIAN SHUTER

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Research interests:

The role of ecological and evolutionary factors in generating intra-specific and inter-specific variation in the life history of fish; the implications of that variation for sustainable harvest management.

The role of climate variation and climate change in shaping the population ecology of freshwater fish.

The impacts of invertebrate invaders on freshwater food chains.

Questions and Answers:

1. *Do you have any comments about any unpublished research you may conduct at this moment which can help this review?*

- Currently working on a study related to higher temperature variability in the inshore.
    - Recent increases in near-shore temperature variability suggests that the temperature changes associated with seiche activity that produces frequent upwellings determines drastic changes in temperature;
    - Wind patterns is expected to change toward a decreased intensity, however, there are still many uncertainties to be solved before there is a definite answer;
    - If the surface temperature increases substantially, but the hypolimnetic layer is not affected so much, then the amplitude of temperature variability in the near-shore will also increase;
    - This research is work in progress and unfortunately temperature variability in the inshore is not emphasized enough in literature;

2. *What are the main gaps in our knowledge related to the physical processes in the lakes and streams that may prevent us understanding the impact of climate change on the Great Lakes basin*?

- There is a relative absence of linkage between physical models and biological models. There are many studies looking at the physical aspect of climate change and they are well understood. There are many studies looking at changes in primary biological production as well, however, they are most of the time not well connected except for some recent studies.

- Linkages will permit to look at the physical processes and understand what is going to happen with the biogeochemical processes.

3. *What processes are poorly understood and need more research and data?*

- The main processes difficult to forecast are wind and precipitation In addition, there are still large uncertainties in determining long scale forecasts for all physical processes mainly due to complexity of the phenomena and insufficient understanding of the linkages between them.
- We need to determine whether the current changes are part of a long term natural cycle, or due to anthropogenic forcing.

4. *What are the main physical processes influenced by climate change and how is that expected to affect the ecosystem?*

- Seasonal development of processes
- Relationship between precipitation and water levels.

5. *On the modelling side, are there any local hydrodynamic/thermal Great Lakes models coupled with global climatic models to ensure input for various climate change scenarios that would produce credible lake processes evolution results?*

- At Great Lakes Environmental Laboratory in Ann Arbour, Michigan, Brian Lofgren is working on coupling local Great Lakes modes with Global Climate Models in order to project future changes in the lakes. However, the work is in early stages and more efforts are required in this direction.

6. *What literature do you recommend on this topic?*

- There are new studies coming out concerning changes to ice-cover physical processes due to climate change.

7.10 DR. NORMAN YAN

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Research Interests:

Identifying key factors that regulate the recovery of lakes from historical damage (e.g. acid and metal damage).

Determine the influence of non-indigenous species on Ontario's lakes (e.g. *Bythotrephes*).

Explore the influence of climate change on zooplankton of Shield lakes, working with provincial government agencies.

Explore the influence of falling calcium concentrations on crustacean zooplankton.

Explore to interactive impacts of multiple environmental stresses on Ontario's inland lakes (e.g. joint effects of climate change and acidification, contaminant partitioning and introduction of exotic species).

Summary:

- Current research:
  - Effects of climate change on omega-3 fatty acids composition of phyto- and zooplankton
  - Effects of temperature changes on other environmental stressors, such as acidification
- Knowledge gaps/areas of concern:
  - Water quality thresholds for environmental contaminants in light of climate change
  - Effects of climate change on ponds and first-order streams
  - Effects of shortening winters and fewer days of ice cover on organisms
  - Relationships between temperature and organism size
  - Identifying and reviewing the temperature thresholds of damage in aquatic organisms
  - Effects of increased drought events bought on by climate change, and how they might interact with other environmental stressors such as acidification

Overview:

Dr. Yan outlined his current research as it relates to climate change, which generally concerns indirect effects of climate change on biota, particularly invertebrate populations. One currently ongoing project in his lab in investigating changes in omega-3 fatty acid composition in phyto- and zooplankton with changes in temperature, which highlights the fact that temperature changes associated with climate change are not just associated with "killing organisms" but that it might have broader effects on things such as trophic patterns, if the nutritional content of prey items changes. Dr. Yan's other climate change-related research involves the influence of climate change on the effects of their stressors, such as acidification in Ontario aquatic systems.

Dr. Yan identified a number of areas where we are currently lacking knowledge regarding the impacts of climate change-related physical changes on lake systems and the associated impacts on biota. He believes that we need to re-assess all current water quality thresholds for contaminants such as copper, DDT, mirex, etc. in the face of climate change. In terms of specific systems, he specified that while ponds and low-order streams are likely to be affected first by warming, we know little to nothing about how these systems will be effected, particularly on the Shield. In terms of specific physical changes on biota, he highlighted further understanding of the effects of shorter winters/days of ice cover, and how that might affect the life cycles of invertebrates as well as the amount of UV damage sustained by these organisms. In addition, there has been some indirect work done on the effects of temperature on body size, and suggested that increased temperatures could lead to increased size at maturity, resulting in altered population structure of invertebrates. Commenting further on the impacts of temperature on organisms, he suggested that a more comprehensive review on the temperature thresholds for organisms damage is needed, for all types of aquatic organisms. Lastly, Dr. Yan indicated that the effects of increased drought events is an important area of climate change research, and the possibility of reacidification of some Ontario lakes. Current work has linked drought events with reacidification, but not necessary directly to climate change.

Questions and Answers:

1. *What are the main gaps in our knowledge related to how the physical effects of climate change may influence lentic biota, particularly plankton and macroinvertebrates?*

- All water quality thresholds for things such as copper, DDT, mirex, etc
    - Should be revised in light of climate change
- Ponds and first order streams, especially on the Shield
    - These systems are likely to warm first
- The effects of a shortening winter, and reduced number of days of ice cover
    - Will organisms switch from multivoltine to univoltime?
    - Is there the possibility of increased UV damage?
        - Look into the work of Craig Williamson, who showed that DNA repair mechanisms are temperature dependent, and do not work as well in colder temperatures.
        - Under climate scenarios, organisms may be more threatened by UV damage in the spring, when water is ice-free earlier and cold
- Relationships between warmer temperatures and organism size
    - Warmer water may lead to smaller size at maturity, despite increased growth rates. This would influence the size structure of invertebrate populations
    - Links between temperature and size are already documented- check out work of D. Atkinson (Advances in Ecological Research 1994, TREE 1997) and M. Moore
    - N. Yan has tested this in *Chaoborus* on the Shield (unpublished) and found a relationship where organisms living in deep, cold lakes were

    - larger than others of same developmental maturity living in warmer waters
    - Lampert also examined the effects of temperature on *Daphnia* size
- What are the thresholds of temperature damage? Need to know everything from *Mysis* to Lake Trout
- Effects of increased drought events
    - Would cause more stress in the fall, and may lead to drought-induced reacidification in some areas → have already shown that this happens, but how much can it happen? (literature at this point may not directly point to climate change)
- Need a good review on the biophysical laws relating to temperature (refer back to project looking at omega-3 fatty acid changes with temperature)
    - For examples, spread of Spiny Water Flea may be limited by climate change

2. *Do you have any comments about any ongoing, unpublished research on this topic?*

- One student currently studying effects of climate change on omega-3 fatty acids in phytoplankton and zooplankton (with M. Arts, Environment Canada)
    - Implications of temperature changes are not just about the thermal tolerance of organisms and higher temperatures killing organisms, but also resulting impacts on food webs (such as through changes in omega-3 fatty acid content)
    - Also examines the effect temperature altering the effects of other stressors, such as acidification

March 6, 2012 – 11:40-12:10pm

7.11 DR. RAM R. YERUBANDI

Research Scientist, Measurements and Modelling of Hydrodynamics and Water Quality of Large Lakes

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Research interests:

Contributing to Water S&T by conducting research on physical limnology and modelling for rehabilitation and conservation of lakes and inland waters.

Creating new knowledge of physical processes and water quality by conducting field studies in large lakes

Circulation and Transport modelling in Lakes and Coastal Oceans

Coupled atmosphere-lake modelling system

Physical Limnology information for Source Water Protection, Taste & Odour, Algal blooms, Attached Algae and Aquaculture

Questions and Answers:

1. *Do you have any comments about any unpublished research you may conduct at this moment which can help this review?*

- There are a couple of papers in press from his group:
  - Journal of Climate, on Lake Ontario warming trends (in press).
  - Atmosphere – Ocean, on modelling physical processes and assessment of climate change impacts in Great Bear Lake.
- There is also some work on assessment of climate change impact in Lake Ontario using 3-D hydrodynamic models, but they are not published yet.

2. *What are the main gaps in our knowledge related to the physical processes in the lakes and streams that may prevent us understanding the impact of climate change on the Great Lakes basin*?

- In general temperature trends are pretty well captured in all lakes, so is ice cover. But when it comes to water levels, one needs to be careful in making assessments to remove natural processes (for example rebound type) to delineate trends. Air lake interaction, particularly turbulent heat transfer is the most important mechanism, therefore it requires more studies.
- Similarly, simple 1-D type lake models coupled to regional climate models, they may be doing a good job in small lakes, but they have a questionable usefulness in climate simulations.

- A complete coupled system will involve climate model linked with proper hydrological and lake models. It is important to have validated ice models running along with it.

3. *What processes are poorly understood and need more research and data?*

- Vertical mixing in lakes is still not solved problem, it requires more detailed measurements of high frequency temperature and other scalars.
- Ice models are still new to Great Lakes, so are real ice thickness measurements. Some efforts are needed in this direction.
- Another problem is downscaling GCM forcing to lake scales. For solving this issue CRCM resolution could be improved, or maybe GEM may be enhanced to have radiation engines to run in the near future.

4. *What are the main physical processes influenced by climate change and how is that expected to affect the ecosystem?*

- Temperature in the lake, therefore stronger stratification is the main result of climate change. Stronger stratification will influence biota through the dependency of dissolved oxygen on aeration. Stronger stratification will further limit turbulent mixing to epilimnion.
- There may be already some influences on cyanobacteria blooms in some parts of the lakes.
- Loss of ice cover is equally important. It will translate into more warming. Longer stratification period will have influence on ecology. Lower water levels, water balance effects are probably more important in habitats and water use. On the other hand increased air temps with lower wind speeds will also influence in similar ways, but effects could be different by influencing circulation patterns.
- Reduced precipitation will be another factor that will influence water balance.

5. *What changes have been already observed and what could be attributed to climate change and what should we expect to occur in the near future?*

- It has been seen already loss of ice cover in Lake Superior and reduced water levels. However, it is not sure if this is due to climate change or natural variability.
- Increased surface water temperature is noticeable in all lakes.

6. *On the modelling side, are there any local hydrodynamic/thermal Great Lakes models coupled with global climatic models to ensure input for various climate change scenarios that would produce credible lake processes evolution results?*

- There are already some 1-D models that are incorporated in CRCM. There are efforts for incorporating 3-D models in GEM, which, hopefully in the near future will be used for climate forecasts.

Table A1. Summary findings from studies modelling the impacts of climate change on fish species' distributions and biogeographical ranges in the Great Lakes Basin (both Canada and U.S.), Boreal Shield, and the Great Plains.

SOURCE	FISH SPECIES	MODEL(S) AND SCENARIO(S)	RESULTS AND GENERAL CONCLUSIONS
Meisner (1990a). Transactions of the American Fisheries Society 119: 282-291.	Brook Trout	Thermal Habitat Availability: hydrometeorological model of stream temperature Climate: GCM climate model (GISS - Columbia University Goddard Institute for Space Studies) with 2 x CO_2 scenario	-elevated air and groundwater temperatures moved thermal habitat availability upstream -summer thermal habitat decreased by 42% in the Humber River and 30% in the Rouge River in Ontario.
Shuter & Post (1990). Transactions of the American Fisheries Society 119: 314-336.	Yellow Perch Smallmouth Bass	Distribution: physical lake model describing annual water temperatures coupled with a detailed young-of-year biological model incorporating larval development, growth, starvation and death Climate: 2 x CO_2 leading to increase of 4°C	-the postwarming limit of smallmouth bass was essentially coincident with the prewarming limit of yellow perch
Stefan *et al*. (1995). In R.J. Beamish [ed] *Climate change and northern fish populations* pgs. 57-72	Cold-water guild (15.3°C)* Cool-water guild (25.1°C)* Warm-water guild (29.2°C)* * Mean optimal temperature	Good Growth Habitat Volume (GGHV) and Area (GGHA): simulation models based on lake morphology (depth, size), trophic status, climate, and thermal criteria for fish growth Climate: GCM climate model (GISS - Columbia University Goddard Institute for Space Studies) with 2 x CO_2 scenario	Cold-water: -GGHV will be reduced in all studied Minnesota lakes after climate change -GGHV will decrease, on average, by ~14% in southern Minnesota lakes and ~8% in northern Minnesota lakes -50% of lakes (mostly well-mixed) will have no GGHV available after climate change Cool-water: -climate change will moderately reduce GGHV for cool-water fish in eutrophic lakes and small lakes with medium depth (17% of all Minnesota lakes) -GGHV will increase, on average, by 8% in southern lakes and 25% in northern lakes

			Warm-water: -GGHV will increase, on average, by 27% in southern lakes and 76% in northern lakes
Minns & Moore (1992). Climate Change 22:327-446.	Lake Whitefish Northern Pike Walleye	Distributions: GPS data of fish species' presence-absence interpolated using Moran's join-statistic Fish Yield Capability: fish yield regression equations (Shlesinger & Regier 1983) Climate: GCM climate models (GISS, GFDL, OSU) with 1 x CO_2 and 2 x CO_2 scenario temperatures	-Yield capability predicted to change in 81% of species' range for Lake Whitefish, 88% for Northern Pike and 87% for Walleye -Areas which currently support highest fish yields for the three species will become areas with low or marginal yield and areas with the highest yields are relocated northwards
Peterson and Kwak (1999)	Riverine Smallmouth Bass	Distribution: age-structured population model based on temperature and river discharge, fish population dynamics, fish harvest Climate: 2 x CO_2 scenario temperatures for Great Lakes region from Rind *et al* .(1989) of 4.0-6.0°C increase and 25% and 2.3% increase in precipitation for summer and winter, respectively	-a 25% increase in spawning/rearing air temperature corresponded to a 6.0% increase in mean adult density in the Kankakee River, Indiana -a 25% increase or decrease in spawning/rearing water discharge corresponded to a 42.2% decrease or 40.8% increase in mean adult density -by 2060, if land-use does not change there will be a 69% increase in mean smallmouth bass density relative to the present -if historical land use is adopted, there will be a 66% increase in the population
Jackson & Mandrak (2002). In Nature McGinn [ed] *Fisheries in a Changing Climate* pgs. 89-98	Smallmouth Bass Fathead Minnow Finescale dace Northern Redbelly Dace Pearl Dace	Thermal Habitat Availability (Smallmouth Bass): Inverse Distance Weighting Interpolation to create isotherms Distribution (Cyprinid): impact factor based on pike and/or smallmouth bass presence Climate: CGCM2 with IPCC (2001) scenario for major warming (A2) for July 2050 and July 2100	-current distributions show that only regions from south-eastern 1/3 of Ontario have thermal conditions suitable for SMB but that area expands to 2/3 by 2050 and all but the most extreme northern part by 2100 -estimated losses in cyprinid populations due to predation by Pike and/or Smallmouth bass: 7,991 populations of Fathead Minnow; 6, 064 populations of Northern Redbelly Dace; 5,510 populations or Finescale Dace; and 5,260 populations of Pearl Dace
Shuter *et al*.	Walleye	Distribution: relative change in	-Walleye decline in both yield and effort in

(2002). *Fisheries in a Changing Climate* pgs. 77-87.		maximum sustained yield (MSY) and effort at maximum sustained yield (ESY) by watershed MSY and ESY: estimated from environmental variables and walleye sensitivity (Shuter *et al*. 1998) Climate: Environment Canada GCM with 2 x CO_2 scenario temperatures	southern Ontario lakes and increase throughout central and northern parts of Ontario when only temperature changes; overall increase in sustainable harvest -if there are concurrent changes in water supply and quality, outcomes are not clear -overall drop in lake levels and DOC could change an increase into a small decrease
Jansen and Hesslein (2004). Environmental Biology of Fish 70:1-22	Lake Trout Yellow Perch	Thermal Habitat Availability: thermal model with two components: interactions at the air–water interface and heat distribution throughout the depth and area of the lake Climate: arbitrary increases of 2°C, 4°C and 9°C	Lake Trout: -at the highest warming, the number of days that surface water was available for fish decreased from 121 days to 66 days (~50%) -all climate scenarios will reduce the window of littoral feeding opportunities from 28 days to as little as 4 days Yellow Perch: -availability of thermal habitat for yellow perch substantially increased with temperature increases of 2° and 4°C and decreased to below current conditions when temperatures increased to 9°C -models using a narrower thermal niche predicted additional reductions in habitat space of 40% for Lake Trout and 60% for Yellow Perch
Chu *et al*. (2005). Diversity and Distributions 11: 299-310.	Brook Trout Walleye Smallmouth Bass Pugnose Shiner Arctic Char	Distributions: regressive models based on presence-absence data Climate: CGCM2 with IS92a emission scenario ("business as usual") for 2020 and 2050	-Brook Trout: decrease by 2050 with range shifts NE and W towards B.C. -Walleye: increase by 2050 to occupy most of Sask, N.B. and N.S. -Smallmouth Bass: high probability that by 2050, it will expand throughout most of NW Ontario and E Maritimes -Pugnose Shiner: may expand throughout S Quebec and central Ontario by 2050, and possibly into the Maritimes by 2050. -Arctic Char: may lose 40% of current range by 2020, and another 23% by 2050

Sharma *et al*. (2007). Global Change Biology 13: 2052-2064	Smallmouth Bass	Thermal Habitat Availability: general linear models based on 27 variables describing climate, lake morphology, geography and water chemistry Climate: CGCM2 with IPCC (2001) scenarios for 'business as usual' (IS92a), major warming (A2), and limited warming (B2) by 2100	-current suitable thermal habitat is restricted to southern Ontario -by July 2100, the majority of lakes in Ontario will contain suitable habitat and the potential extent of Smallmouth Bass distribution varies between the three climate change scenarios (which predict different degrees of warming)
Lyons *et al*. (2010). Journal of Fish Biology 77: 1867-1898	Coldwater guild: 3 species Coolwater guild: 16 species Warmwater guild: 31 species	Distribution: empirical models linking 69 environmental variables (geography, geology, topography, land cover/use, stream flow, temperature) to fish species' occurrence across streams Climate: GCM climate model with IPCC (2007) scenarios for limited warming (B1), moderate warming (A1) and major warming (A2)	-23 species declined in distribution, 23 species increased, and 4 had no change with climate warming -predicted total combined loss of stream length for declining species was 5,497 km per species under limited, 14,915 km per species under moderate, and 21,046 km per species for major warming -total combined gain in stream length for increasing species was 2,896 km per species under limited, 5,543 km per species under moderate, and 6,719 km per species for major warming -3 cold-water species declined substantially with increasing water and air temperatures and 1 species was extirpated -16 cool-water species were expected to decline with warming with 3 species being extirpated -among the 31 warm-water species, 3 were expected to decline, 4 showed no change in distribution, and 23 increased in distribution
Steen *et al*. (2010)	Brook Trout Brown Trout Chinook Salmon Coho Salmon Largemouth Bass	Distribution: classification tree fish distribution models based on habitat (temperature, geology and hydrology) and land cover variables Climate: no change (2001 levels); mild change (+3°C by 2100); severe change (+5°C by 2100) in air temperatures	Brook Trout – prevalence drastically reduced and virtual eradication from Muskegon watershed Brown Trout – reduction in prevalence across watershed Rainbow Trout – almost eradicated from watershed Salmon – almost eradicated from Bigelow and

	Northern Pike Rainbow Trout Smallmouth Bass Walleye		Cedar Creeks; some habitat in lower Muskegon river Bass and Pike – increases across watershed Walleye – decrease by ~50% across watershed