2015

State of Climate Change Science in the Great Lakes Basin:

A Focus on Climatological, Hydrologic and Ecological Effects

Ontario

McMaster University

OCC ONTARIO CLIMATE CONSORTIUM

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REPORT PURPOSE AND BACKGROUND

There is near unanimous consensus that climate change is occurring and its effects are already being observed across the Great Lakes Basin. Given the magnitude and range of the potential impacts on physical, chemical and biological processes in the Basin – and the importance of the environmental services those processes contribute to, including the well-being and livelihood of Great Lakes communities –"Climate Change Impacts" have been included as an Annex of the the 2012 Great Lakes Water Quality Agreement (GLWQA) and the recently ratified Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health, 2014 (COA).

The purpose of the 2015 State of Climate Change Science in the Great Lakes Basin report is to synthesize available science on the observed and projected impacts of climate change in the Great Lakes Basin and document the climate change assessment methods applied in the region. This report was initiated in support of commitments under Annex 9-Climate Change Impacts to take into account the climate change impacts on the chemical, physical and biological integrity of the Waters of the Great Lakes and communicate and coordinate binationally regarding ongoing developments of domestic science. The report draws upon the range of research conducted by various levels of government, academia and other organizations and the growing body of knowledge in areas of ecological research and climate change. This report provides researchers, managers and decision makers with a time-stamped, thorough and methodical examination of that climate change science.

The last 15 years have witnessed a tremendous outpouring of new research on the impacts of climate change on the physical, biological, chemical, economic, and social systems, as well as adaptive management research in the Great Lakes Basin. A review of this literature is presented and synthesized according to a framework of themes that addresses the impacts of climate change on: the physical environment; the chemistry of the Great Lakes Basin; aquatic and terrestrial ecosystems, the biodiversity of the Basin; and the socio-economic systems. Climate change practitioners and researchers were then consulted to develop consensus-based confidence levels for that information, to validate syntheses developed from the literature, and to identify any gaps in the information. In addition, a comprehensive review was conducted on studies within the past five years (2010-2014) that employed climate models. This review examined how climate models have recently been used in the region to assess future projections of climate, climate change impact assessments, adaptive management strategies, and characterizations of climate vulnerabilities.

OVERVIEW OF REPORT SECTIONS

The State of Climate Change Science in the Great Lakes Basin report consists of four sections.

Part 1: The Use of Climate Information in the Great Lakes Basin

This section summarizes recent trends and practices in the use of climate modelling and analysis across a range of management themes pertinent to the Great Lakes Basin, along with an overview of currently available datasets in the region. It discusses how climate information has been used in impact studies and vulnerability assessments, including the types of models, emissions scenarios and downscaling methods used in this research. In addition, it looks at the strategies used to mitigate uncertainty in the results of current climate change models.

Part 2: Data Confidence Assessment of Great Lakes Climate Change Science

This section presents the results from consultations with a cross-section of climate change researchers who were asked to rank the information for each impact theme on the basis of three criteria: (1) the agreement among the available studies; (2) the type, amount and quality of the evidence; and (3) any self-identified limitations of the research. This ranking was done both independently and using a group consensus approach for the two themes with which each participant was most familiar. The confidence levels for each theme were then categorized as low, medium, or high, corresponding to the framework used by the Intergovernmental Panel on Climate Change (IPCC). A summary of the confidence levels for each impact is present in the accompanying table, "Projected Impacts of Climate Change in the Great Lakes Basin."

Part 3: A Synthesis of Climate Change Impacts and Vulnerabilities in the Great Lakes Basin

This section provides a detailed state-of-the-art review of the vulnerabilities of the Great Lakes Basin. The review is based on key literature organized according to: (1) physical effects; (2) environmental chemistry and pollutants; and (3) ecological effects and biodiversity. A brief summary of the projected effects of climate change on each impact theme is presented in the accompanying table, "Projected Impacts of Climate Change in the Great Lakes Basin," and this information is also available in the database associated with this project.

Part 4: Knowledge Gaps

This section classifies knowledge gaps identified for each of the impact themes. In some instances, the authors of the literature cited identified knowledge gaps. In addition, experts in the environmental effects of climate change were asked at a workshop to provide insight into knowledge gaps, inconsistencies and uncertainties in the research. The identification of these knowledge gaps will help inform priorities-setting for future research to support climate change vulnerability assessments and action. A summary of the knowledge gaps is presented in the accompanying table, "Knowledge Gaps."

Accompanying Knowledge Database

As part of the comprehensive review of Great Lakes climate change studies conducted from 2010 through 2014, a Microsoft Access® database was created to house, allow the querying, and facilitate analysis of research, meta-information and results. This database contains 254 studies, and over 2000 individual estimates of climate change impacts across a wide range of research themes. The database is available for download at http://ontarioclimate.org/our-work/the-state-of-climate-change-science-in-the-great-lakes.

PROJECTED IMPACTS OF CLIMATE CHANGE IN THE GREAT LAKES BASIN

	Theme	General projections	Trend	Category	Data confidence
PHYSICAL EFFECTS	**Climatology**				
	Air temperature	• 1.5°c - 7°c increase by the 2080s depending on climate scenario and model used. • Greater increases in the winter. • Increased frost-free period and growing season.	↑		high evidence high agreement
	Precipitation	• 20% increase in annual precipitation across the Great Lakes Basin by 2080s under the highest emission scenario. • Increases in rainfall, decreases in snowfall. • Increased spring precipitation, decreased summer precipitation. • More frequent extreme rain events.	↑		high evidence medium agreement
	Drought	• Projected increases in frequency and extent of drought.	↑		low evidence high agreement
	Wind	• Increased wind gust events.	↑		low evidence low agreement
	Ice storms	• Greater frequency of freezing rain events.	↑		low evidence low agreement
	Water temperature	• 0.9°c - 6.7°c increase in surface water temperature by the 2080s. • 42-90 day increase in ice free season. • Increased period of stratification.	↑	Lakes Rivers Wetlands	high evidence low agreement low evidence high agreement low evidence low agreement
	Water levels & surface hydrology	• Water levels in the Great Lakes naturally fluctuate by up to 1.5m. • Long-term water levels in the Great Lakes peaked in the 1980s and have been decreasing since. • Projections of future lake water levels vary; however, they generally suggest fluctuations around lower mean water levels. • Lower water levels are due to several factors including warmer air temperatures, increased evaporation and evapotranspiration, drought, and changes in precipitation patterns.	↓	Lakes Rivers Wetlands	high evidence low agreement low evidence high agreement low evidence low agreement
	Ice dynamics	• Projected decreases in ice cover duration, ice thickness, and ice extent. • Increased mid-winter thaws, changing river ice dynamics.	↓	Lakes Rivers	medium evidence high agreement low evidence low agreement
	Groundwater	• Recharge rates will be greatest in the winter.	↑		low evidence low agreement
	Natural Hazards				
	Flood	• Increases in flood severity and frequency.	↑		medium evidence medium agreement
	Fire	• Projected increases in number and extent of fires.	↑		medium evidence medium agreement
ENVIRONMENTAL CHEMISTRY & POLLUTANTS	**Chemical effects** (Oxygen, Acidity (ph), Phosphorus, Nitrogen, Carbon, Mercury & other organohalogens)	• Likely increase in dissolved organic carbon, phosphorus, and nitrogen levels. • Likely increase to the toxicity and mobilization of mercury. • Due to increasing atmospheric CO_2 levels, CO_2 concentrations in the water will increase as well, resulting in lower pH levels.	↑		low evidence low agreement

ECOLOGICAL EFFECTS AND BIODIVERSITY

Theme	General projections	Trend	Category	Data confidence
Aquatic species	• Range contraction: coldwater fish (e.g., Brook Trout, Lake Trout), Painted Turtle. • Range expansion: cool and warmwater fish (e.g., Walleye, Smallmouth Bass), American Bullfrog, Northern Leopard Frog. • Coldwater habitat space is decreasing while warmwater habitat space is increasing. • Competition is changing due to range expansions and contractions. • Fragmented rivers may impede expansion ability of species. • Advances in spring phenology of amphibians.	*Not Assessed*	Range shifts Genetic changes Altered phenology Habitat alteration	medium evidence medium agreement low evidence low agreement low evidence low agreement medium evidence medium agreement
Trees and plants	• Range expansion: Oak-birch zone, Carolinian species, Sugar Maple, Hickory. • Range contraction: Boreal species, Spruce-Fir zone, Jack Pine, White Pine. • The climate niche for tree species in Ontario will dissipate and shift northwards. • In the south, trees will likely experience reduced growth rates, reproductive failure, and increased disease and mortality. • Forest fragmentation will reduce widespread tree migration. • Plant productivity will increase if they are not otherwise limited. • Distribution and abundance of wetland vegetation will change. E.g., wetland vegetation requiring little water such as sedges, grasses, wet meadows, and trees will replace emergent and submergent species.	*Not Assessed*	Range shifts Genetic changes Altered phenology Habitat alteration	medium evidence medium agreement medium evidence medium agreement medium evidence medium agreement medium evidence medium agreement
Wildlife	• Range expansion: Southern Flying Squirrel, White Tailed Deer, American Woodcock, Fisher, Red Fox. • Range contraction: Canada Lynx, Alder Flycatcher, Northern Flying Squirrel. • Increase in 'generalist' species and decrease in 'specialist' species. • Shifting ranges may be impeded by geographic barriers, biotic stress, and landscape fragmentation. • >45% decrease in optimal habitat for 100 climate threatened bird species in Ontario. • Increased risk of hybridization (e.g., Carolina Chickadee and Black-capped Chickadee). • Earlier breeding and hatching of bird species. • Asynchrony between environment and life history needs. • Disruption of predator-prey relationships (e.g., Canada Lynx-Snowshoe Hare cycle).	*Not Assessed*	Range shifts Genetic changes Altered phenology Habitat alteration	medium evidence medium agreement low evidence low agreement medium evidence medium agreement medium evidence medium agreement
Pathogens and parasites	• Pathogens and parasites are likely to increase in range and prevalence. • Parasite-host relationships are changing due to warming temperatures.	*Not Assessed*	Aquatic Trees and plants Wildlife	low evidence low agreement low evidence high agreement low evidence low agreement
Invasive species	• Non-native species may increasingly become established. • Current invasive species will be able to expand their ranges further north due to warmer temperatures.	*Not Assessed*	Aquatic Trees and plants Wildlife	low evidence high agreement low evidence high agreement low evidence low agreement

KNOWLEDGE GAPS

Summary of Knowledge Gaps by Theme	Report Section
Climate Modelling in the Great Lakes Basin • The ability to model processes and feedbacks between the earth's surface and atmospheric systems at local scales across the Great Lakes Basin is limited. • The application and advancement of dynamical downscaling is limited in the Great Lakes Basin. There is a lack of integration of emerging model scenarios into research, needed to ensure future findings build on existing knowledge base. • A prognostic and retrospective analysis (such as hind casting) is needed to validate model performance. • The coverage and quality of information from climate and weather observations networks has not been assessed for its ability to support adaptive management and the development of climate change and impact information, including refinement of earth system models, analytical tools, and impact thresholds/system responses to climatic changes. • The limitations, deficiencies, and assumptions, used in non-climatological research and other applications, in particular downscaling techniques, Global Circulation Model (GCM) selection, emission scenarios, and overall confidence in findings has not been well communicated.	1.2, 3.1, 4.1
Water Temperature • Consideration of the spatial dynamics of lakes has not been incorporated into water temperature modelling. • There is limited monitoring and modelling of lake thermal profiles and surface-temperature based analyses. Changes in wind (due to climate change) have not been incorporated into ice dynamic models.	3.1.2, 4.2
Water Levels and Surface Hydrology • There are uncertainties in the relative roles of precipitation, runoff, evaporation and evapotranspiration in water level modelling. **Lakes** • There is a lack of clarity in the understanding of multiple factors (including hydroclimatic factors) influencing water level projections for the Great Lakes. • The diversity of inland lake types and the impacts of climate change on those lakes has not been well characterized. **Rivers** • There is a lack of clarity in the understanding of multiple factors (including hydroclimatic factors) influencing water level projections for the Great Lakes. • The diversity of inland lake types and the impacts of climate change on those lakes has not been well characterized. **Wetlands** • There has been a lack of detailed research on the vulnerability of wetlands, such as patterns of wetland drying. • There is limited understanding of how climate impacts the water budgets of wetlands. • Wetland monitoring has not been geared to evaluate impacts of projected changes in water levels.	3.1.3, 4.3
Groundwater • Groundwater recharge and discharge rates and patterns are not well understood in the Great Lakes basin. • An inventory of groundwater resources has not been completed for the basin. • There is limited understanding of the magnitude/direction of groundwater changes.	3.1.5, 4.4
Precipitation and Extreme Events • Research identifying indicators for extreme weather events related to flooding and drought risks is limited. • Precipitation projections have limited resolution and could better characterize precipitation cycle feedbacks. • The consequences of altered disturbance regimes, such as fire and drought are not well documented.	3.1, 3.1.6, 4.5

Chemical Effects • Projections of changes in lake and river chemistry are limited (such as oxygen, carbon, nitrogen and phosphorous levels). • Carbon dioxide fertilization effects have not been incorporated into carbon cycle modelling. • The changes in pesticides/biocide uses and applications, with pathogen, parasite and invasive species changes have not been factored into models of chemical effects. • Projections of changes in chemical uses and applications are limited. • Knowledge and data of climate change and its direct effects on chemical exposure, fate and transport are limited. • Monitoring is not geared up to conduct rigorous chemical and pesticide monitoring and testing, including a carbonate chemistry and acidification.	3.2, 4.6
Species Ranges and Ecosystem Shifts • Expanding ecological modelling beyond species-level responses to climate change could help address multi-species interactions and ecosystem changes. • The consideration of impacts of climate change on the local scale, including micro-climate niches is limited. • Research is limited on the impacts of climate change on coastal ecosystems. • Monitoring of species and community-level changes is necessary to refine hybrid models, which could lead to a better understanding of the reconfiguration of ecosystems and inform changes in chemical and pesticide use.	3.3.1, 3.3.4, 4.7
Genetic and Phenologic Change • There is a gap in research identifying and examining the genetics of fitness-related traits that will impact adaptation of species to climate change. • Research in genetic matching to identify genotypes best suited to future climates is limited. • Research of the political, ethical, operational and scientific aspects of the assisted migration of species is limited. • Research investigating asynchronies resulting from phenological changes in species and ecosystems is limited.	3.3.2, 3.3.3, 4.8
Invasive Species, Parasites and Pathogens • Limited integrated research on climate change and invasive species identify and investigate invasive species that may expand into the Great Lakes Basin. • Limited research on aquatic, tree and wildlife parasites and pathogens that may expand into the Basin.	3.3.5, 3.3.6, 4.9
Cumulative Effects and Integration of Land Use • Further integration of the cumulative effects of other environmental stressors into climate change impact analyses would be beneficial. • The integration of the impacts of land-use management decisions into climate change modelling is limited.	4.10, 4.11
Community and Human Effects* • Cumulative effects assessments that examine multiple environmental stressors have been limited. The synthesis of human effects would be helpful to ensure an integrated research strategy for Great Lakes climate change science, including effects on social, cultural, economic, health, built infrastructure, and political systems. • Dissemination of climate information to resource users, decision makers and practitioners could be improved. ** Note that these themes are given substantially less detail treatment throughout the report, and as such recommendations are less specific and detailed.*	3.4, 4.12
Use of Climate Science for Adaptive Management • The development and promotion of tools that increase accessibility and effective use of climate change science would help the use of this information in evidence-based adaptive management. • Leadership on evidence-based adaptive management and dialogue between researchers and decision makers is limited.	4.11, 4.13

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ACRONYMS

AR4	Fourth Assessment Report (IPPC)
AR5	Fifth Assessment Report (IPPC)
CCCMA	Canadian Centre for Climate Modelling and Analysis
CGCM	Coupled Global Climate Model
CO_2	Carbon Dioxide
COA	Canada-Ontario Agreement Respecting the Great Lakes Basin Ecosystem
CMIP5	Fifth Coupled Model Intercomparison Project
CRCM	Canadian Regional Climate Model
DFO	Department of Fisheries and Oceans Canada
DOC	Dissolved Organic Carbon
EC	Environment Canada
EPA	United States Environmental Protection Agency
ESM	Earth System Model
GCM	Global Climate Model
GDP	Gross Domestic Product
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gas

GLC	Great Lakes Commission
GLEAM	Great Lakes Environmental Assessment and Mapping Project
GLFC	Great Lakes Fishery Commission
GLISA	Great Lakes Integrated Sciences + Assessments
GLWQA	Canada-United States Great Lakes Water Quality Agreement
HadCM	Hadley Centre Coupled Model
HBV	Hydrologiska Byråns Vattenbalansavdelning
ICLEI	International Council for Local Environmental Initiatives
IJC	International Joint Commission
IPCC	Intergovernmental Panel on Climate Change
IUGLS	International Upper Great Lakes Study
MCMC	Markov Chain Monte Carlo
MNRF	Ontario Ministry of Natural Resources and Forestry
MOECC	Ontario Ministry of the Environment and Climate Change
NARCCAP	North American Regional Climate Change Assessment Program
NH_4	Ammonium
NO_3^-	Nitrate Ion
NO_2^-	Nitrite Ion
NOAA	United States National Oceanic and Atmospheric Administration
NRCAN	Natural Resources Canada
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SRES	Special Report on Emissions Scenarios
SWAT	Soil and Water Assessment Tool
VIC	Variable Infiltration Capacity model

I. INTRODUCTION

I.I. The Great Lakes Basin and its Governance

The Laurentian Great Lakes are, collectively, the largest body of freshwater lakes in the world, covering an area of 244,000 km^2 and containing approximately 23,000 km^3 of water (Breffle et al. 2013). The terrestrial portion of the Great Lakes Basin represents approximately one third of the land mass of Ontario, covers portions of Quebec and significant portions of eight U.S. states (Figure 1), and features varied climates, soils and topography. Containing 84% of North America's surface freshwater, the region is home to more than 40 million people in Canada and the United States and is of great economic, environmental and social importance (Environment Canada and US EPA 2011). Great Lakes industry contributes $5 trillion to the economy, makes up 30% of the combined U.S. and Canada GDP, and provides more than 43.4 million jobs (Krantzberg and deBoer 2006, World Business Chicago 2013). Manufacturing, forestry, agriculture and shipping are all important industries that rely on access to significant water resources, while the Basin is the source of drinking water for more than 24 million people. It is also a major reservoir of biodiversity, containing the world's largest collection of freshwater coastal dunes and sustaining over 4,000 species of plants, fish and wildlife (Government of Ontario 2012). A critical, ongoing challenge is balancing competing needs, including industrial and agricultural production, ecosystem health, drinking water resources, and recreational and cultural uses in a way that ensures prosperity and sustainability.

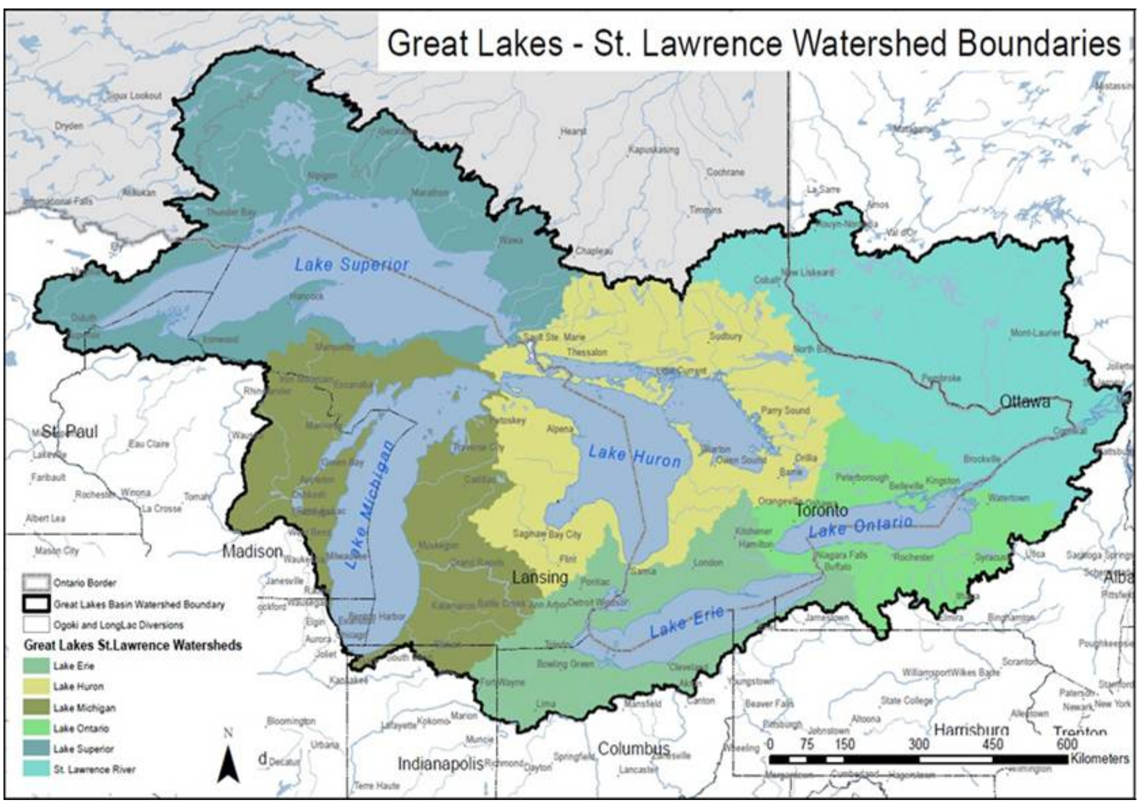


Figure 1: Map of the Great Lakes Basin showing the individual lake drainage basins.

The need to conserve and protect ecosystems in the Great Lakes Basin has been the basis for several policy tools that address critical themes, including water quality, species habitat and contaminants (Figure 2). Beginning with the *Boundary Waters Treaty* of 1909, and followed by the Canada-United States *Great Lakes Water Quality Agreement* (GLWQA), an international treaty first signed in 1972, among other treaties and agreements, the Basin has enjoyed a rich history of management and stewardship. The GLWQA was recently amended in 2012. For over four decades, Canada and Ontario have worked collaboratively together through the *Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health* (COA), first signed in 1971, under which Canada delivers on its obligations under the GLWQA. Involving the participation of eight federal departments and three provincial ministries, the purpose of COA is "conserve Great Lakes water quality and ecosystem health" and "sustainable region for present and future generations".

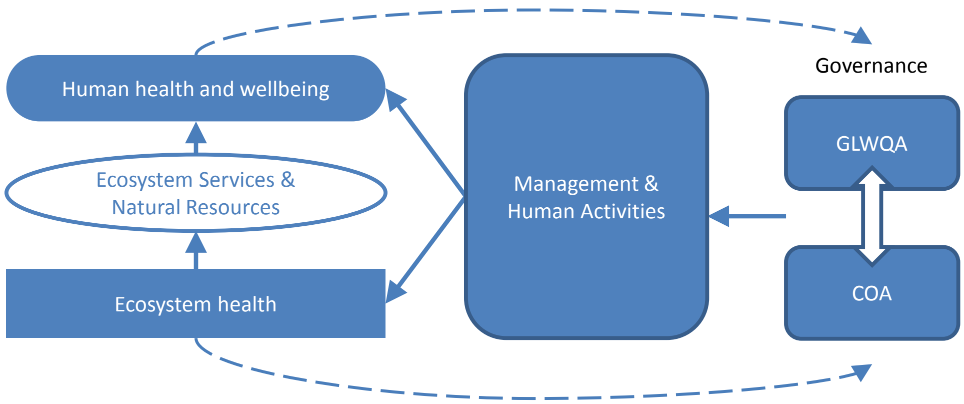


Figure 2: Conceptual diagram showing the relationship between Great Lakes governance (GLWQA and COA), management and human activities, and their effect on ecosystem health, which underpins human health and well-being.

I.II. Climate Change Impacts, Adaptive Management, and Governance in the Great Lakes Basin

Climate change is perhaps the greatest environmental challenge facing the ecosystem health of the Great Lakes Basin. In recent years, expert panels across the Basin have called for both an improved understanding of ecological vulnerability and a more strategic approach to achieving climate resilience (e.g., U.S National Climate Assessment; The Ontario Expert Panel on Climate Change Adaptation 2009). The recognition of climate change as an emerging issue of concern, as well as its inclusion in Annex 9 of the GLWQA and Annex 9 of the COA, reflects growing concern by national, provincial, state and local governments (in addition to key interest groups and stakeholders) that the impacts of climate change are already being observed and documented. There is growing consensus that further changes are anticipated in the future and that action to address vulnerabilities and risk and to develop adaptation options is needed now. Annex 9 specifically commits Canada and the U.S. to take into account the climate change impacts on the chemical, physical and biological integrity of the Waters of the Great Lakes, to consider such climate change impacts in the implementation of the Agreement and to communicate and coordinate binationally regarding ongoing developments of domestic science, strategies and actions to build capacity to address climate change impacts on the Great Lakes Basin Ecosystem.

Three significant climate change synthesis reports published in 2014 provide background/context and have greatly advanced the collation of scientific information related to climate change –

Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation (Warren and Lemmen 2014), *Climate Change Impacts in the United States: The Third National Climate Assessment* (Horton et al. 2014; Melillo et al. 2014; Pryor et al. 2014), and *Lake Superior Climate Change Impacts and Adaptation* (Huff et al. 2014).

Work to address climate change impacts by various agencies and stakeholders throughout the Great Lakes Basin has accelerated in recent years, focused largely on improving our collective knowledge of climate change vulnerabilities, risks and adaptation needs. This progress is evident through the growing body of scientific literature, numerous adaptation planning guidance materials and tools, and local and watershed adaption plans and studies (e.g., such as the International Upper Great Lakes Study, Lake Simcoe Climate Change Adaptation Strategy). However, core challenges remain in (1) addressing source of, or working to reduce, uncertainties associated with future climate projections; (2) the characterization of climate change impacts and vulnerabilities across a range of systems; and (3) effective decision-making in the context of such uncertainty. Uncertainty and the need for clearer definitions related to climate change impacts have been partly attributed to the fact that many resource managers lack a clear definition of "climate change adaptation" defined by proactive planning (Petersen et al. 2013).

Adaptive management has emerged as a process for addressing decision-making challenges associated with climate change, in particular information uncertainty, and the evolving and complex nature of climate impacts, vulnerabilities, and management environments (Williams 2011, Lim et al. 2005). In the Great Lakes Basin, examples of adaptive management and governance are beginning to emerge, with key examples being the establishment of the Great Lakes-St. Lawrence River Adaptive Management Committee of the International Joint Commission (IJC), for the on-going review and evaluation of water level regulation plans under changing climate conditions (See Box 1) (IGLSLR-AMTT 2013, Abdel-Fattah and Krantzberg 2014). There are also numerous guidance documents available to aid decision makers in the use of adaptive management at a general level (Bizikova et al. 2008, ICLEI 2010), for infrastructure (Canadian Council of Professional Engineers 2011), for watershed management (EBNFLO Environmental AquaResource Inc. 2010), and in relation to ecosystems and natural resources (Swanston and Janowiak 2012, Gleeson et al. 2011). These guides and supporting tools (including the data and information portals) are intended to help local authorities make

Box 1: Adaptive management and the Great Lakes Basin

Adaptive management is a decision-making process for ensuring policies, programs and management plans are responsive to changing environmental conditions, such as climate (Williams 2011a, Lim et al. 2005). Adaptive management involves: understanding and documenting the nature (timing, magnitude, spatial extent, etc.) of a system's reaction to the environmental condition or change in question; identifying a range of appropriate responses; and monitoring, evaluating and adjusting implemented responses.

For example, in addressing the uncertainty associated with extreme water levels in the Great Lakes Basin, in 2013 the International Joint Commission released a draft report, "An Adaptive Management Plan for Addressing Extreme Water Levels," which identified two elements of adaptive management:

1. on-going review and evaluation of the effectiveness of the regulation plan rules at meeting their intended objectives; and
2. collaboration on developing and evaluating solutions to problems posed by extreme water level conditions that cannot be solved through lake regulation alone.

(IGLSLR-AMTT 2013)

more informed choices regarding climate change vulnerability, risks and adaptation options.

In addition to the tools mentioned above, several researchers in the Great Lakes Basin have developed approaches for combining climate information with decision-making approaches. Brown et al. (2011) and Lemieux et al. (2014) both used climate projections in addition to expert identification of vulnerabilities and thresholds. Iverson et al. (2012) combine a decision support scoring system with a species habitat model to present a risk matrix for comparing climate change impacts. Price et al. (2012) combine landscape modelling methods with scenario-building informed by expert knowledge, noting that experts may also provide information useful for developing narratives to explain model outputs. A variety of other modelling and expert consultation approaches have been applied to inform decision making. For instance, Mortsch (2010) describes integrating elements of community vulnerability and adaptive capacity into adaptation planning in the Upper Thames River watershed. Oni et al. (2012) developed a modelling framework for a hydroelectric power reservoir to examine flow management options based on potential climate change and energy demands. Schuster et al. (2012) modelled projected precipitation changes in the context of water resource decision making, such as for stormwater infrastructure design. Expert consultation has been applied to examine Ontario's low water response mechanism, indicating that it may not be resilient enough to operate under conditions of serious low flow (Disch et al. 2012). Improving communication of climate information is another strategy for improving decision making and community engagement, which is the aim of tools such as the Great Lakes Water Level Dashboard developed by Gronewold et al. (2013) to communicate variability in lake levels. Veloz et al. (2012) developed a similar set of tools in contemporary climatic analogs for Wisconsin's end-21st-century climate to show that expected changes will be almost entirely different from current conditions in the state.

Given the importance of scientific knowledge and information as an input to adaptive management, a shared understanding of the state of the science, including current strengths, gaps and levels of confidence, is critical to identifying research priorities and co-operatively identify and respond to climate change impacts across the Great Lakes Basin. It is also critical that capacity exists to ensure the information can be used by the necessary actors at each stage of the knowledge generation and use cycle (Lemos et al. 2014, Bidwell et al. 2013) (Figure 3).

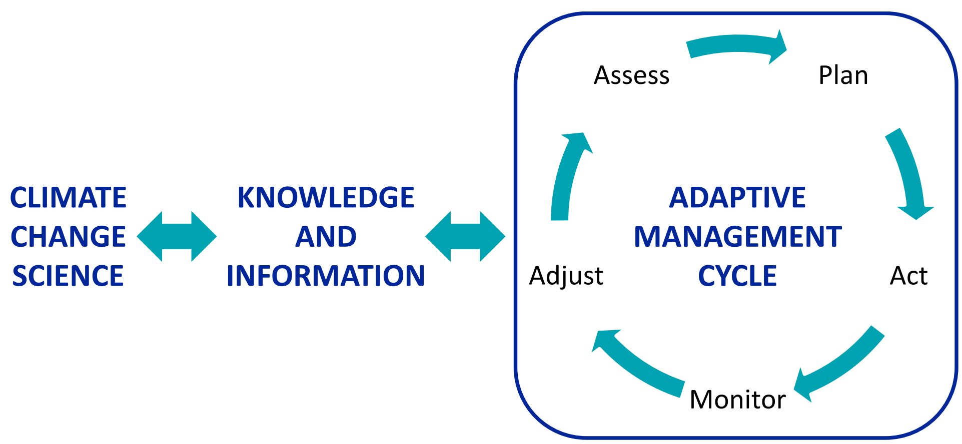


Figure 3: Conceptual diagram showing the relationships between climate change science, the resultant information and knowledge it produces, which is then used in adaptive management. Adaptive management also informs knowledge of climate change science.

I.III. Report Objectives and Structure

The purpose of this report is to provide researchers, managers and decision makers with a time-stamped (2015), thorough and methodical examination of the state of climate change science in the Great Lakes Basin. A particular focus is placed on the ecosystem-based management themes addressed in two key partnership frameworks governing management of the Basin: (1) the binational GLWQA; and (2) the COA. Given the breadth of issues addressed in the GLWQA and COA, the state of climate change science is presented and synthesized with respect to the range of physical, chemical, and ecological systems managed or considered in these partnership agreements. A more limited discussion of socio-economic considerations is also presented, however the main focus of this report is ecosystem-based science. Additional emphasis is placed on collating information on the state of information and science that is fundamental in climate change adaptation planning, namely future projections of climate, climate change impact assessments and characterizations of climate vulnerabilities in the region.

This report was designed to provide a firm foundation for future work in the Great Lakes Basin by identifying knowledge strengths, weaknesses, gaps, priorities and opportunities. It recognizes that the Great Lakes Basin consists of the aquatic ecosystems of the five Great Lakes themselves, as well as the watersheds that influence Basin-wide health. While the primary focus is on ecosystems, connections to economic activities and social well-being that are directly tied to the health of ecosystems are also considered, such as agriculture, nature-based tourism and human health. Four sections comprise the report:

- **Part 1: The Use of Climate Information in the Great Lakes Basin –** summarizes trends and practices in the use of climate modelling and analysis across a range of management themes. This section provides a breakdown of how climate information is used in climate change impact and vulnerability assessments, including the types of models, scenarios and downscaling methods used in this research. This provides an understanding of the range of approaches used to study different climate change impacts in the Great Lakes Basin, as well as strategies to address uncertainty. The analysis of how climate models are used in the Great Lakes Basin focuses specifically on assessing a five-year time period (2010-2014) to identify and synthesize the most recent practices in research that relies on models and scenarios. This information is intended to aid in the prioritization of climate change research supported by federal and provincial/state agencies and our many partners, including under the GLWQA and COA.
- **Part 2: Data Confidence Assessment of Great Lakes Climate Change Science –** Expert consultations were conducted with a cross-section of ecosystem researchers in November 2014 to elucidate levels of confidence associated with the current science and knowledge across a range of themes. This section features confidence rankings, based on a relative comparison among the themes being assessed, with each theme evaluated using the Intergovernmental Panel on Climate Change (IPCC) guidelines on data confidence (Mastrandrea et al. 2010).
- **Part 3: Synthesis of Climate Change Impacts and Vulnerabilities in the Great Lakes Basin –** provides a detailed review of the vulnerabilities of the Great Lakes Basin. The physical, chemical, ecological and socio-economic vulnerabilities of the Basin are summarized from the academic and grey literature in a time-stamped, state-of-the-science

review. A summary of research results are available in the database associated with this project.

- **Part 4: Knowledge Gaps** – classifies knowledge gaps identified from the cited literature. Experts in the effects of climate change on ecosystems were asked to provide insight into research gaps and uncertainties. The identification of knowledge gaps will help in setting priorities for future research to support climate change vulnerability assessments.

II. METHODS AND DATA

This report presents the results of a meta-analysis of trends in scientific research pertaining to climate change across a range of themes relevant to the Great Lakes Basin. Searches of the academic and grey literature were used to identify and extract information on relevant research topics. These scientific papers and research reports were grouped according to a framework of themes that addresses the impacts of climate change on: the physical environment; the chemistry of the Great Lakes; aquatic and terrestrial ecosystems and biodiversity of the Basin; and several other areas, including agriculture, economics, infrastructure and human health and well-being. Table 1 cross-references the themes used in this report to the ecosystem-based Annexes of the GLWQA and COA. The reports supporting these themes were reviewed, summarized and any patterns or inconsistencies were noted. In addition, climate change practitioners were consulted to develop consensus-based confidence levels for that information, to validate syntheses developed from the literature, and to identify any gaps in the information. Since climate analysis and modelling are an important component of the GLWQA and COA (as covered in Annex 9 of both documents), this was also included as a theme.

Table 1: Mapping of report themes to GLWQA and COA annexes.

Report Theme	Section	GLWQA Annex	COA Annex
Climate Analysis and Modelling	1.2	9. Climate Change Impacts	9. Climate Change Impacts
Physical and Chemical Effects			
Climatology	3.1.1	9. Climate Change Impacts	9. Climate Change Impacts
Water Temperature	3.2	2. Lakewide Management 4. Nutrients 6. Aquatic Invasive Species	1. Nutrients 5. Lakewide Management 6. Aquatic Invasive Species
Water Levels and Surface Hydrology	3.3	2. Lakewide Management 7. Habitat and Species	5. Lakewide Management 7. Habitat and Species
Ice Dynamics	3.4	2. Lakewide Management	5. Lakewide Management
Groundwater	3.5	8. Groundwater	8. Groundwater Quality
Natural Hazards	3.6	2. Lakewide Management 7. Habitat and Species	2. Lakewide Management 7. Habitat and Species
Environmental Chemistry and Pollutants	3.7	1. Areas of Concern 3. Chemicals of Mutual Concern 4. Nutrients 5. Discharges from Vessels	1. Nutrients 2. Harmful Pollutants 3. Discharges from Vessels 4. Areas of Concern

Nutrients	3.7.2	4. Nutrients	1. Nutrients
Air Pollution	Not included in detail	1. Areas of Concern 2. Lakewide Management	4. Areas of Concern 5. Lakewide Management
Ecological Effects and Biodiversity			
Aquatic Ecology	3.8	2. Lakewide Management 7. Habitat and Species	5. Lakewide Management 7. Habitat and Species
Aquatic Invasive Species	3.8.6	6. Aquatic Invasive Species	6. Aquatic Invasive Species
Terrestrial Ecology	3.8	2. Lakewide Management 7. Habitat and Species	2. Lakewide Management 7. Habitat and Species
Terrestrial Invasive Species	3.8.6	7. Habitat and Species	7. Habitat and Species
Community and Human Impacts			
Adaptive Governance and Decision Making	Introduction and Part 4	2. Lakewide Management 10. Science	5. Lakewide Management 10. Science 12. Engaging Communities 13. Engaging First Nations 14. Engaging Métis
Agricultural Production	Not included in detail	2. Lakewide Management 4. Nutrients	1. Nutrients 5. Lakewide Management
Human Well-being and Socioeconomics	3.4	1. Areas of Concern 2. Lakewide Management	4. Areas of Concern 5. Lakewide Management

II.I. Systematic Review of Climate Information Usage

The aim of Part 1 of this report was to analyze the current use and application of climate change scenarios, climate models, downscaling techniques and other analytical tools used in climate change science in the Great Lakes Basin. Focus was placed on understanding the use of these tools across the range of themes listed in Table 1. To conduct this analysis, a systematic review was completed to identify a comprehensive list of studies within the past five years (2010-2014) that employed some form of climatological analysis or climate model output within subsequent modelling or analysis.

Institute for Scientific Information (ISI) Web of Science (including the Science, Social Science and Humanities citation indices) and Science Direct databases were searched to identify peer-reviewed English-language articles with search terms applied to title, keywords and abstract. In addition, grey literature was identified by expert consultation and initially focused on the following sources:

- Environment Canada (EC)
- Fisheries and Oceans Canada (DFO)
- Ontario Ministry of Natural Resources and Forestry (MNRF)
- Ontario Ministry of the Environment and Climate Change (MOECC)
- United States Environmental Protection Agency (US EPA)
- United States National Oceanic and Atmospheric Administration (US NOAA)

- International Joint Commission (IJC)
- Great Lakes Commission (GLC)
- Great Lakes Fishery Commission (GLFC)
- Great Lakes Integrated Sciences + Assessments (GLISA)
- Natural Resources Canada (NRCAN)
- Regional watershed management agencies, including Ontario Conservation Authorities

After conducting the search, articles were assessed for relevance to the topic. Articles were excluded if they were outside the scope of the review, such as climate change impacts outside of the Great Lakes-St. Lawrence Basin. Articles that did not report on climate change models, scenarios or future predictions were excluded. The resulting references were then cross-checked with an existing database of literature on climate change science in the Great Lakes previously compiled by the MNRF and DFO.

Once an inventory of articles and grey literature was collected, each was independently reviewed and key information pertaining to the use of climate information was extracted and entered into a Microsoft Access database. Appendix 1 contains a description of the information fields extracted for each article. This database was then analyzed along a number of different dimensions to generate the analysis in Part 1 of this report.

II.II. Assessment of Knowledge Confidence

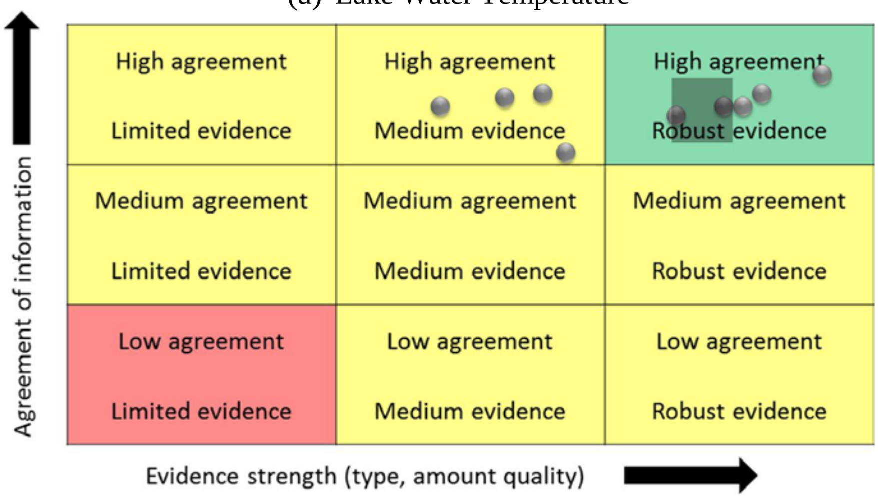
There is significant variability in both the volume and the diversity of information on climate change impacts to ecosystem and management themes in the Great Lakes Basin. In addition, uncertainty plays a central role in the projection and understanding of many of the impacts of climate change. As a result, it was necessary to rely on practitioners and researchers to evaluate the confidence of currently available information and identify knowledge gaps. For this report, two groups of experts and practitioners were consulted:

1. **Ontario ecosystem practitioners:** On November 25 and 26, 2014, 66 researchers and practitioners participated in a symposium designed to elucidate and document perspectives on the confidence, strengths and gaps in the state of climate change information applicable to the Great Lakes Basin with respect to a range of ecosystem management themes. The findings of the workshop on data confidence and knowledge gaps are summarized in Parts 2 and 4 respectively.
2. **The Climate Change Impacts (Annex 9) Extended Subcommittee of the GLWQA:** This committee is comprised of 26 members, and each member was provided an opportunity to review and provide comments on this report, review the database for completeness and suggest articles for inclusion in the analysis.

The method for deriving confidence levels was to subdivide the available climate change information into a series of themes by subject, based on the physical, chemical or biological effects being studied. The experts and practitioners were then asked to rank the information for each theme on the basis of three criteria: (1) the agreement among the available studies; (2) the strength of the evidence (i.e., the type, amount and quality); and (3) any self-identified limitations of the research. This ranking was done both independently and using a group consensus approach for the two themes with which each participant was most familiar. Finally, the confidence levels for each theme were categorized as "low ," "medium ," or "high ," corresponding to the framework used by the IPCC (Mastrandrea et al. 2010). Figure 4 represents the matrix used to determine the confidence levels in the preparation of the IPCC Fifth Assessment Report colour-coded to represent the low (red), medium (yellow), and high (green) data confidence categories. Figure 4 shows examples of data confidence ranking of the research from two themes (the effects of climate change on lake water temperature and alterations to wildlife habitat) including both the group consensus and the individual expert assessment of all the available research for that theme.

These rankings are intended to provide context for a reader in interpreting the vulnerability narratives compiled for each theme (in Part 3 of this report), as well as to identify those topics where there may be deficiencies, inconsistencies or gaps in the research.

(a) Lake Water Temperature



(b) Habitat Alteration for Wildlife

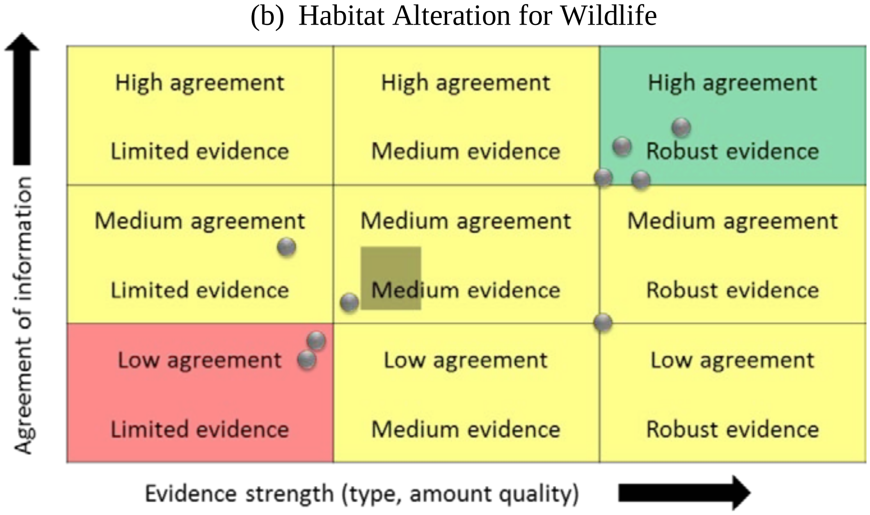


Figure 4: Confidence determinations based on Mastrandrea et al. (2010) matrix for the IPCC 5th Assessment Report for research addressing (a) lake water temperature, and (b) habitat alteration for wildlife. Circles indicate individual expert ranking on the available research for that theme and squares indicate group determination. The colors indicate the categorization of data confidence into low (red), medium (yellow) and high (green).

II.III. Synthesis of Climate Change Impacts and Vulnerabilities

The aim of Part 3 of this report was to synthesize the historical and projected impacts of climate change in the Great Lakes Basin. In order to align with the ecological emphasis in the GLWQA and COA a systematic review of the key literature on climate vulnerability and impacts was conducted, which focused on: (1) physical effects; (2) environmental chemistry and pollutants; and (3) ecological effects and biodiversity. Within each theme, historical patterns of climate change were summarized followed by an examination of the projected changes. The implications of such changes were also discussed. While a cursory examination of community and human impacts of climate change is also included, this was not a focus of the review and is considered to be beyond the scope of this report.

PART 1. THE USE OF CLIMATE INFORMATION IN THE GREAT LAKES BASIN

1.1. Background and Part 1 Objectives

For the purposes of this report, climate information has been defined as observations or estimates of atmospheric variables for any historical or future period in a given geography. This definition includes "baseline observed data (range of time steps), trends, variability, and higher-order statistics, extremes, inter-annual variability, and inter-decadal variability, for both the past and projected future climate" (UNEP 2009, p.4). Despite the wide range of datasets included in this definition, there are examples of each being used within the body of Great Lakes climate change science to convey evidence about how the atmosphere has or is projected to change and the implications for natural and man-made systems. The use of climate information in a given study is however, highly dependent on the specific research questions posed, outcomes sought, and methodologies employed.

The objective of Part 1 of this report is to present and discuss key trends in how climate information is being used across the range of research themes explored within the scientific literature on Great Lakes climate change impacts. Such a discussion is critical to understanding the state of climate change science, as climate information is the basis for almost all impact studies. A focus is placed on understanding the types of datasets used, approaches for selecting data and methods used for localizing, or downscaling, information.

Three dominant classes of climate information have been identified within the literature reviewed for this study. These categories are based on a recent guidance document related to the use of climate information in impact and vulnerability research, produced by the Ouranos Consortium in Quebec (Charron 2014). Charron (2014) determined that the level of effort, complexity of variables and amount of spatial and temporal detail increases as a user's need advances (Charron 2014) (Figure 5).

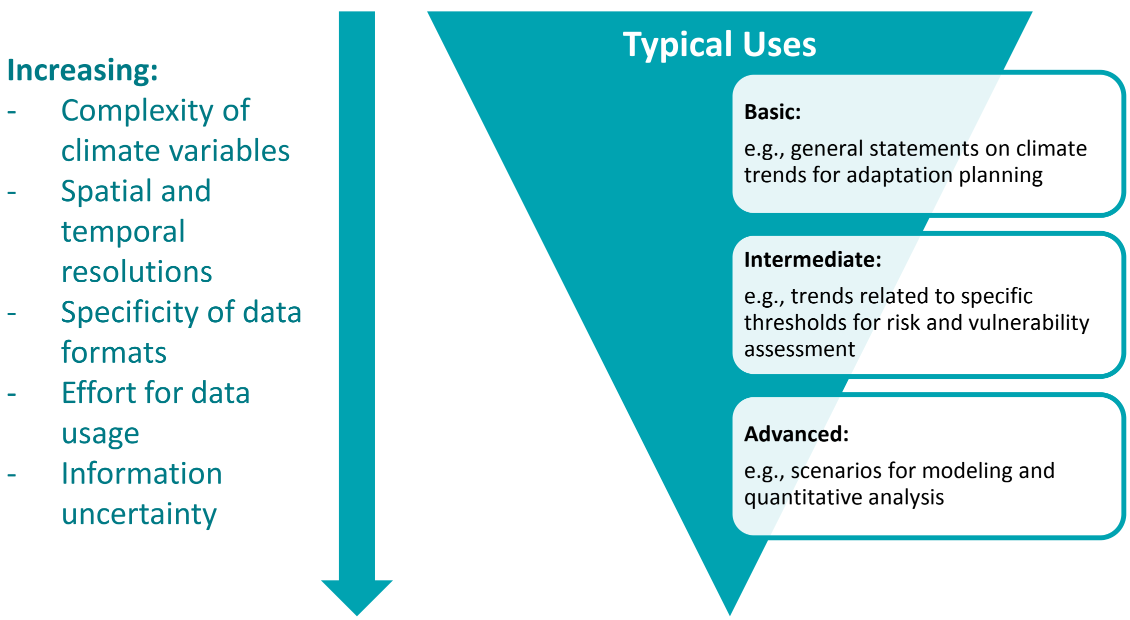


Figure 5: Schematic diagram showing the relationship between varying levels of climate information complexity and typical categories of users (adapted from Charron 2014).

In the Great Lakes Basin, the following three categories of climate information were identified as comprising the majority of studies:

(1) Simple trend analysis (Basic Information) – characterizing trends in general climate variables (e.g., temperature and precipitation) for various historical or future periods. An example would be determining the mean change in annual temperature and precipitation between a baseline and future period.

(2) Development and analysis of impact-specific indicators (Intermediate Information) – developing and analyzing specific indicators designed to represent the interactions of climate with a given system or impact under study. These indicators are typically defined using thresholds and may incorporate multiple climate variables, for example determining the return period for a rainfall event of a specified intensity and duration at given point location.

(3) Integration of climate information into dynamic models for impact assessment (Advanced Information) – inputting observed, synthetically adjusted or modelled climate time series into physically-based or statistical models, such as hydrologic, crop yield and ecological models. These secondary models (e.g., hydrologic, etc.) require localized climate information, often with the aim of translating climate projections into quantitative information related to a specific management theme and geographic area of interest.

Regardless of the type of climate dataset and its particular use in given study, all climatological analyses are ultimately derived from a time series. There are many choices users make when selecting a time series for analysis, and ultimately those choices influence research results. For historical datasets, choices pertain to properties such as duration, interval, number of missing records, location, and source (i.e., station, radar, satellite, gridded reanalysis, modelled, etc.). The number of dataset properties considered greatly increases when the time series of interest relates to future projections. When relying on future climate information, users need to select from a range of emission scenarios, global climate models, spatial and temporal downscaling and disaggregation techniques. As a result of large numbers of historical and future climate datasets used in Great Lakes climate change science, there is often significant variability in estimated changes in atmospheric variables and impacts. This variability ultimately translates into information uncertainty, particularly for future climate projections.

There is typically much greater variability in projections of future climate compared to historical observations for a given area (IPCC 2014). Natural spatial and temporal variability in climate can however, also be difficult to capture in historical datasets, which adds to overall uncertainty in climate change science. Levels of uncertainty are particularly heightened in locations or at scales where landscape features, such as topography and open water, influence atmospheric processes but may not be adequately captured in climate models or observed datasets. For example, convective precipitation is often cited as an atmospheric process that is difficult to capture accurately in both historical and modelled datasets (Giorgi 2009, Mailhot et al. 2012). Similarly, global climate models (GCMs) are often cited as being limited in their applicability for the Great Lakes Basin because many models do not explicitly incorporate the lakes themselves as open-water grid cells. Given the potential uncertainties associated with the climate information, in particular projection data, it is critical to understand how this information is being used in the scientific applications and the associated assumptions that may ultimately be embedded in results.

1.2. Overview of Climate Change Modelling and Analysis in the Great Lakes

1.2.1. Historical and Baseline Data

Historical and baseline climate information is often the basis for climate change science in the Great Lakes. It has many uses including characterizing historical trends, calibrating and validating climate models, and providing a reference for future projections, among many other uses. While Environment Canada and the U.S. NOAA collect and maintain official station-based climate and weather archives in accordance with World Meteorological Organization (WMO) standards, there are a range of products derived from these datasets that are often used in scientific applications to represent baseline conditions. Examples include reanalysis datasets used to produce spatially distributed estimates of climate variables; extreme rainfall statistics such as intensity-duration-frequency curves; and in-filled time series for used in dynamical modelling (e.g., see EBNFLO and AquaResource 2011). Based on a recent inventory of climate datasets covering the Great Lakes Basin conducted by the Ontario Climate Consortium, there are fourteen different historical data products derived from observations (Appendix 2). While each of these datasets has been validated independently, they are all slightly different in their accuracy and biases for a given study area. Therefore, the choice of historical dataset has the potential to influence ultimate results. In addition, radar and satellite products are being increasingly used to characterize observed climate; however, their use in climate change studies to date are minimal.

The selection of a baseline period for climate change impact analysis is a critical assumption within all climate change studies. It is difficult to compare changes among studies due to the fact that there are multiple possible ways in which baseline historical periods are defined and baseline periods have continued to evolve as data becomes available. Figure 6 provides an overview of the baseline periods used in various studies, and demonstrates that the majority of studies are using periods of between 20 and 40 year duration, which is consistent with the WMO guidelines for climatological analysis, however 19% of studies used periods of less than 20 years. The vast majority of studies use a baseline period beginning in the 1960s or 1970s, with fewer studies using a more recent baseline period beginning in the 1980s. The selection of baseline period is an important assumption because it is widely recognized that the signal of climate change in meteorological records is greater with time (IPCC 2014). The literature shows 1961-1990 is often chosen as a baseline period. The implication of selecting a later baseline period is that climatic changes may be less apparent.

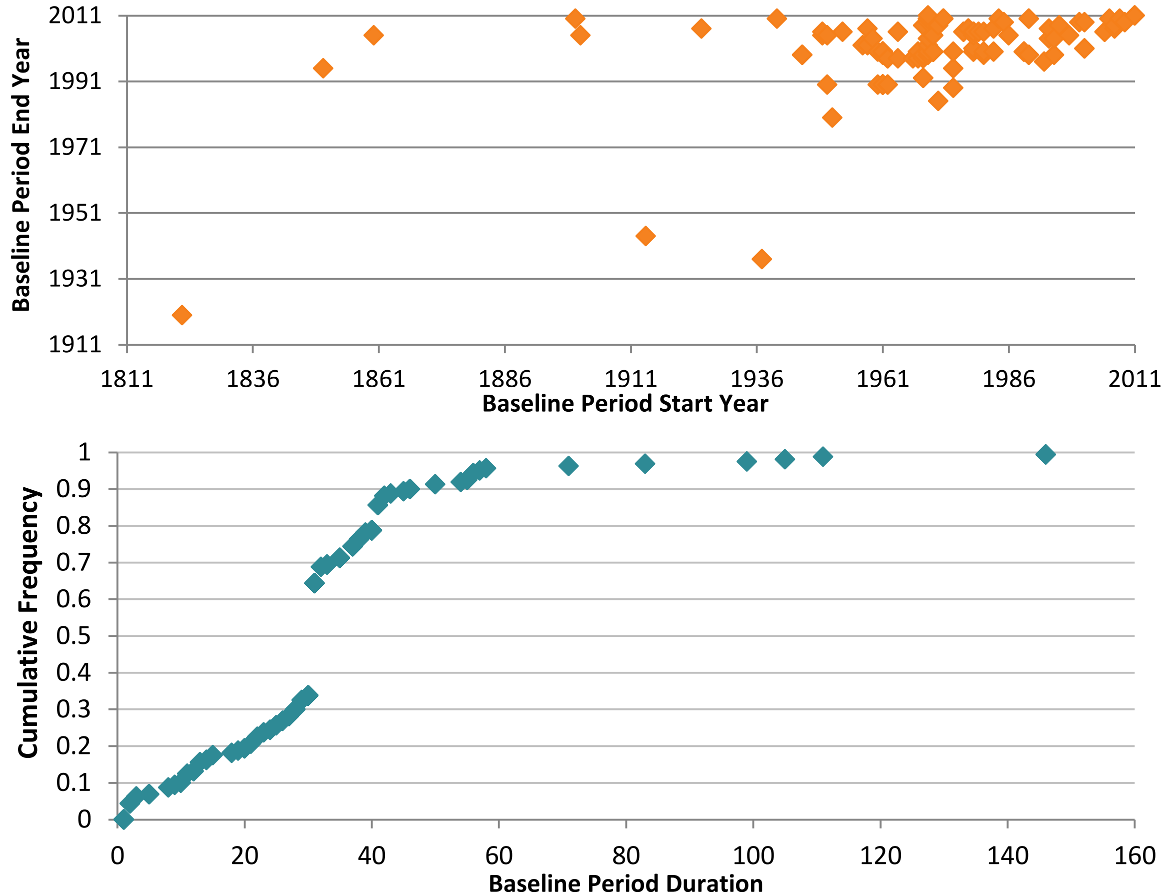


Figure 6: Scatterplot showing the distribution of start and end years for the baseline periods used in studies reviewed (Top Plot) and the cumulative frequency of different baseline period durations (Bottom Plot) (N = 161).

1.2.2. Evolution of Climate Modelling

Most scientific studies of climate change in the Great Lakes Basin rely on projections of future climate. It is important to acknowledge that while there are many downscaled products available in the Great Lakes Basin, each is ultimately derived from a global climate model (GCM). GCMs are dynamical system-based models that represent complex interactions between physical processes in the atmosphere, ocean, cryosphere and land surface, and they are currently the most advanced tools available for estimating how the global climate system responds to various natural and anthropogenic stresses, such as increasing greenhouse gas emissions. The next generation of climate models known as Earth System Models (ESMs) combine GCMs with models of other biological or physical processes, with the purpose of producing more comprehensive tools and results. There are a range of different GCMs and ESMs produced by modelling centres from around the globe, and each represents physical processes that influence climate differently.

Climate models are continuously being developed and, thus, the complexity and range of processes represented in these models have increased over time (Cubasch et al. 2013). Newer models feature improved parameterization of physical processes, such as cloud dynamics, mass convection, radiation balances and the indirect effect of aerosols in the atmosphere at finer horizontal and vertical resolution. For instance, the first generation of the Canadian Centre for Climate Modelling and Analysis (CCCMA) model, CGCM1, was developed in the 1990s (Flato et al. 2000). It has since been superseded by three newer versions, each of which represents new knowledge and state-of-the-art science, such as treatment of sea-ice and atmospheric components. The CCCMA is only one representation of a modelling centre that contributes climate change projections to the official body of science used by the IPCC.

There are currently 28 different climate modelling centres that have undergone similar evolutions in climate model development, resulting in a large repository of models available for Great Lakes climate science applications. Since each GCM provides a slightly different conceptualization of the earth-atmosphere system, there remains uncertainty in future projections, just based on the variety of models available. Additionally, although there have been many advances in climate modelling, the process of refining models leads to new scientific questions, the identification of which do not necessarily reduce overall uncertainty (Gober 2013). Finally, it is important to note that despite the breadth of climate models currently available, the history of GCM development shows there are only a handful of original independent models from which current model linages can be traced (Randall 2011), reinforcing the notion that advances in climate modelling doesn't necessarily reduce overall projection uncertainty.

1.2.3. Evolution of Emission Scenarios

When using climate models to analyze climate change, each model integrates atmospheric mass and energy inputs to represent a given set of future conditions associated with greenhouse gas emissions (GHG). The suite of emissions scenarios available to users has evolved over time. Early emission scenarios applied simple change factors to historical greenhouse gas emissions, such as a doubling of atmospheric concentration of CO_2, with no transient changes in emissions over time. In its 2007 Fourth Assessment Report (AR4), the IPCC developed a more advanced representation using various "storylines" of human development and their associated GHG pathways in the Special Report on Emissions Scenarios (SRES) (IPCC 2000). These scenarios are grouped into four storylines based on population and economic growth, technology and income distribution, among others (IPCC 2000).

In the most recent Fifth Assessment Report (AR5), the IPCC employed a new suite of scenarios, known as Representative Concentration Pathway (RCP) scenarios. RCPs represent different projections of radiative forcing, which is a "measure of the net change in the energy balance of the Earth system in response to some external perturbation" (IPCC 2014). Each RCP is framed as a combination of varying levels of emissions, adaptation and mitigation activities. While socio-economic considerations factor into the RCPs, they do not employ the same socio-economic storylines as the earlier SRES scenarios (Taylor et al. 2012). The RCPs also represent a greater range of projections in only four scenarios as opposed to the SRES's 40 possible scenarios. Figure 7 presents a comparison of key emission scenarios used in the AR4 and AR5 reports and demonstrates that RCP8.5 represents the greatest GHG forcing in the AR5 report and thus the greatest level of change among the RCPs. It corresponds roughly to the SRES A2 scenario and A1FI (not depicted). Scenario RCP2.6 is the lowest forcing scenario and does not correspond to any of the dominant SRES scenarios presented in Figure 7. RCP4.5 represents a moderate-forcing scenario and corresponds roughly to the SRES B1 scenario. Currently, evidence at the global scale shows emissions to be most closely aligned with the RCP8.5 scenario (Fuss et al.

2014). The SRES scenario A2 is known as the "business as usual" emission scenario, whose trajectory was mirrored by measured emissions (IPCC 2000).

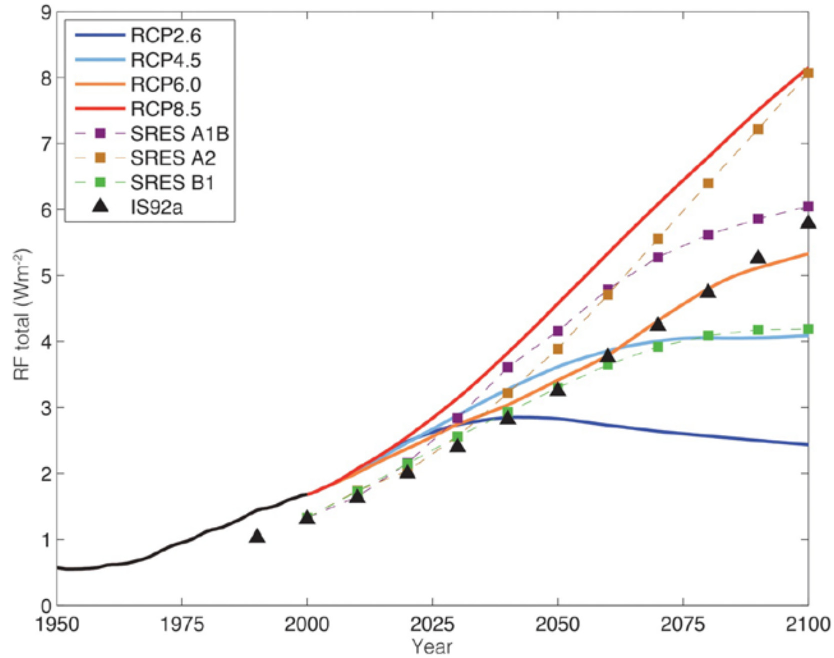


Figure 7: Comparison of various emission scenarios from AR4 and AR5 (from IPCC 2014). IS92a represents a 1%/annum increased in CO_2 from 1990 to 2100.

1.2.4. Downscaling for the Great Lakes Basin

A key attribute of global-scale climate models that has limited their accuracy in the Great Lakes Basin is the fact that most run at spatial scales often too coarse to capture the physical processes driven by important landscape features in the Great Lakes Basin, such as the Great Lakes themselves. As a result, numerous downscaling methods have been developed to translate coarse resolution climate projections into regional-scale climate information – an approach common for local and regional applications around the world. Nevertheless, there are still many assumptions embedded in all downscaling methods, which do not necessarily translate to improved accuracy of climate projections. Downscaling techniques are generally divided into the categories of (1) dynamical, and (2) statistical methods.

The goal of statistical downscaling is to develop statistical relationships that link large-scale variables represented in GCMs and ESMs with local or regional climate variables that are important to local dynamics. Several statistical downscaling methods are employed throughout the Great Lakes Basin, with the predominant ones being weather typing, regression models, machine learning, and weather generators. A key limitation of statistical methods is their relatively low accuracy in replicating sequences, or the serial properties, of historical time series (Wilby et al. 2004). Another commonly referenced limitation associated with statistical downscaling is its reliance on historical statistical relationships between observed variables, which may not hold true under future climate regimes defined by a different set of physical conditions (Wilby et al. 2014). These limitations are reflections of the fact that statistical downscaling does not explicitly incorporate the dynamic and complex physical processes that drive local climate.

Dynamical downscaling is another approach to localizing GCM and ESM outputs and is based on developing a Regional Climate Model (RCM), which contains equations and data inputs that aim to capture the unique climate physics of a region. This approach requires boundary conditions from GCMs to provide forcing data for the RCM. While RCMs can represent local-scale features and certain physical processes more effectively than statistical downscaling, RCMs are computationally intensive to develop and run, require substantial amounts of input data, and rely on more detailed algorithms for representing the earth-atmosphere interaction and dynamics, many of which aren't fully understood.

It is important to note that both types of downscaling approaches are impacted by the uncertainty associated with the GCMs or ESMs used as inputs. Each climate model has certain biases and, as a result, these can be propagated through downscaled datasets in chaotic and unpredictable manners. Additionally, because downscaling methods also contain their own assumptions and may introduce biases into projections, simple de-biasing methods are also used to adjust future projections. One common approach to addressing this limitation has been to express changes in climate using differences between modelled historical and future periods, thus removing any absolute bias in models. This approach is often termed the "Delta Method," and has been the primary mode of generating spatially distributed projections of climate projections by applying the calculated "deltas" to historical station or gridded data contained within a given GCM or ESM cell. This is the approach used in many existing datasets used throughout the Great Lakes Basin, including AquaResources Inc. and EBNFLO Environmental (2011), McKenney et al. 2011a, Reclamation (2013) and IPCC (2014); however, the techniques for applying these data to historical records have varied among these datasets.

The use of multiple models and scenarios in an ensemble has evolved as a common approach to addressing the uncertainty associated with having a diverse range of individual scenarios (Collins et al. 2013). The use of these multi-model approaches is becoming more common because they reduce signals associated with individual model bias and provide an overall picture of general trends, representing a weight-of-evidence approach. For instance, the Fifth Coupled Model Intercomparison Project (CMIP5) ensemble was a major input for the AR5. The CMIP5 considers hundreds of different model runs from almost 30 modelling centres.

Much of the climate change modelling and analysis in the Great Lakes Basin, has been motivated by a desire to improve the accuracy of lake water levels, water quality impacts and climate processes directly related to the lakes (such as lake-effect snow). Initial work on water levels used the results from equilibrium-response experiments, focusing on temperature, precipitation, evaporation, water levels and river discharge (Mortsch et al. 2000). In these studies, $2 \times CO_2$ equilibrium climate scenarios were used to study hydrologic changes across the Basin, such as open water and Basin-wide increases in evaporation and energy budgets (Lofgren et al. 2011; Mortsch and Quinn 1996). Subsequently, modelling experiments were used to simulate the response of the climate system to gradual increases in emissions, and they included ocean-atmosphere coupling and the effects of aerosols (e.g., Lofgren et. al. 2002). Researchers have also used climate simulations to project changes in a range of physical, chemical and biological properties of the Great Lakes. However, low horizontal resolution, poor representation of the soil and vegetation processes, poor representation of surface water, and poor representation of the linkage between energy (heat) exchange at the surface and evotranspiration, have been limitations in translating global-scale modelling into more refined localized analysis of physical processes, such as water levels, and evapotranspiration in the Great Lakes Basin (MacKay and Seglenieks 2013; Lofgren et al. 2011). Key advances of recent climate modelling in the Great

Lakes Basin have featured the integration of multiple nested RCMs and lake dynamic models (Notaro 2014, Gula and Peltier 2012,Wang and Huang 2013, Wang et al. 2013, 2014a, 2014b, 2014c, 2014d, D'Orgeville et al. 2014, Wang 2014e; Music et al. 2015).

As with historical baseline information, there is a range of future climate datasets that are used in scientific applications in the Great Lakes Basin. Each dataset represents a unique approach to generating future climate projections and, thus, makes different assumptions due to selection of the climate models, downscaling methods and emission scenarios; they, therefore, vary in their utility for a particular user.

1.2.5. Future Projection Uncertainty

One particular challenge in projecting climate change is that it depends on future human behaviour, which is largely unpredictable. For example, it is impossible to predict what will happen to the global economy in the future, and we do not know how much GHG emissions will increase. Therefore, different scenarios are used as plausible alternative futures to accommodate uncertainty and assess the range of possibilities. Another source of uncertainty is model imperfection; scientists are constantly advancing our collective understanding about how the Earth reacts to rising GHG emissions. This is tied to our understanding of the complex interactions between the earth's surface, atmosphere, and the human and natural processes that influence these dynamics. The climate is often characterized as a "chaotic system," which reacts in unpredictable ways (Taylor et al. 2012). Despite these fundamental sources of uncertainty, it is widely accepted that climate models and the use of scenarios are the most sophisticated analytical tool available for understanding complex systems and planning for an uncertain future.

Despite advances in climate modelling methods, no model produces a perfectly accurate representation of the climate system. For instance, climate model uncertainty is attributed to a model's representation of the climate and response to external forcing, which has inherent natural variability. Scenario uncertainty is linked to uncertainty about future emissions of GHGs and other forcing agents. Thus, the range of outputs produced by climate simulations does not cover all of the possible future climate changes (Brown 2012). Although model spread is frequently used as an indicator of climate response uncertainty in the literature, this measure is insufficient by itself, as it does not consider other factors such as model quality (Collins et al. 2013).

Furthermore, the use of process models forced with climate simulations adds further sources of uncertainty. For instance, projections of pollutant transport may rely on several process models in addition to climate information and scenarios. While advances in climate change science have improved the characterization of uncertainties in long-term projections, the magnitude of the uncertainties has not changed significantly (Collins et al. 2013). Overall, these sources of uncertainty create significant challenges for decision makers who must evaluate this information and, ultimately, act upon it. Stakeholder-based scenario planning is one approach for integrating climate projections with other sources of information on climate change impacts and system sensitivities to advance decision-making despite potentially large uncertainties (Wilby et al. 2014; Brown 2012). With respect to temperature, the difference between emission scenarios is regarded as the largest source of uncertainty, followed by the choice of global climate model and downscaling method (IPCC 2014). With respect to precipitation, the pattern is slightly different, with GCM selection being the largest source of uncertainty, followed by emission scenario (Wilby et al. 2014). It should be noted, however, that the sources of uncertainty associated with a given combination of climate model, emission scenario and downscaling method are not independent.

1.3. Recent Uses of Climate Information in Great Lakes Science

This section focuses on trends in the use of climate information within Great Lakes climate change research. The analysis was completed using results from a systematic review of scientific and grey literature conducted in the Great Lakes Basin (see Methods and Data section for details). A total of 254 studies were analyzed, covering a five-year time period from 2010 through 2014 (see Appendix 1). It should be noted that not all articles contained information on every aspect of climate information usage in Section 1.3. The number of studies with information pertaining to each aspect analyzed is presented in the associated figure captions. The 2010–2014 timeframe was chosen because it represents the most recent period for climate change research, and corresponds to the same timeframe during which CMIP5[1] modelling was completed and released for public usage. As such, it was felt that this timeframe would capture a surge of research using the updated CMIP5 climate information. Dataset usage is broken down by report theme, climate model and scenario chosen, the downscaling method, and approaches for uncertainty analysis. Ultimately, the aim of this analysis is to provide a sense of where and how climate information is being applied in the Great Lakes Basin.

1.3.1. Breakdown by Report Theme

Of the studies that used information based on either historical trend analysis or future climate scenarios, approximately 49% applied to study areas located in Canada, 14% were determined to cover geographies on both sides of the border, and 36% were categorized as being applicable to only the U.S. There may be a slight bias toward Canadian studies due to inclusion of information from the Canadian DFO and Ontario MNRF research synthesis, however, the academic literature search was designed to capture all studies published in any of the Great Lakes Basin states, provinces and Lake drainage basin.

With respect to the study themes, the vast majority of studies using climate information pertain to water levels and hydrology, climatology (including new methods for downscaling and analysis), and various aspects of ecological modelling (Figure 8). Additional details on how these projections are used within the themes pertaining to hydrology and water levels, and ecological applications are provided in Part 2 of this report.

Climate change projections are frequently used as inputs for other types of models to project the response of a range of physical and biological processes, such as ecosystem dynamics or water levels. A diverse range of process models were used in the reviewed research to study climate change impacts on many aspects of the Great Lakes Basin, including water quality, fire occurrence and snow accumulation. Hydrological models were most commonly used, followed by ecosystem models and bioclimatic envelope approaches to assess changes in ecosystems and species range (Figure 9). Commonly applied hydrological models include the Soil and Water Assessment Tool (SWAT), the Variable Infiltration Capacity (VIC) model and the Hydrologiska

[1] CMIP5 – is a framework for the study of the output of global coupled ocean-atmosphere general circulation models.

Byråns Vattenbalansavdelning (HBV) model, which were applied to study both rivers and lakes in the basin (Figure 9).

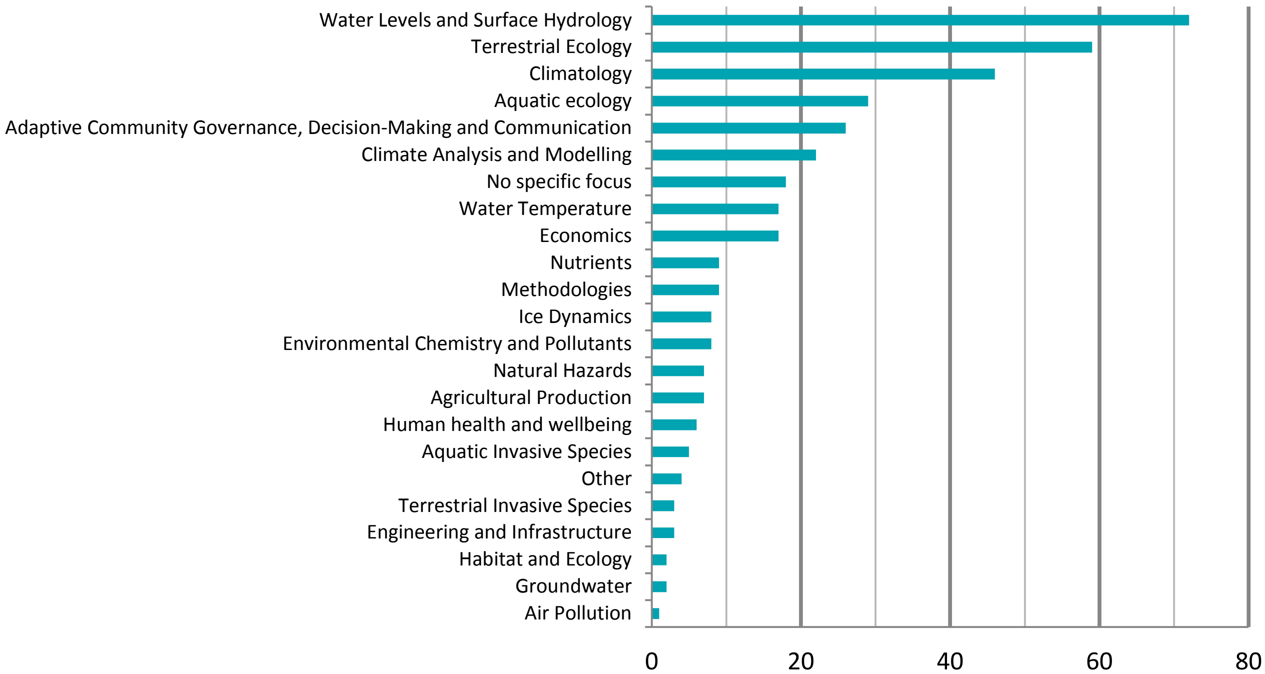


Figure 8: Number of studies associated with different research themes of the total 254 studies reviewed.

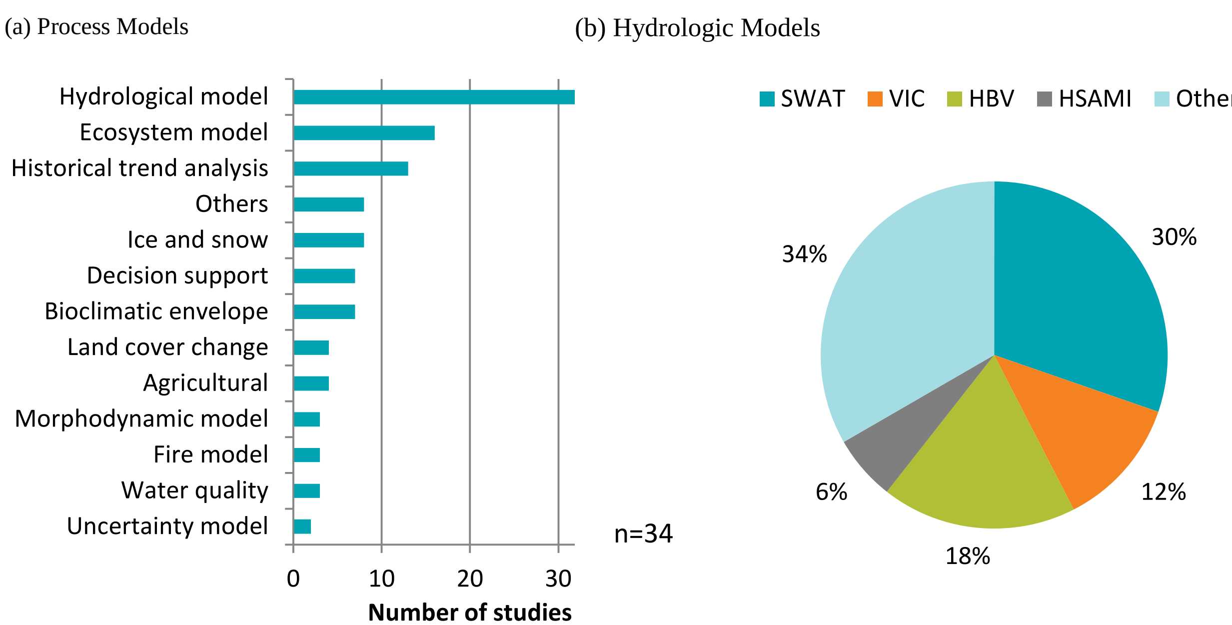


Figure 9: Breakdown of (a) process models using climate scenarios as inputs and (b) hydrologic models among the studies reviewed. Specific models and usage in individual studies can be found by consulting the accompanying knowledge database.

1.3.2. Climate Models and Scenarios

The largest proportion of the research reviewed used various generations of the Canadian Centre for Climate Modelling and Analysis (CCCMA) Coupled Global Climate Model (CGCM), followed by the Hadley Centre Coupled Model (HadCM) and the Geophysical Fluid Dynamics Laboratory (GFDL) model (Figure 10). Four generations of the CGCM were used in the reviewed research, with most applying the CGCM3 model, which was also used in the IPCC AR4 report. The most recent CGCM4 model was reported in a small number of studies (Figure 11). Ensembles of multiple models are increasingly common. Some studies used small sets of climate models. In cases where ensembles of eight or more models were used, they were grouped into their own category for the analysis; however, these represent a small proportion of modelling studies. An examination of the research in the review period showed an average of 2.3 models were used per study, with 34% using only one model and 12 % using four or more. Research using large ensembles (more than eight) was generally focused on climatology or hydrology.

A range of emission scenarios were used in the reviewed research (Figure 12). Most corresponded to the four SRES scenarios A1, A2, B1 and B2 from the IPCC AR4 report, some of which are shown graphically in Figure 7. Some of the research used simple projected temperature ranges. For instance, Steen et al. (2010) used a temperature increase of either 3 or 5°C in a classification tree model to estimate the probability of game fish presence. The A2 scenario that projects the most extreme future was used most often as a 'worst case' scenario. The lowest-forcing B1 scenario was also applied frequently. Many studies used both the A2 and B1 scenarios to capture the spread of SRES emission scenarios. On average, studies used two scenarios in their research. In addition, earlier scenarios (such as 2 x CO_2) were used infrequently in the reviewed research. The IPCC AR5 report was released in 2013; therefore, only a small proportion of research applied the updated RCP scenarios (Figure 12).

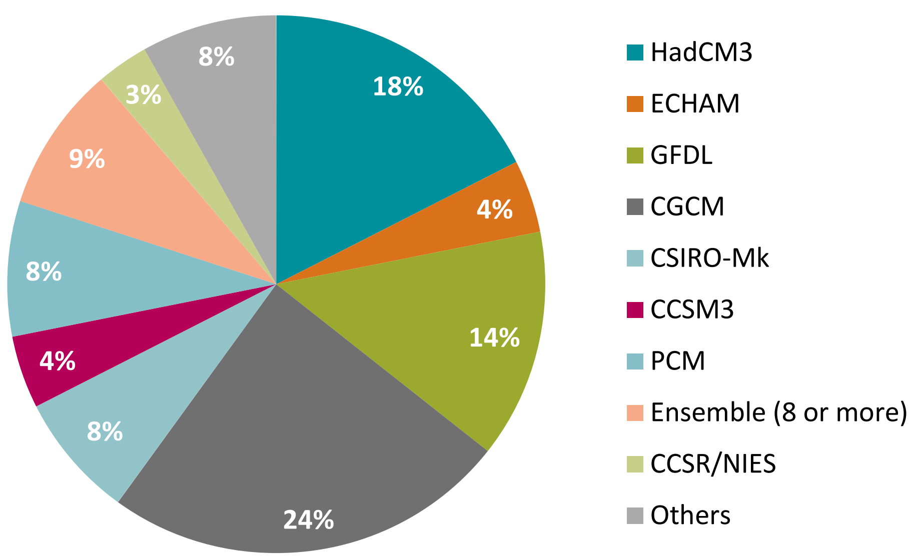


Figure 10: Breakdown of percentage of different global climate models used in studies reviewed. (N = 180).

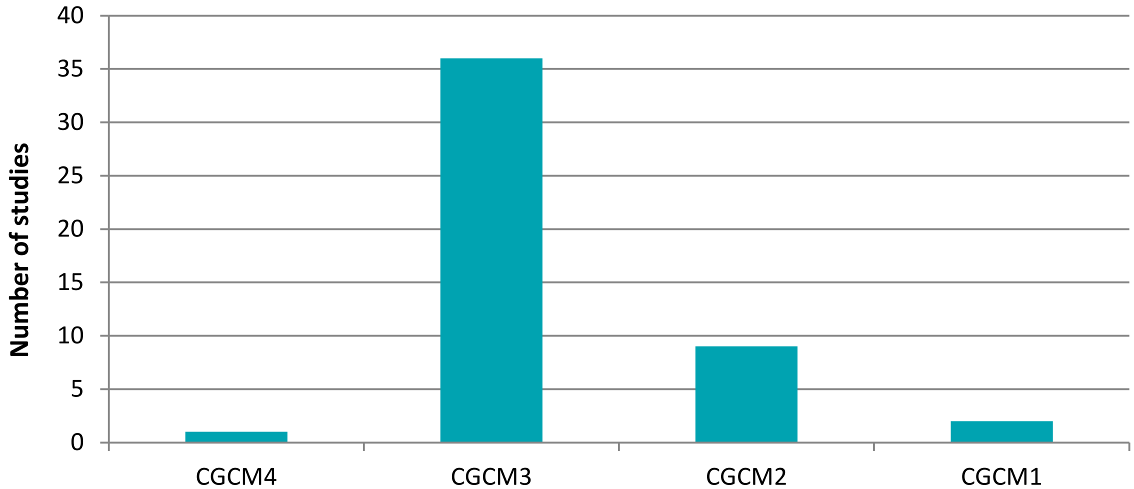


Figure 11: Breakdown of different versions of the Canadian Global Climate Model used in the studies reviewed (N = 180).

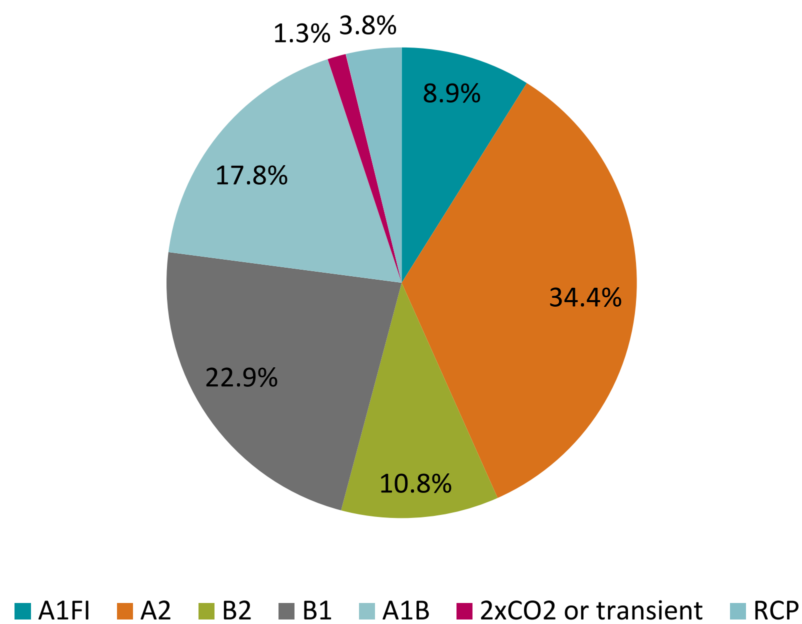


Figure 12: Percent breakdown of the emission scenarios used in the studies reviewed (N = 180). Average of 1.9 scenarios used per study (Scenarios A1 and B21 = 0).

1.3.3. Downscaling

Downscaling methods were used in the majority of climate modelling studies included in the review. For this analysis, they are divided into the following categories: dynamical modelling (RCM); synoptic weather typing; weather generators or perturbation of historical observations; the delta method; other statistical methods, such as bias correction and disaggregation; and none (raw GCM was used).

Statistical methods (bias correction and disaggregation) were the most commonly used downscaling method (Figure 13), and were most commonly used for temperature and precipitation (see Appendix 3 for a full listing of downscaled datasets). However, new advances have recently emerged in the area of wind downscaling (Kirchmeier et al. 2014). Dynamical approaches were used less in the reviewed research, and included the Canadian RCM (de Elia and Côté 2010, Music and Caya 2007) and multiple models from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009), as well as RegCM3 models.

A small number of studies applied a combination of both techniques. For instance, in a water levels study, MacKay and Seglenieks (2013) applied a cascade with the CRCM developed for Great Lakes applications (GLRCM) and combined this dynamical approach with bias correction of simulated net basin supply. Combined downscaling methods have also been applied for future flow estimation in ungauged basins (Samuel et. al 2012). Additional examples of high-resolution dynamical modelling that explicitly incorporate the Great Lakes are Gula and Peltier (2012), Notaro et al. (2014); Wang et al. (2013, 2014a, 2014b, 2014c, 2014d), D'Orgeville et al. (2014), Kirchmeier et al. (2014), Wang 2014e, Music et al. (2015). However, most of these more recently developed datasets are quite new and, therefore, are not as readily available or commonly used in scientific applications examined for this analysis.

It should be noted that a significant challenge in conducting this analysis was the limited amount of information available on how downscaling was conducted. Often, descriptions of climate change information were vague, which, in addition to posing difficulty in this meta-analysis and methods assessment, it makes it difficult for studies to be replicated. Within the studies reviewed, authors often recognized the need to include information on which global climate models were selected, however information on downscaling, emission scenarios and other data processing techniques were not described with sufficient detail.

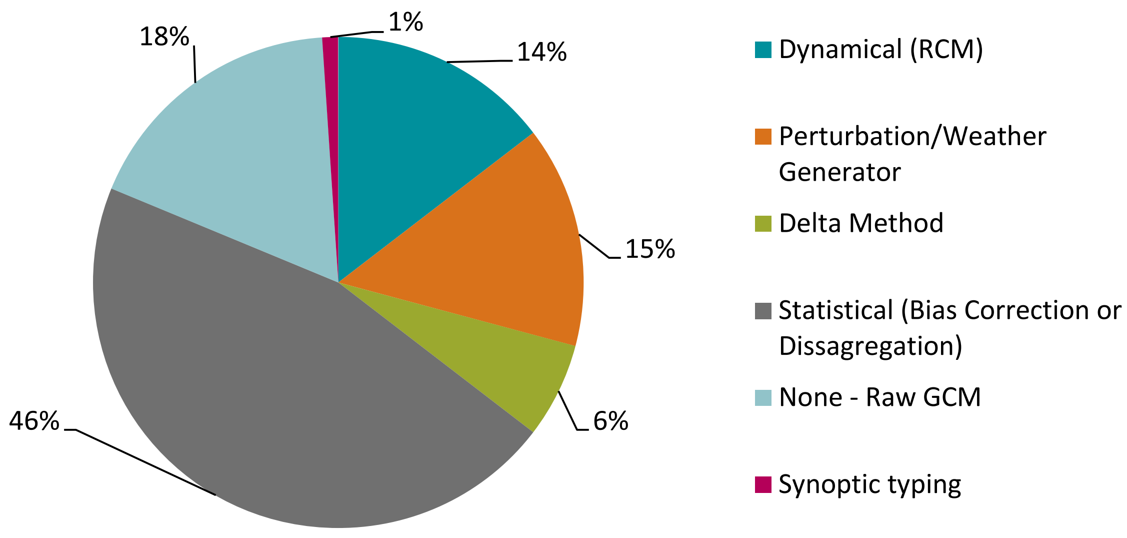


Figure 13: Percent breakdown of the use of different kinds of downscaling methods among the studies reviewed (N = 96).

1.3.4. Uncertainty Analysis

Studies that used a limited number of climate models or scenarios are less able to characterize the large uncertainty associated with estimating possible climate futures. Even where uncertainty was addressed by using an ensemble of climate model projections (i.e., using multiple models and/or scenarios to establish a range of projection values), it is important to note that other factors, such as model parameterization, performance and the variable under study are also potential ways of communicating uncertainty (Collins et al. 2013). Downscaling can also introduce uncertainty, such as in the case of an extreme rainfall study where only one station was used for a weather generator method (Peck et al. 2012). Few studies however, use multiple downscaling methods or thoroughly investigate natural spatial and temporal climatic variability, which can have a large influence on overall uncertainty associated with some variables, such as wind and precipitation. In addition, future conditions may be beyond the observed range, such as in the case of fire-weather values, leading to uncertain interactions (Boulanger et al. 2013). Finally, gaps in historical data can present a barrier to estimating changes in ecosystems with trend analysis methods.

Of the 254 articles reviewed, approximately half described their uncertainty analyses in detail. While it is difficult to categorize individual studies because uncertainty analysis methods vary widely among the articles reviewed, some dominant techniques of uncertainty analysis emerged:

- Bayesian Theory combined with Markov Chain Monte Carlo (MCMC) approach;
- sensitivity analysis of process models with respect to climate, such as Monte Carlo approaches;
- validation of future datasets using model performance metrics;
- statistical tests using significance levels to compare changes and trends;
- graphical comparisons of trends, statistical distributions and ensemble ranges; and
- qualitative descriptions of sources of uncertainty.

Bayesian Theory combined with MCMC has been widely used to quantify uncertainties associated with global or regional climate projections (Wang et al 2013, Wang 2014e, Wang et al. 2014a). Many reviewed studies used process models to study the impacts of climate change on ecosystem processes; these have their own limitations and assumptions, such as assuming no land use changes or disturbances. For instance, Verhaar, et al. (2011) used a morphodynamic model (SEDROUT4-M) with inputs from a hydrological model (HSAMI) to study bed transport in St. Lawrence tributaries, and they note that more advanced 2D models would be needed to simulate erosion. Many of the same approaches used in climate model uncertainty analysis were also employed to analyze process models. Additionally, the output of process models are often analyzed as the sole source of total uncertainty for a given project.

PART 2. DATA CONFIDENCE ASSESSMENT OF GREAT LAKES CLIMATE CHANGE SCIENCE

Climate change has significant implications for the physical and chemical environment, ecosystems, and society. While research on the consequences of climate change on these systems is growing through the incorporation of climate change scenarios into current environmental and socio-economic models, there remains uncertainty and challenges. One such challenge is our understanding of how climate change scenarios (e.g., GCM, RCMs or other methods) can best be used to assess sensitivity, vulnerability, adaptation options and resilience. Given the inherent uncertainties in climate change, all assessments and associated decision making will be done under varying degrees of uncertainty. The challenge is how to use climate change assessment information to inform the decisions knowing the implications of this uncertainty.

To address the variability of information available among themes, an assessment of data confidence for the environmental themes was conducted. A group of research practitioners were assembled representing expertise on the physical and chemical effects of climate change and the impacts it may have on ecological biodiversity in the Great Lakes Basin. The group of 66 researchers and practitioners were brought together at the MNRF’s 1st Annual Climate Change Symposium: Ecosystem Vulnerability in the Great Lakes Basin on November 25 and 26, 2014 in Peterborough, ON. Data confidence was assessed using the same matrix framework used by the IPCC (Mastrandrea et al. 2010, see Figure 4), which requires a relative ranking based on the “agreement of information,” the “evidence strength (type, amount, quality),” and any self-identified limitations in the literature reviewed. Based on the expertise and area of study of participants, individuals independently ranked data confidence for two themes, including the sub-thematic topics. The individual experts were then assembled into a group and landed on a group consensus for the themes. Figure 4 shows examples of data confidence ranking for two themes (the effects of climate change on lake water temperature and alterations to wildlife habitat). In addition to the data confidence ranking, experts were asked to identify additional knowledge gaps in their themes (Part 4). The final rankings of data confidence from the expert review are provided in Table 2.

In Part 3, a literature review has been compiled of the impacts of climate change on the physical, environmental chemistry, ecosystems, and social systems of the Great Lakes Basin. However, the quantity and quality of data available for each thematic topic differs (themes assessed are listed in Table 2). As a result, a data confidence ranking has been provided for each of the thematic literature reviews in Part 3 to provide an assessment of how to interpret the information reviewed, the confidence one may place in the available science, and the conclusions one may draw from it. The data confidence has been represented by the following logos: representing low data confidence and to interpret with caution, medium data confidence, and high data confidence.

Table 2: Data confidence for each of the thematic topics reviewed in Part 3.

	Theme	Data confidence
Physical Effects	**Climatology**	
	Air temperature	high evidence high agreement
	Precipitation	high evidence medium agreement
	Drought	low evidence high agreement
	Wind	low evidence low agreement
	Ice storms	low evidence low agreement
	Water temperature	
	Lakes	high evidence low agreement
	Rivers	low evidence high agreement
	Wetlands	low evidence low agreement
	Water levels and surface hydrology	
	Lakes	high evidence low agreement
	Rivers	low evidence high agreement
	Wetlands	low evidence low agreement
	Ice dynamics	
	Lakes	medium evidence high agreement
	Rivers	low evidence low agreement
	Groundwater	low evidence low agreement
	Natural Hazards	
	Flooding	medium evidence medium agreement
	Fire	medium evidence medium agreement
Environmental Chemistry and Pollutants	**Oxygen**	low evidence low agreement
	Acidity (ph)	low evidence low agreement
	Phosphorus	low evidence low agreement
	Nitrogen	low evidence low agreement
	Carbon	low evidence low agreement
	Mercury and other organohalogens	low evidence low agreement

	Theme	Data confidence
Ecological Effects and Biodiversity	**Aquatic species**	
	Range shifts	medium evidence medium agreement
	Genetic changes	low evidence low agreement
	Altered phenology	low evidence low agreement
	Habitat alteration	medium evidence medium agreement
	Trees and plants	
	Range shifts	medium evidence medium agreement
	Genetic changes	medium evidence medium agreement
	Altered phenology	medium evidence medium agreement
	Habitat alteration	medium evidence medium agreement
	Wildlife	
	Range shifts	medium evidence medium agreement
	Genetic changes	low evidence low agreement
	Altered phenology	medium evidence medium agreement
	Habitat alteration	medium evidence medium agreement
	Pathogens and parasites	
	Aquatic	low evidence low agreement
	Trees and plants	low evidence high agreement
	Wildlife	low evidence low agreement
	Invasive species	
	Aquatic	low evidence high agreement
	Trees and plants	low evidence high agreement
	Wildlife	low evidence low agreement

PART 3. A SYNTHESIS OF CLIMATE CHANGE IMPACTS AND VULNERABILITIES IN THE GREAT LAKES BASIN

3.1. Physical Effects

3.1.1. Climatology

Data confidence

Air Temperature

Over the last 60 years (1950-2010), the Great Lakes Basin has experienced an increase in average annual air temperature between 0.8-2.0°C (Lemieux et al. 2007, McKenney et al. 2011a, Vincent et al. 2012). Warming has occurred across all four seasons, with the greatest temperature increases occurring in the winter and spring (McKenney et al. 2011a, Zhang et al. 2011). This warming trend is projected to continue over the next century with model results showing 1.5-7°C increases in average temperature depending on the emissions scenario applied (Lofgren et al. 2002, Hayhoe et al. 2010, McKenney et al. 2011a; Figure 14). Mean annual air temperature is projected to increase more in the northern portion of the Great Lakes Basin compared to the south (Figure 14). Minimum air temperature is projected to increase more than maximum air temperature (Colombo et al. 2007, Hayhoe et al. 2010, McKenney et al. 2011a, Price et al. 2011, Zhang et al. 2000). Climate change modelling results also show air temperature increases to be greater in winter months, meaning fewer frost days per year (Hayhoe et al. 2006, Gregg et al. 2012).

Warmer minimum temperatures have already been observed to have produced longer frost-free periods and, consequently, a longer growing season. Growing seasons have advanced by 1-1.5 days per decade during the past 50 years (Schwartz et al. 2006), which is important for plants, aquatic primary productivity and fish, whose life cycles are all highly dependent on temperature. Extreme heat events are also projected to increase in frequency and intensity (Gao et al. 2012; Cheng et al. 2012c), which has important consequences for habitat, particularly for aquatic ecosystems.

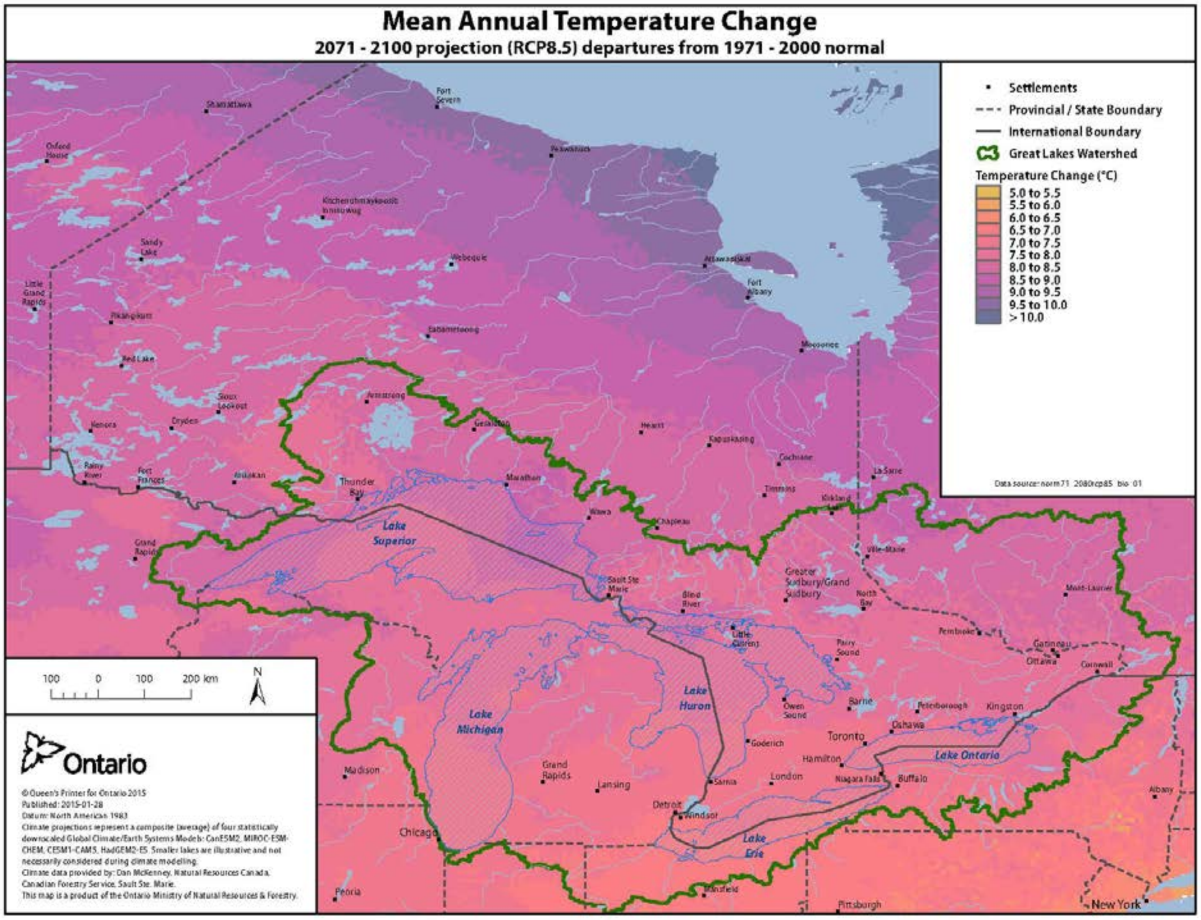


Figure 14: Projected changes in mean annual air temperature by 2071-2100 forced by the IPCC RCP 8.5 Watts/m^2 scenario. Climate projections represent a composite of four statistically downscaled (delta method) Earth System Models: CanESM2, MIROC-ESM-CHEM, CESM1-CAM5, HadGEM2-ES. Climate data was provided by D.W. McKenney (Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie, ON).

Data confidence

Precipitation

Changes in precipitation patterns have been observed in the Great Lakes Basin from 1950 to 2000 with conditions becoming slightly wetter; however, these changes fall within the variability of annual precipitation over time (McKenney et al. 2011a). In the next century, annual precipitation is expected to increase by up to 20% across the Great Lakes Basin with greater annual precipitation projected for Lake Superior (Lofgren et al. 2002, McKenney et al. 2011a; Figure 15). Lake effect precipitation continues to be observed in future projections and is projected to increase due to decreasing ice cover on lakes (Burnett et al. 2003, Notaro et al. 2014; Figure 15). Smaller increases in precipitation may not be sufficient to offset the more significant projected rises in temperature and, as such, may lead to drier conditions. The form of precipitation is also expected to change, with more precipitation falling as rain and freezing rain and less as snow. Shifts in the timing of precipitation are expected, where rainfall will increase in the spring but decrease in the summer (Kling et al. 2003, Hayhoe et al. 2010). Heavier downpours are currently twice as common as they were a century ago, and this trend is expected to continue in the 21st century (Changnon and Kunkel 2006).

The largest snowfall losses in North America are projected for the Great Lakes Basin with declines of up to 48.1% by the late twenty-first century (Notaro et al. 2014). These declines in snowfall are also projected to delay the onset of the snow season (Notaro et al. 2014). The Great Lakes Basin is projected to experience fewer snow events; however on the Canadian side those snow events are likely to be more intense (Notaro et al. 2014).

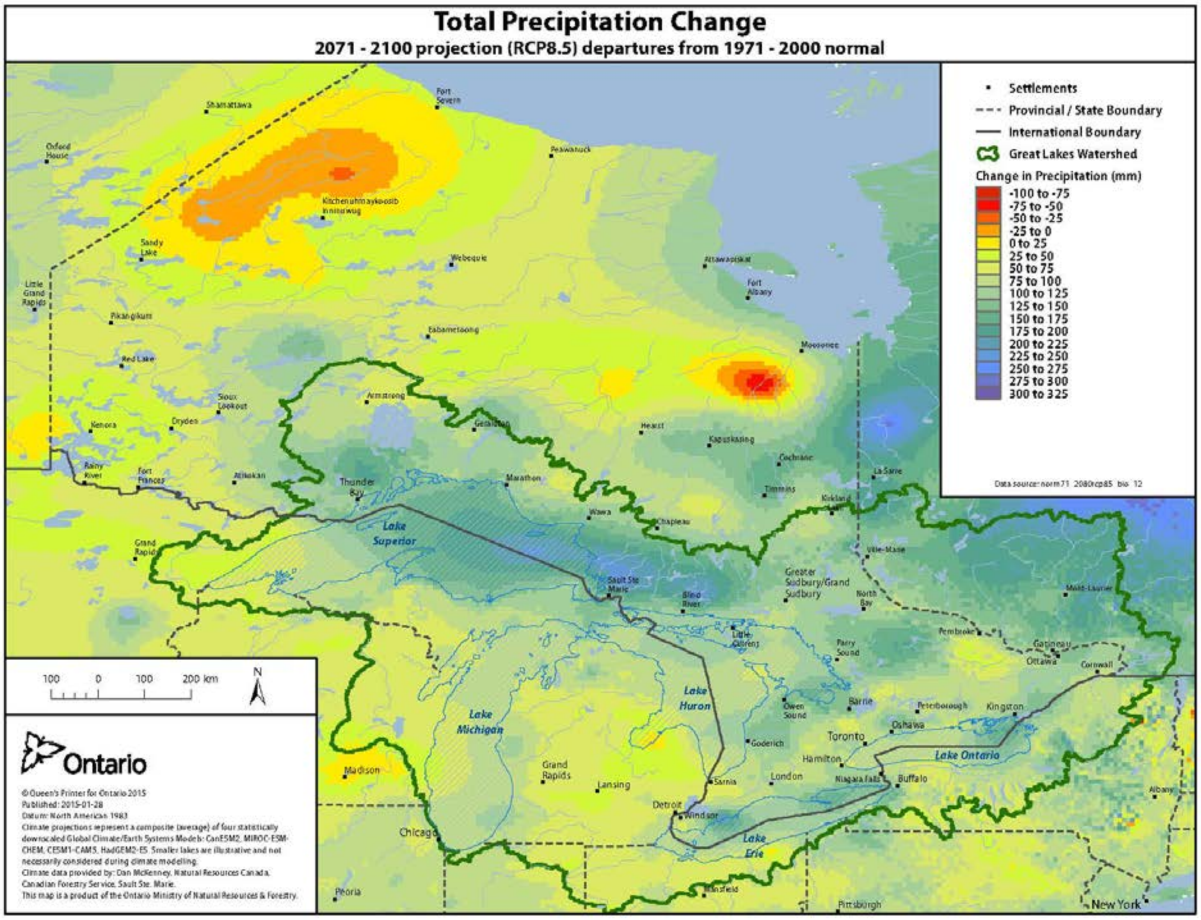


Figure 15: Projected changes in annual precipitation by 2071-2100 forced by the IPCC RCP 8.5 Watts/m2 scenario. Climate projections represent a composite of four statistically (delta method) downscaled Earth System Models: CanESM2, MIROC-ESM-CHEM, CESM1-CAM5, HadGEM2-ES. Climate data was provided by D.W. McKenney (Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie, ON).

Data confidence

Drought

In North America, there has been a trend toward increasing droughts since the 1950s including in the upper Great Lakes Basin, though droughts in this region tend to be less intense and of shorter duration (Burke et al. 2006, Bonsal et al. 2011). Prolonged drought is one of the most costly natural disasters for Canada, having numerous socio-economic impacts, ranging from impacts on agriculture and aquatic ecosystems to human health and recreation (Bonsal et al. 2011, Jeong et al. 2014). Environmental damage also increase under drought conditions, such as wetland loss, ecological habitat destruction and reduced water quality. Studies have suggested that there will be increased precipitation in the winter and decreased precipitation in the summer months in the Great Lakes Basin (see section 3.1.1 Precipitation; Bush et al. 2014). A modelling study conducted by Colombo et al. (2007) suggests that precipitation in the Lake Erie/Lake Ontario basins will decrease by 10% in the warm season and increase by 20% in the cold season. Decreased summer precipitation, combined with increased temperatures and evapotranspiration are projected to result in large increases in future drought risks for most parts of the United States and southern Canada (Burke et al. 2006, Bonsal et al. 2011, Jeong et al. 2014). One study modelled projections using an ensemble of eight GCMs and found decreased soil moisture for most regions of the world (Sheffield and Wood 2008). For central and eastern North America, short-term and long-term droughts were projected to become more common, as did the spatial extent of these droughts (Sheffield and Wood 2008). Another study using RCM found that long term and extreme droughts would become more prevalent in the Basin in nearly all of the 10 GCMs investigated (Jeong et al. 2014).

Data confidence

Wind

Wind is a difficult variable to assess using climate models because of the localized nature of gusts and the fine-scale land and atmospheric process that generate wind. Few studies have examined how climate change might alter wind patterns in the Great Lakes Basin. Nonetheless, it is possible to make some inferences on how wind may change in the future.

Increasing air and surface water temperatures and a reduction in the gradient between air and water temperatures in the Great Lakes may cause wind speeds to increase as the lower atmosphere becomes more unstable and atmospheric turbulence increases (Austin and Colman 2007, Desai et al. 2009, Huff et al. 2014). As a result of climate change, wind speeds are also projected to become more variable within and between years (Pryor and Barthelmie 2010). Austin and Colman (2007) found that open-water wind speeds on Lake Superior increased by 0.05 m/s per year from 1979 to 2005, which is significant when compared to mean summer wind speeds of 4 to 6 m/s. Trends in Lake Superior show that summer wind speeds have increased more than in other seasons (Austin and Colman, 2007). Yao et al. (2012) found through modelling that wind speeds in the Great Lakes Basin will decrease by 1% to 3% by 2071-2100. This decrease, however, is an average and extreme events are likely to have higher wind speeds. A study conducted for southwestern Ontario, projected more wind gusts by the end of the century (Cheng et al. 2012b). Wind gusts in excess of 90 km/h are expected to increase by 70% for the 2046-2065 period compared to the 1994-2007 period under an A2 scenario (Cheng et al. 2012b).

Wind is an important force in the structure and function of lake ecosystems because it provides energy for waves, is a principal force for lake currents and shifting ice cover, and influences the thermal regime of lake water (Derecki 1976, Ryder and Pesendorfer 1988). Increases in the frequency, duration and average speed of wind could cause a number of changes to inland and Great Lake aquatic ecosystems, including increased evaporation rates of lake water, increased speed of ice-out in spring, increased wind erosion and storm damage along coastlines, and increased deposition of wind-blown sediment in rivers, lakes and wetlands (Dove-Thompson et al. 2011). Increased wind speeds may also affect thermocline depth and bio-geochemical cycles (Austin and Colman 2007, Desai et al. 2009).

In 2011, numerous high wind events, including an F4 tornado, destroyed parts of Goderich along the Lake Huron coast, and numerous other tornados damaged infrastructure and forests throughout the Basin (Francis et al. 2011). Blowdown and wind erosion will potentially emerge as serious concerns for terrestrial ecosystems in coming decades. Blowdowns can become a fire hazard as the fallen biomass becomes increasingly drier and more likely to combust. Also, damaged trees are more susceptible to pathogen invasion and mortality (Ayres and Lombardero 2000, Flannigan et al. 2000). Wind erosion affects agricultural lands and sandy soils, which can result in soil and nutrient losses, and reduced crop yields (Natural Resources Canada 2000). Risk is increased with drier conditions resulting from changes in the timing and amount of precipitation and changes in temperature (Natural Resources Canada 2000). Using a limited ensemble of downscaled climate projections, Lee (2012) demonstrated that F2 and stronger tornado days will increase anywhere from 3.8 to 12.7% by the 2090s. This same research showed that the Lower Great Lakes are projected to experience an increase in tornado days, while the Upper Great Lakes states experience a decrease (Lee 2012).

Data confidence

Ice Storms

Ice storms can have significant impacts on communities and the natural environment. These storms occur in the winter when temperatures fluctuate around 0°C and humidity is close to 100%. Rain becomes supercooled when passing through cold air just above the surface thus creating a layer of ice on whatever surface it lands on. The ice then begins to coat objects such as power lines and tree branches causing breakage (Gay and Davis 1993).

Ice storm damage ranges from breakage of individual branches to the destruction of entire forest stands and, if drought follows, the risk of fire increases (Irland 2000). Ice storms have the potential to accelerate forest succession since early successional species sustain greater damage and have less capacity to grow new branches than later successional species (Brommit et al. 2004). Ice storms also have the potential to alter the species composition of the Great Lakes Basin forests because of differences in the level of crown damage that can be sustained by species. White Oak (*Quercus alba*), Red Oak (*Quercus rubra*), and many Pine species (*Pinus* spp.) are more tolerant to crown damage and will likely become more prevalent in the forest canopy if severe ice storms increase in intensity and frequency, and Eastern White Pine (*Pinus strobus*), American Beech (*Fagus grandifolia*) and Trembling Aspen (*Populus tremuloides*) will become less prevalent (Brommit et al. 2004).

One of the most extensive ice storms occurred in 1998 and affected 62 million hectares covering much of eastern Ontario, western Quebec and northeastern United States (Irland 2000, Chiotti and Lavender 2008). In that storm, eastern North America received 80 mm or more of freezing rain (Lecomte et al. 1998). This storm caused 28 deaths, cost more than $5.4 billion in damages and left 250,000 people in Ontario without power for up to 24 days (Lecomte et al. 1998, Kerry et al. 1999). The 2014 ice storm in Toronto affected a smaller area in the Great Lakes Basin but had similar types of impacts on communities and the natural environment.

While the frequency of ice storms was originally projected to increase with climate change in the Canadian side of Great Lakes Basin (Dale et al. 2001), more recent estimates from across Ontario have suggested that such changes aren’t certain (Cheng et al. 2011). Modelling by Cheng et al. (2007) suggested that freezing rain events could increase by 45 to 135% by the 2080s, with a greater increase occurring in the northern Great Lakes than the southern Great Lakes (Cheng et al. 2007). Cheng et al. (2011) demonstrated however, that for many parts of Ontario changes in freezing rain frequency were not discernable when a larger ensemble of GCMs were analyzed. Meanwhile, the United States side of the Basin may experience fewer freezing rain events in part due to the warmer temperatures at lower latitudes and the urban heat island effect (Lambert 2011). Evidence from finer-scale downscaling studies focussed on snowfall, such as Gula and Peltier (2012) and Notaro et al. (2011), does suggest that there will be less instances of snowfall, however more intense winter rain and snow, particularly in snowbelts, is likely.

3.1.2. Water Temperature

Data confidence

Lake Temperatures

Increasing water temperatures are projected to impact both inland lakes and the Great Lakes. In the last century, surface water temperatures of the Great Lakes have increased by as much as 3.5°C (Austin and Colman 2007, 2008, Dobiesz and Lester 2009, Minns et al. 2011). Lake Superior surface water temperatures are increasing more rapidly than air temperatures (Austin and Colman 2007). In the coming century, surface water temperatures are projected to increase by 2.9 to 6°C depending on the climate change scenario and location in the Great Lakes Basin (Trumpickas et al. 2008, 2009, Chu *in review*). Lake Superior water temperature is projected to have the greatest increase, whereas Lake Ontario is projected to show the least warming (Trumpickas et al. 2008, 2009, Chu *in review*). Trumpickas et al. (2015) observed that projected nearshore water temperatures increase more rapidly in sites with low fetch (the area of a lake over which the wind blows in a generally constant direction) than in sites with high fetch.

Warming surface water temperatures produce changes in the thermal dynamics of lakes, such as increased water temperature at depth, periods of thermal stratification (see Box 2), shifted thermocline depths and increased duration of the ice-free season (see Section 3.1.4, Ice Dynamics). These combined changes in thermal dynamics will affect the nutrient dynamics, dissolved oxygen concentrations, productivity and availability of suitable habitat for warmwater species inhabiting the epilimnion, coolwater species in the metalimnion, and coldwater species in the hypolimnion (Dove-Thompson et al. 2011, Minns et al. 2014b). An increase in the duration of the stratification period combined with increased water temperatures will result in decreased oxygen levels in bottom waters, potentially creating hypoxic zones (Trumpickas et al. 2009, Mishra et al. 2011). Enhanced stratification also reduces the mixing of nutrients, thereby limiting primary production and affecting food supply for higher trophic levels (Gregg et al. 2012). As the climate warms, the length of the stratification period will increase and the thermocline may become deeper (Chu *in review*). Austin and Allen (2011) found that interannual variability in wind speed is the predominant driver of variability in the vertical stratification scale.

In the past century, the length of the summer temperature stratification period in Lake Superior increased by approximately 25 days (Austin and Colman 2008). Austin and Allen (2011) found that the greatest controls on summer-averaged surface lake temperature in Lake Superior were most sensitive to the climate variables of air temperature, decreased ice cover, and decreased wind speed. In the western Great Lakes region, Mishra et al. (2011) found that the length of the stratification period increased from 5 to 30 days from 1916-2007. The number of days with surface water temperatures greater than 4°C will increase by 90 days in Lake Superior and 42 days in Lake Erie by 2100 under the A2 climate change emission scenario (Dove-Thompson et al. 2011).

Changes in thermal dynamics of lakes are also projected to reduce the amount of suitable thermal habitat during the summer months for coldwater fish; however, due to an increase in the ice-free season, overall, coldwater habitat will increase (Minns et al.2014a,b). Warmer water temperatures are expected to have negative impacts on coldwater fish, such as Lake Trout (*Salvelinus namaycush*), including impairments to metabolism, growth and recruitment (McDermid et al. 2013, Kelly et al. 2014). Changes in water temperature of the epiliminion and littoral zones of lakes may favour warmwater species, which will alter the composition of fish communities. Furthermore, fish productivity may increase due to an increase in food supply and growth rates in warmer waters (Dove-Thompson et al. 2011).

Data confidence

River Temperatures

Climate change is expected to result in increased water temperatures of flowing water ecosystems and these increases in water temperature are expected to closely mirror air temperature increases (Kling et al. 2003, Allan et al. 2005). The response of stream temperature to climate change is complex and dependent on topography and geography of the drainage basin (Meisner et al. 1988) and surrounding vegetation (Hauer and Hill 1996). Stream warming may be buffered by shade from riparian vegetation and by cool groundwater seeps (Kling et al. 2003). Typically, the greatest source of heat in freshwater is solar radiation, which is particularly true for rivers or streams that are exposed to direct sunlight (Hauer and Hill 1996). Many small streams, however, are located under tree canopy cover that shades the water from direct sunlight. In these situations, transfer of heat from the air and the flow of groundwater are more important than direct solar radiation in governing stream temperatures (Hauer and Hill 1996).

Groundwater discharge plays an important role in maintaining cooler temperatures in streams and perpetuating coldwater refugia during summer (Kaya et al. 1977, Bilby 1984, Mortsch et al. 2003) and warmwater refugia in winter (Cunjak and Power 1987, Meisner et al. 1988). This cooling influence could be reduced as groundwater temperatures increase in response to increases in air temperature (Meisner et al. 1988). Maximum annual average stream temperatures ranges are 13.2°C in the Lake Superior basin and 32.0°C in the Lake Erie basin (Chu *in review*). Within the basins stream temperatures vary by 12 to 17°C across the Basin, with the Lake Erie basin showing the greatest range of temperatures, and Lake Ontario and Lake Superior basins having the least variation. Stream temperatures were modelled by Chu (*in review*) for the Great Lakes Basin's main tributaries (longest main channel and connected tributaries) and hydrologically connected lakes within tertiary watersheds to assess the impacts of climate change on stream temperature and the subsequent vulnerability of fish species distributions as a result of changing thermal habitat. Coldwater habitats are the prevailing thermal type in Great Lakes Basin streams; however, this may change as cool- and warmwater habitat is projected to double by 2071-2100 (A2 scenario; Chu *in review*). The greatest warming of stream temperatures is predicted to occur in the Upper St. Lawrence River basin with an average increase of 2.4°C under the A2 scenario, while the Lake Ontario basin will experience the least warming with average increases of 1.4°C under the A2 scenario (Chu *in review*).

Warmer stream temperatures will lead to increased rates of decomposition and nutrient cycling, releasing more nutrients into streams, there by fuelling increased primary productivity.

Conversely, climate change will also lead to oxygen depletion, slowing decomposition and limiting primary productivity (Kling et al. 2003). Temperature is an important factor in stream ecosystems that affects overall productivity, metabolic activity, growth rates, timing of spawning events and distribution (Chu et al. 2010). Increases in stream temperatures may provide more suitable habitat for species that prefer warmer temperatures throughout the ice-free season, but may limit the distribution of other species that prefer cooler temperatures (Chu et al. 2008). Chu et al. (2008) found that streams with high groundwater discharge may naturally offer more suitable habitat and thermal refugia for coldwater fishes as the climate changes. Research into the thermal regimes of streams in the Great Lakes Basin has linked the influence of landscape conditions and climatic variables (Chu et al. 2010).

Box 2: Thermal stratification in lakes

Lake basin shape, lake size, inflow volume, depth, wind exposure and latitude determine the strength and duration of thermal stratification and the seasonal amount of habitat available to cold-, cool-, and warmwater organisms (Wetzel 1975, Allan et al. 2005). In spring, warming temperatures, rain and wind break up lake ice. At this time of year, similar temperatures at all depths (in combination with wind) allow the lake water to circulate freely (Wetzel 1975). As spring temperatures increase, the surface waters warm more quickly (and become less dense) than bottom waters, which in turn create a thermal resistance to mixing (Wetzel 1975). A difference of a few degrees is enough to stop the mixing action. Lakes with sufficient depth thermally stratify into three layers:

- **Epilimnion:** The upper layer is comprised of warm (in dynamic equilibrium with air temperature) circulating water that is oxygenated and biologically productive (McCombie 1959, Wetzel 1975, Allan et al. 2005). Photosynthesis and other production processes generally occur in the epilimnion (Wetzel 1975).
- **Metalimnion:** The middle layer or thermocline contains water with a steep thermal gradient or temperature change. Temperature in the thermocline decreases rapidly at a rate of at least 1°C for each meter of depth (Ryder and Pesendorfer 1988).
- **Hypolimnion:** In north-temperate lakes found in the Great Lakes Basin, this layer consists of deep, cold, and relatively undisturbed water underneath the metalimnion. Water temperature decreases more gradually with depth than the metalimnion until maximum density is reached at 4°C (Wetzel 1975, Ryder and Pesendorfer 1988).

With declining air temperatures in late summer and fall, the solar heat entering a lake decreases and is eventually exceeded by heat lost to the atmosphere. As surface waters cool, the denser waters sink, mix and progressively erode the metalimnion. Once the thermocline disappears, mixing of the entire water column resumes, and once the temperature of the water reaches the point of maximum density (4°C) ice begins to form (Wetzel 1975).

Where it occurs, groundwater input significantly influences the hydrology and thermal regime of lakes, streams and rivers because it provides base flow and moderates the effect of seasonal air temperature fluctuations on water in temperate climates (Ward 1985). For example, groundwater indirectly contributes more than 50% of the flow in streams that discharge into the Great Lakes (Grannemann et al. 2000). Groundwater temperatures vary little throughout the year and approximate average annual air temperature (Power et al. 1999). Accordingly, groundwater is a critical factor in the establishment and maintenance of aquatic habitat (Mortsch et al. 2003) because groundwater seeps often provide thermal refuges for fish in summer when temperatures are high.

Data confidence

Wetland Temperatures

There have been no climate change assessments for water temperatures in the wetlands using climate model-based scenarios. Yet temperature is a key determinant in the distribution, productivity and functioning of wetland ecosystems. Warmer air temperatures will extend the growing season, alter the timing and impact of seasonal events, and increase evaporation and transpiration rates (Mortsch et al. 2006). Wetlands, such as bogs, that depend on precipitation and surface runoff rather than groundwater are particularly sensitive to drying (Clair et al. 1998, Mortsch et al. 2003, Allan et al. 2005). Peatlands are likely to dry due to increased evapotranspiration. The drying will promote establishment of woody species and increase the rate of peat decomposition and carbon loss (Wrona et al. 2006). Fracz and Chow-Fraser (2013) found that up to 6% of the coastal wetland area in Georgian Bay, Lake Huron could be lost along with the associated fish habitat if water levels decline as projected.

3.1.3. Water Levels and Surface Hydrology

Fluctuating water levels are natural phenomena in the Great Lakes Basin based on complex interactions between water gains through precipitation and losses through evaporation and transpiration, as well as human activities such as water withdrawal. While water level fluctuations will continue as the climate changes, projections indicate they are likely to occur around lower mean water levels (Mortsch et al. 2003, Taylor et al. 2006, Hayhoe et al. 2010, Environment Canada 2013).

Climate change projections suggest continued changes in the hydrology of the Great Lakes Basin, including higher risk of more intense drought and flooding, and changes in the factors that influence Great Lakes water levels. Most climate change projections suggest that there will be an overall decline in water levels from the combined effects of warming air temperatures, increased evaporation and evapotranspiration, drought and changes in seasonal precipitation patterns (Moulton and Cuthbert 2000, Lofgren et al. 2002, Angel and Kunkel 2010, Hayhoe et al. 2010, Bekele and Knapp, 2010, Lofgren and Hunter 2011). Projections include more runoff in winter and less runoff in summer (Croley 1990, Lofgren et al. 2002, Kundzewicz and Mata 2007, Nohara et al. 2006, Huicheng et al. 2013, Boyer et al. 2010a, Rahman et al. 2010). Winter runoff has historically been limited by winter conditions, where most precipitation fell as snow and remained in the snow pack until spring (Mortsch et al. 2003). Warmer winter temperatures may increase the number of winter rainfall events (Boyer et al. 2010b) and, due to limited infiltration potential into frozen ground, larger volumes of water may runoff into streams and rivers. Additionally, increased winter precipitation will melt some of the snow pack, further increasing stream and river flow (Mortsch et al. 2003, Notaro et al. 2014). Grillakis et al. (2011) reported that future simulations projected an increase in interannual stream discharge and noted important changes in the exceedence probability (recurrence interval) of extreme precipitation events.

Lower water levels and timing of these events will affect aquatic ecosystems in many ways, including loss of hydraulic connectivity, altered coastal margins and nearshore habitat structure, changes in coastal wave power and direction, and increased erosion (Mackey 2012). Substrate changes (such as the loss of littoral sand deposits as water levels decline, and newly created shallow water areas and exposed lakebed) in the nearshore zone of the Great Lakes increase vulnerability to the expansion of invasive species (Meadows et al. 2005). Changes to chemical and physical processes, such as nutrient cycling, oxygen dynamics and thermal stratification, will influence water quality (Wrona et al. 2006). Lower water levels could amplify the effects of contaminants (Mortsch et al. 2003, Wrona et al. 2006). For example, stored sulphur in wetlands and the littoral zone of lakes may be exposed to air and re-oxidized causing the re-acidification of water (Yan et al. 1996, Schindler 1998).

Data confidence

Lakes

Both natural and human activities influence variability in lake water levels and alter water levels across time scales ranging from hours to millennia, (MacKay and Seglenieks 2013). Natural factors include the amount of inflow and outflow in each lake, crustal movement, storm surges and seiches; whereas human factors include water diversions, dredging and control structures (Wilcox et al. 2007). Between 1918 and 1998, lake levels fluctuated 1.19m in Lake Superior and 2.02m in Lake Ontario (Moulton and Cuthbert 2000). Due to the size of the Great Lakes and the relatively small size of their outflow rivers, extreme high or low conditions can persist for a considerable period of time (IUGLS 2012).

The International Joint Commission's International Upper Great Lakes Study (IUGLS 2009) found that lake level changes in the Great Lakes between 1985 and 2005 were primarily driven by hydroclimatic variables, particularly over lake precipitation, basin runoff and lake evaporation. Several projections of Great Lakes water budgets and water levels have been studied (Croley 1990, Lofgren et al. 2002, Angel and Kunkel 2010, Hayhoe et al. 2010 and MacKay and Seglenieks 2013). Studies that include climate model scenarios suggest that water levels could change between -1.38 m and +0.35 m by 2100 (Lofgren et al. 2002, Angel and Kunkel 2010, Mackay and Seglenieks, 2010). While there may be a decline in the Great Lakes' net basin supply and water levels (Mackay and Seglenieks 2010), the projected values still remain within a relatively narrow historical range (IUGLS 2012). Amplified seasonal signals for lake levels in the future may also be more common (MacKay and Seglenieks 2013, Music et al. 2015). However, Lofgren and Gronewold (2012) criticize the widely-used methods of calculating potential evapotranspiration using temperature as a proxy, suggesting that it exaggerates projected increases and an energy budget approach should be used to adjust potential evapotranspiration (Lofgren et al. 2011). They note that this is a subject of emerging relevant research in the Great Lakes Basin.

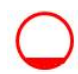
Lower water levels can reduce and impair fish movement, access to spawning and nursery habitat, and migration (Koonce et al. 1996, Mortsch et al. 2003, Wrona et al. 2006), particularly in streams or inland lakes in the Basin with a high proportion of littoral habitat.

Data confidence

Rivers

Historically, significant volumes of water have been stored over winter in the snow pack and released in the spring freshet. The timing and magnitude of runoff is a critical factor influencing biotic and ecosystem processes (Poff et al. 1997). The change to stream flow rate resulting from climate changes has proven difficult to forecast. For the western Great Lakes, the 2-year precipitation amount has increased by approximately 2% per decade, while the 100-yr storm amount has increased by 4% to 9% per decade (DeGaetano 2009). Observations have shown an increase in stream flow in the Great Lakes Basin. There have been statistically significant increases in some precipitation and streamflow gages over the period 1930 to 2000 (McBean and Motiee 2008). However, other studies have shown that because of the combined effects of increased temperatures, decreased precipitation and increased evaporation; climate change will reduce the volume of stream flow (Dove-Thompson et al. 2011). Reduced stream flow into lakes will lengthen the lake water renewal time (Schindler 1998, Schindler et al. 1996a, Mortsch et al. 2003), which could increase the risk of anoxic conditions. Earlier ice-out and snow melt will cause peak flows to occur earlier in the season, and ephemeral streams will dry up sooner. An earlier (and possibly reduced) freshet may occur in response to warming, which could lead to changes in the seasonality of river flows particularly in areas where most of the winter precipitation falls as snow (Westmacott and Burn 1997, Whitfield and Canon 2000, Barnett et al. 2005). In response to warmer winter temperatures and increased winter precipitation in the Great Lakes region for the period 1976-1995, hydrologic pattern changes included higher winter flows, changes in timing of the spring peak, and lower summer flows (Whitfield and Cannon 2000). More frequent and heavy rainfalls will lead to more frequent and larger floods, increasing rates of erosion and pollution from upstream sources, ultimately degrading water quality (Kling et al. 2003). Rahman et al. (2012) showed a significant increase in spring and winter streamflow but a decrease in the fall by the 2041-2070 time period under an A2 scenario using a CRCM. Downscaling projections of precipitation and temperature changes from the IPCC AR4 report project annual streamflow to increase on all rivers surrounding Lake Michigan by the late-century (2070-2099) (Cherkauer and Sinha, 2010). Changes in stream flow will impact the timing of fish and insect life cycles (Kling et al. 2003). Changes in the timing and volume of the freshet are expected to affect the spawning of fish. Due to an increase in the frequency and duration of ephemeral streams drying and of perennial streams becoming intermittent, species with resting life stages may dominate communities due to their ability to persist under harsh conditions (Kling et al. 2003). Flooding can also reduce aquatic vegetation while increasing the volumes of silt and organic debris deposited downstream. These secondary effects of changes to stream flow can impact productivity, destroy eggs and displace fish (Dove-Thompson et al. 2011). The vulnerability of a particular fish species to flooding increases if the spawning season coincides with periodic flooding (Moyle and Vondracek 1985).

Data confidence



Wetlands

Shorter, warmer winters and longer summers will result in increased evapotranspiration and evaporation leading to decreased water levels in wetlands (Environment Canada 2013). Wetlands across the Great Lakes Basin are vulnerable to drying and reduction in wetland area due to changes in air temperature and precipitation. Modelled effects on wetlands to 2100 project that the most vulnerable regions may be in the southern parts of the Lake Ontario and Lake Erie basins, the eastern region of the Lake Superior basin, the central part of Lake Huron and the northwestern part of the Upper St. Lawrence River basin under an A2 scenario (Chu *in review*).

Water-level fluctuations have a strong influence on the structure and function of wetlands (Mortsch 1998, Hebb et al. 2013). Increased runoff during severe rain events in winter and summer may alter wetland ecosystem function, including the reconfiguration of plant and animal species and their relationships (Mortsch 1998, Mortsch et al. 2006, Hebb et al. 2013). Reduced water levels will eliminate or modify wetlands that function to maintain shoreline integrity, reduce erosion, filter contaminants, absorb excess storm water, and provide fish and wildlife habitat (e.g., the natural succession of wetland plants and fish spawning areas; Whillans 1990, Bedford 1992, Wilcox and Meeker 1995, Edsall and Charlton 1997, Mortsch 1998, Branfireum et al. 1999, Devito et al. 1999, Mortsch et al. 2003, Lemmen and Warren 2004, Taylor et al. 2006). BaMasoud and Byrne (2011) predict that lower water levels in Lake Erie will erode the current beach and swamp forests of Point Pelee National Park, leading to a net loss in the land habitat by 2050.

In the Great Lakes Basin, water level fluctuations are an important driver of changes in species composition and the preservation of wetland species diversity. Fluctuations also contribute to the formation of distinct wetland vegetation zonation (Lishawa et al. 2010) and the formation and stabilization of dunes (Wilcox et al. 2007, IUGLS 2012). Projected declines in water levels are expected to have several impacts on wetland ecosystems (Fracz and Chow-Fraser 2013). Vegetation composition ranges from forested and shrub dominated wetlands in areas that are rarely covered with water, to dense emergent marshes where water is present on a short-term basis, to submersed and floating leaf communities where standing water is typically present. These wetland plant community assemblages may change in response to changing water depths (Wilcox et al. 2007), and lower water levels can result in reduced plant species diversity and the onset of non-native species invasion (US EPA 2006). *Typha X glauca*, an invasive hybrid cattail, has become increasingly prevalent in Great Lakes coastal wetlands, and its presence has been correlated with extreme low water levels (Lishawa et al. 2010). Changes in water levels may also affect invertebrates, aquatic mammals and fish that rely on wetland habitats. Increased variability in Great Lakes water levels may alter the phenology of coastal wetland-dependent fish communities and other aquatic organisms due to changes in seasonal timing and duration (Casselman and Scott 2002, Fracz and Chow-Fraser 2013). Water level fluctuation also has an effect on the nutrient flux between sediments and the water column due to the oxidation of nutrients exposed when water levels recede (Steinman et al. 2012). The magnitude of water level fluctuation and length of desiccation affect the amount of nutrients released (Steinman et al. 2014). Due to the low water levels of the Great Lakes from 2000 to 2014, a significant amount of coastal wetland sediment is exposed, which serves as a large source of nutrients as water levels re-inundate these areas (Steinman et al. 2014).

3.1.4. Ice Dynamics

Data confidence

Lakes

Changes in air temperature and surface water temperature on the Great Lakes influence the extent and duration of ice cover on the lakes. Warmer temperatures will change ice dynamics phenology of the Great Lakes and inland lakes throughout the Basin (Assel et al. 1995, Assel and Robertson 1995, Fang and Stefan 1998, Quinn et al. 1999, Magnuson et al. 2000, Lofgren et al. 2002, Assel et al. 2003, Kundzewicz and Mata 2007, Brown and Duguay 2010, Minns et al. 2014a).

Over the past century, there was a strong trend toward later freeze-up and earlier break-up of ice on lakes (Magnuson et al. 2000, Lofgren et al. 2002, Kling et al. 2003, Chiotti and Lavender 2008, Howk 2009, Minns et al. 2014a). On the Great Lakes, the ice cover period has decreased by 1 to 2 months (Magnuson et al. 2000, Lofgren et al. 2002, Kling et al. 2003). For example, the duration of ice cover on Lake Superior between 1856-2007 decreased at a rate of 3 days/decade, or 45 days over the 150 years (Howk 2009). In Lake Ontario, the ice break-up date occurred 7-12 days/century earlier from 1822-1995 (Magnuson et al. 2000). There has also been a decline in the amount of ice that formed each year on the Great Lakes (Karl 2009, Wang et al. 2012a). For the period 1973-2010, there has been an overall decrease in annual ice coverage of 71% across the Great Lakes (Wang et al. 2012a).

Projected warming, particularly in winter months, will lead to further decreases in the duration and extent of lake ice cover in the Great Lake Basin (Lofgren et al. 2002, Shuter et al 2013, Minns et al. 2014a, Notaro et al. 2014, 2015). For example, Minns et al. (2014) projected that by 2070-2100, ice break-up could advance by up to 17 days in the Great Lakes Basin, while freeze-up could occur up to 30 days later. This would lead to an increase in the open water season (Minns et al. 2014a). Furthermore, Minns et al. (2014a) modelled that maximum ice thickness will decrease throughout the century.

Climate-induced shortening of the ice-in season will affect evaporation rates (Allan et al. 2005). In the Great Lakes, the greatest losses due to evaporation occur in late autumn and winter when cold, dry air passes over the warmer lakes (Mortsch et al. 2003, Blanken et al. 2011, Lenters et al. 2013). Years with high ice cover are usually followed by cooler summer water temperatures and lower evaporation rates, but these high ice winters are typically preceded by high autumn evaporation rates (Lenters et al. 2013). Austin and Colman (2008) suggest that observed decreases in ice cover is the main factor driving the increases in thermal stratification period rather than warming air temperature. Notaro et al. (2015) used dynamically downscaled CMIP5 simulations, indicating that increases in lake evaporation will occur with increases in total lake-effect precipitation, in the form of rainfall rather than snow. The period of ice-on and ice-off conditions has implications for physical, chemical and biological cycles in water bodies (Latifovic and Pouliot 2007). Longer ice-off periods can increase water temperature and evaporation. This leads to lower water levels and can also have implications for many aspects of aquatic ecosystems. Longer ice-off periods can also negatively impact coldwater fish species survival by reducing the opportunity to exploit specialized feeding strategies that rely on ice cover (Shuter et al. 2012)

Ice dynamics affect many ecosystem features and socio-economic opportunities; therefore, these changes can impact lake ecosystems in a variety of ways. Ice protects the shoreline and prevents erosion during winter storms. Therefore, a reduction in the ice-in period will render shorelines more susceptible to extreme storm events (Mortsch et al. 2003). Extension of the ice-free season and increased water temperatures will lengthen the overall period of productivity. This may lead to increased oxygen consumption in the deeper waters as algae decompose and settle to the bottom, which may limit the amount of oxygen available to species inhabiting deeper waters (Wrona et al. 2006). Ice cover protects fish habitat by maintaining water at temperatures closer to 4°C than 0°C (Minns et al. 2014a). Ice fishing provides important country foods[2] for many First Nations communities, and ice is important to trappers who use it to gain access to their traplines. Recreational and some commercial fishing opportunities require ice for access and a fishing platform as well (Minns et al. 2014a). On the other hand, a shorter ice-in season means a reduced risk of low dissolved oxygen conditions, which will increase the chances of over-winter survival of fish eggs (Mortsch et al. 2003, Gregg et al. 2012) and fish (Stefan et al. 2001, Vincent 2009). Reduction in the duration of ice cover and associated warming may be beneficial to fish populations where productivity and growth are currently limited by the duration of open water periods (Hostetler and Small 1999, Stefan et al. 2001). A shorter ice-in season also means that fewer atmospheric airborne particulates are stored in the snow and ice pack. As a result, more of

[2] Country foods - refers to items that traditionally composed the diets of aboriginal communities in remote northern regions of Canada.

the annual deposition of toxic material will be gradually introduced into the system and the size of the spring-time toxic pulse that is flushed into the lake will be smaller.

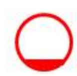
Data confidence

Rivers

The hydroclimatic factors that control river ice processes are highly complex (Beltaos and Prowse 2009). As with lakes, the duration of ice cover on streams and rivers is expected to decrease with later freeze-up and earlier thaw (Jones et al. *in press*). Since most water-induced geomorphological activity occurs during freeze-up and break-up (e.g., ice scouring of the embankment), the significance of ice dynamics in shaping stream and river channels may be reduced in a warmer climate (Prowse et al. 2006a,b). Rivers in the northerly portion of the Great Lakes Basin will increasingly experience mid-winter thaws and shorter winter ice periods, which may also lead to more frequent ice jams; while rivers in the southern portion of the basin may not freeze at all, or for only brief periods, forming thermal regimes characteristic of many rivers in the United States (Jones et al. *in press*).

Historic winter climate regimes have resulted in river ice dynamics that include ice scouring of the river bottom, associated loss of winter habitat for fish and other organisms, and active geomorphological processes during the spring melt, particularly where large amounts of ice are pushed up against the shore or embankment (Ryder and Pesendorfer 1988, Prowse et al. 2006a,b). A warmer climate may increase the availability of winter habitat because of increased winter flow rates and higher dissolved oxygen levels. Streams and rivers that traditionally freeze to the bottom during winter may experience increased flow in response to higher winter temperatures and increased winter precipitation. Reduced ice thickness in some areas may provide year-round flowing water, which will increase habitat availability and improve survival of species susceptible to winter kill (Wrona et al. 2006). A climate-induced decrease in the duration of the river ice-in season, or an increase in the size and frequency of open water sections where re-aeration can occur, may decrease the potential risk of oxygen depletion (Prowse and Beltaos 2002).

Data confidence



3.1.5. Groundwater

The relationship between climate change and groundwater is much more complex than the relationship between climate change and surface water resources. In the Great Lakes Basin limited research has been conducted to understand groundwater vulnerabilities. Climate change will impact groundwater quality and quantity through direct interactions with surface water and indirectly through the recharge process (Jyrkama and Sykes 2007, Green et al. 2011). Groundwater recharge is influenced by several factors including climatic factors, such as precipitation, wind, temperature and vegetation, which affect evaporation, transpiration and the process of interception (Jyrkama and Sykes 2007). Snowpack and a frozen soil layer are likely to change in duration and extent due to climate change and these variables impact the process of groundwater recharge. Climate change is also expected to have more subtle influences on groundwater. For example, flow is predicted to increase through earthworm burrows as the climate changes, which may increase the transport of contaminants (Dadfar et al. 2010).

Groundwater is a part of the hydrologic cycle that really demonstrates the uncertainty in projecting secondary impacts of climate change using climate modelling scenarios. Studies have shown not just differences in the magnitude of change, but also the direction of change. Jyrkama and Sykes (2007) projected that groundwater recharge in the Grand River watershed could increase due to climate change by 100mm/year over a 40 year period. Due to warmer winter temperatures, more precipitation will fall as rain rather than snow, thereby decreasing runoff by reducing the amount of water stored in the snowpack and increasing groundwater recharge through increased infiltration (Jyrkama and Sykes 2007). Groundwater recharge rates will increase most significantly during the winter months since it will be easier for water to infiltrate the ground (Jyrkama and Sykes 2007). Several other studies also showed a slight increase in winter season recharge (Sulis et al. 2011, Wiley et al. 2010). Other studies however have projected a 19% decrease in recharge using the CCCMA climate models and a 3-4% increase in recharge using Hadley climate models (Croley and Luukkonen 2003, Piggott et al. 2005).

The increased variability in the hydrologic cycle due to climate change increases the uncertainty in groundwater recharge estimations (Sousa et al. 2014). Shallow aquifers may be particularly sensitive to decreased groundwater recharge (Chiotti and Lavender 2008). Furthermore, due to more frequent intense precipitation events, groundwater quality may decrease as a result of accelerated hydrologic connections between surface and groundwater (Sousa et al. 2014).

3.1.6. Natural Hazards

Data confidence

Flooding

Flooding resulting from spring runoff and extreme precipitation occur in the Great Lakes Basin. The timing, frequency and intensity of these two sources of flooding are expected to differ in their responses to climate change. As air temperature increases there will be less snowfall and therefore a reduction in snowmelt (Notaro et al. 2014). Consequently, spring runoff is projected to decline (Shaw and Riha 2011). Nevertheless, as temperatures increase, evaporation will increase, as will the amount of moisture that can be stored in the air. These changes will result in more intense precipitation events (Bush et al. 2014). Changes in the timing and severity of hydrologic extremes may be one of the most significant impacts of climate change (Cunderlik and Ouarda 2009).

During the first half of the 20th century, there were less than 10 flood disasters per decade in Ontario; however, by the 1990s the frequency of floods per decade had increased five-fold (Cheng et al. 2012a). Heavy precipitation events are becoming heavier. Between 1958 and 2007, the heaviest 1% of rain events increased by 31% in the US Great Lakes Basin resulting in more flooding, runoff, and sediment and nutrient loading impacts (Karl et al. 2009). The impacts of climate change on flooding vary greatly at the local level depending on the physical properties of river basins and land use within the region (Cunderlik and Simonovic 2007). The IPCC (2007) have projected increases in the severity and frequency of floods related to extreme events. Models of future insurance claims due to flooding using climate projections have shown a 30% increase in claims for the 2081-2100 period (Cheng et al. 2012a). Cunderlik and Simonovic (2007) modelled future precipitation patterns under an A1 scenario and found that 200mm 24hr storms will occur more frequently by 2050. In the summer months, increased drought combined with increased frequency and intensity of heavy rainfall events will produce high runoff and result in localized urban flooding (Gregg et al. 2012). Climate change will decrease the suitability of current methods of establishing safety levels for hydraulic structures, as precipitation and temperature changes will render long-term projections unreliable (Seidou et al. 2012).

Adamowski et al. (2013) found that maximum stream flow in the Great Lakes Basin occurred 25 days earlier and was 10% lower in amplitude between 1969 and 1992 therefore spring runoff flooding would decrease as well. Floods due to snowmelt in the Great Lakes Basin are occurring earlier in the year as a result of climate change (Cunderlik and Ouarda 2009). Climate change will result in more precipitation falling in the winter as rain rather than snow possibly leading to higher stream flows throughout the winter (Hayhoe et al. 2010, Gregg et al. 2012).

Data confidence

Fire

Fire is an ecological process that is sensitive to climate change because fuel (vegetation) moisture is an important determinant of fire behaviour (Weber and Flannigan 1997). Accordingly, altered precipitation and temperature patterns across North America will affect fire risk, with some areas experiencing greater risk and others less risk (Flannigan et al. 2000). Generally speaking, the hardwood dominant Carolinian forest (along the southeast shore of Lake Huron and the northern shores of Lakes Erie and Ontario) and the Great Lakes-St. Lawrence forest (spanning the majority of the Great Lakes Basin with the exception of a 300 km gap where the boreal region touches the north shore of Lake Superior and the small deciduous (Carolinian) forest region in the southern part of the Basin) have substantially longer fire cycles than the boreal forest and are not ecologically dependent on fire for forest renewal and succession (Duveneck et al. 2014).

Fire is projected to increase as climate changes (e.g., Street 1989, Flannigan and Van Wagner 1991, Stocks et al. 1998, 2000, 2003, Bergeron et al. 2004, Flannigan et al. 2005, Amiro et al. 2009, Le Goff et al. 2009), particularly in the boreal region, including an earlier start to the fire season and a significant increase in the geographical expanse of severe fire danger. Despite using different models and data, most projections suggest an increase in fire frequency and burn area by the end of the century as a result of more frequent and severe drought due to climate change (Dale et al. 2001, Girardin et al. 2013, Terrier et al. 2013, Podur and Wotton 2010). But increased fire severity will not be consistent across North America. For example, projections by Flannigan et al. (1998) suggest increased precipitation in the east could decrease fire activity. Between 1963 and 2003, the fire season length in the northwest of Ontario increased by 6 to 8 days and 1 to 2 days in forests across the Great Lakes Basin. Terrier et al. (2013) predict an increase in fire occurrence of 10-25% by 2090 and models by Boulanger et al. (2013) predict a 2.2-fold increase in the number of fires and a 2.4-fold increase in area burned. By 2100, fire risk in central Quebec is predicted to increase for June, July, and August and decrease slightly for May, inferring less frequency of spring fires but a prolonged period of high fire risk (Le Goff et al. 2009).

In the southern Great Lakes Basin fire is not a large driving force in the ecosystem with only 0.09-0.13% if the area burned annually (Cleland et al. 2004, White and Host 2008). Furthermore, managed forests in the Basin experience few fires because of the high initial fire suppression success rates (Ward et al. 2001). Nevertheless, more severe fire weather may create fire spread conditions that reduce fire suppression success (Flannigan et al. 2005) and result in larger burns (Colombo 2008). Drought combined with suitable fire temperatures can create conditions that reduce the effectiveness of fire suppression techniques (Fleming et al. 2002). The combination of higher temperatures and increased drought may create a 'tipping point' beyond which fire suppression is no longer feasible or effective (Flannigan et al. 2005, Bergeron et al. 2010). Forest fire management agencies will need to consider these findings when planning fire management strategies under climate change (Wotton et al. 2010). There is also a strong interrelationship between forest fire risk and the impacts of forest pests and diseases, since dead trees increase the fuel load (Dale et al. 2001). With warmer temperatures, potentially more extreme weather events, and more prolonged and frequent periods of drought, forest fire risks could increase with climate change.

3.2. Environmental Chemistry and Pollutants

The effects of climate change on aquatic ecosystem chemistry are complex because temperature, precipitation and water levels can affect chemical pathways in many ways. Furthermore, the concentrations and types of chemicals in the Great Lakes Basin vary greatly according to location, climate, physiography, geology, surrounding land use patterns and biota (Hynes 1970, MacDonald et al. 1991, Khairy et al. 2014). The impacts of climate change on environmental chemistry, nutrient levels, pollutants and water quality will vary within and between watersheds. Booty et al. (2005) found that projected changes in peak flow patterns resulted in varying effects on phosphorus, carbon and nitrogen levels within a watershed. Taner et al. (2011) showed that climate change may impact the timing of nutrient cycling between lake sediments and the water column due to interacting stressors, including lake warming and modified loadings. And in a watershed modelling study on climate change effects on stream water quality Cyril and Weng (2011) found that increased runoff associated with climate change can lead to greater loading of total suspended solids.

3.2.1. Chemical Effects

Data confidence

Oxygen

Dissolved oxygen concentrations are important to the health of aquatic ecosystems. Most aquatic organisms, particularly fish, prefer dissolved oxygen concentrations of 5 mg/l or greater; concentrations below 2-3 mg/l are hypoxic (Ficke et al. 2007). As temperatures increase, anoxic conditions (a more severe condition of hypoxia) may occur because: (1) warm water holds less oxygen than cold water; and (2) oxygen demands are greater due to increased rates of decomposition and respiration (Lehman 2002, Ficke et al. 2007, Committee on Environment and Natural Resources 2010). Dissolved oxygen concentrations vary along streams and rivers according to water temperature, groundwater flow and stream flow (Hauer and Hill 1996). Seasonal variation of dissolved oxygen levels in rivers can result from: (1) leaf inputs in the autumn, which increases oxygen demand and reduces oxygen levels; (2) seasonal photosynthesis peaks and declines; (3) winter ice cover on rivers; and (4) high discharge conditions (Hynes 1970). Warmer water temperatures may reduce the length of the ice season and, therefore, reduce the risk of winterkill caused by oxygen depletion. In stratified lakes, summer dissolved oxygen levels in the epilimnion are constantly being renewed through exposure to the atmosphere and mixing promoted by wind. The hypolimnion, however, deoxygenates in response to metabolizing bacteria that use oxygen to break down detritus (Wetzel 1975, Upchurch 1976). Less dissolved oxygen below the thermocline would decrease available habitat in stratified lakes for coldwater fish, such as lake trout (Crowder et al. 1996, Magnuson 1998, Chu *in review*). A longer stratification period will lead to more pronounced variations in oxygen concentrations through the water column (Vincent 2009). A water quality sensitivity analysis for the Grand River in southwestern Ontario showed that, in conjunction with nutrient loading, dissolved oxygen levels were more sensitive to changes in water temperature, particularly over-night water temperature, than to changes in flow (Minshall 2000). In the Bay of Quinte, Minns et al. (2011) report a trend of oxygen depletion with declines in phosphorus, as well as in areas that experience surface water mixing to the bottom which results in warmer bottom water temperatures.

Data confidence

Acidity (pH)

Acid rain, resulting from decades of sulphur dioxide and nitrogen oxide emissions by North American industry stressed aquatic ecosystems in many parts of North America (Minns et al. 1990, Doka et al. 2003). For example, in the 1970s, more than half of the Great Lakes Basin was subjected to acidic precipitation ranging from a pH of 4.2 to 5.5, which had significant impacts on biodiversity (Rubec 1981). Much of the soil in the central part of the province of Ontario has low capacity to neutralize acids because it is underlain by the Precambrian Shield (Environment Canada 1988, Schindler 1998, Crins et al. 2009). In response to a reduction in industrial emissions, some inland lakes (e.g. Clearwater Lake) have begun to show signs of recovery; however, many of these lakes are still acidifying or show no signs of recovery (Keller 2009).

Climate change may exacerbate the effects of acid deposition. In warmer, drier climates, increased exposure of peatlands and wet soils to atmospheric oxygen will cause re-oxidation of sulphur that has been deposited as acid rain and stored away in soils and vegetation (Yan et al. 1996, Magnuson et al. 1997). During periods of high stream flow, flooding or extreme precipitation events, pulses of sulphuric acid will be released into aquatic ecosystems following periods of drought (Schindler 1998). Pulses will be more acidic in the eastern Great Lakes Basin because of high sulphate deposition and less acidic in the northwest where deposition has been less (Schindler 1998). Acidification also exacerbates the effects of increasing water temperatures because dissolved organic carbon (DOC) is greatly reduced in lakes with pH below 5 (Schindler 1998). Reduction of DOC greatly increases the penetration of solar energy, which in turn deepens the thermocline (Dillon et al. 1984) and permits increased penetration of harmful UV radiation (Schindler 1998).

The pH values of the Great Lakes range from 8.0 to 8.35, and are less alkaline than the ocean, making the Great Lakes more susceptible to pH fluctuations due to a lower buffering capacity (NOAA 2010). The CO_2 levels of Lake Superior over the last decade have remained in relative equilibrium with atmospheric CO_2 (Atilla et al. 2011). If this relationship continues, it is expected that the pH of Lake Superior will decrease by 0.30 pH units by the end of the century (NOAA 2010). This is twice the rate of pH decline observed in the oceans. Due to the fact that the Great Lakes mix vertically in the spring and fall, anthropogenic CO_2 is able to penetrate the entire water column, thereby causing a more rapid rate of acidification at depth (NOAA 2010). As pH decreases, the saturation of calcium carbonate also decreases making it more difficult for calcifying organisms, such as snails, freshwater clams and crayfish, to biosynthesize their shells. In acidifying environments, it is important to monitor other important aquatic organisms, such as phytoplankton, the primary producers in aquatic ecosystems that have seen a reduction in biodiversity and biomass (Moiseenko 2005). Studies have also demonstrated physiological effects of acidification on other Great Lakes ecosystem organisms, including benthic organisms, zooplankton, and ecologically and economically important fish species (Moiseenko 2005, NOAA 2010).These changes in pH could also potentially affect all of the below mentioned chemicals among others.

3.2.2. Nutrients

Data confidence

Phosphorus

The major sources of phosphorus in both streams and lakes are rainfall and terrestrial run-off, particularly when streams and rivers are located adjacent to agricultural lands (Hynes 1970). During the 20th century, the accelerated use of phosphorus in various agricultural, industrial and domestic applications, the inefficient treatment of industrial and municipal waste/discharge, and erosion from agricultural lands led to an increase of phosphorus in aquatic ecosystems (Wetzel 1975). Excessive amounts of phosphorus in aquatic ecosystems promote the growth of photosynthetic organisms, such as algae, to such densities that water quality declines. In some cases, such as Lake Erie, this leads to hypoxia – a lack of oxygen in the water – affecting deep water fish, such as yellow perch (*Perca flavescens*; Environment Canada 2001, Dove-Thompson et al. 2011). Furthermore, algal blooms and cyanobacteria can become an issue for human health and the socio-economics of water ways (Moore et al. 2008, Michalak et al. 2013). In the Great Lakes Basin, progress has been made to reduce the introduction of phosphorus into ecosystems and, consequently, phosphorus related productivity of lakes has declined (Chu et al. 2004, Michalak et al. 2013). Even so, phosphorus continues to enter aquatic ecosystems from surrounding watersheds, particularly as a constituent of wastewater effluents (Medeiros and Molot 2006).

Climate change in the Great Lakes Basin will affect water quality in the lakes because of changes in: (1) extreme weather events; (2) changes in timing and amount of seasonal flow; (3) temporal and spatial distribution of primary productivity; and (4) sediment release of phosphorus. The release of phosphorus from sediments is temperature dependant; therefore, warmer water temperatures may increase phosphorus levels (Malmaeus et al. 2006). Climate change is also expected to increase the occurrence of heavy rainfall events associated with increases in the frequency and intensity of storms in the Great Lakes Basin (Hayhoe et al. 2010), leading to more phosphorus entering the system (Jeppesen et al. 2009). Changes in seasonal stream flow patterns can have a significant impact on the amount of phosphorus entering lake ecosystems. Projected lower mean stream flow (see Section 3.1.3) and higher non-point source run-off could increase phosphorus levels (Mortsch et al. 2003, Crossman et al. 2013) and affect productivity of aquatic organisms. A study conducted by Crossman et al. (2013) predicted increases in total phosphorus entering Lake Simcoe; the greatest increase in phosphorus projected was found to occur during the winter months due to increased precipitation. Despite reduced stream flows in the summer months, phosphorus is still projected to increase due to less dilution of point sources, such as a sewage treatment plants (Crossman et al. 2013). Woodbury and Shoemaker (2012) showed that under climate change scenarios (Karl et al. 2009) there would be an increasing amount of precipitation, flow, and total phosphorus loading to the reservoir over time, despite no changes in the amount of phosphorus applied to the watershed.

Most algal biomass is produced in a primary bloom in spring and a secondary bloom in autumn in response to thermal mixing and nutrient availability. With a longer more stable projected thermocline, the spring algal bloom in some parts of a lake is projected to diminish because the earlier stratification will cap or cut-off nutrient supply (Brooks and Zastrow 2003). Fall production could also decrease due to an extension of the stratified period (Malmaeus et al. 2006). Nearshore areas may not be as nutrient-limited because they receive nutrients from catchment run-off and are exposed to wave and wind mixing (Bootsma 2001), which in turn decreases the amount of oxygen available to other organisms (National Assessment Synthesis Team 2001). Michalak et al. (2013) showed that a large algal bloom in Lake Erie in 2011 was the result of combined climate and agricultural trends that are consistent with expected future conditions.

Data confidence

Nitrogen

The use of nitrogen compounds (i.e., NO_3^-, NO_2^- and NH_4^+) in agriculture and domestic activity has increased the influx of nitrogen into lakes and streams in the Great Lakes Basin (Upchurch 1976). Climate change may also increase decomposition rates by 4-7%, which would increase nitrogen. However, plants grown under elevated CO_2 have a lower nitrogen concentration; therefore, the change due to an increase in decomposition rates due to climate change might be offset (Moore et al. 1999).

The projected temperature increases, along with the changes of timing and magnitude of precipitation may increase contaminant influxes into aquatic ecosystems. These projected changes would increase the exposure of aquatic organisms, resulting in higher contaminant loads (Wrona et al. 2006). The increased water temperatures will combine with nitrogen to increase primary productivity. Increased nitrogen concentrations, in combination with phosphorus and other nutrients, will accelerate eutrophication, which is characterized by abundant plankton (possibly leading to anoxia) and high turbidity (Wetzel 1975, Ryder and Pesendorfer 1988). The increased prevalence of anoxia in deep waters can lead to increased losses of nitrogen from the ecosystem through denitrification (Vincent 2009).

Data confidence

Carbon

Carbon is the fundamental building block of all living things (see Box 3). Therefore, it is critical to understand how climate change will impact carbon cycling and availability in terrestrial and aquatic ecosystems of the Great Lakes Basin. Limited research is available on the coupling of climate change and carbon availability, but some trends can be predicted based on our knowledge of carbon cycles. Projected higher water temperatures will lead to enhanced microbial decomposition of organic materials, which will increase the production of dissolved organic carbon (DOC) (Wrona et al. 2006, Oni et al. 2012). With warmer water temperatures and longer growing seasons, metabolic rates will increase resulting in greater demand for carbon, which could lead to a decrease in the amount of bio-available carbon in ecosystems (Mortsch et al. 2003). Projected changes to terrestrial vegetation may also lead to changes in aquatic vegetation, which may influence carbon availability and the associated distribution and abundance of stream biota (Allan et al. 2005).

Changes in precipitation patterns and intensity will alter DOC fluxes as water quantity and residence times are impacted (Oni et al. 2012). Lower water levels in streams and rivers will increase aeration of sediments, thereby increasing dissolved organic carbon levels (Oni et al. 2012). Oni et al. (2012) found that climate change may lead to a shift of summer DOC maxima toward the winter season and an extension of summer levels into autumn in the Lake Simcoe watershed.

Wetlands are an important source of DOC for ponds, lakes and streams in the Great Lakes Basin. The outflow of DOC results from precipitation and basin topography and will be affected by changes in temperature and precipitation. Climate change has been linked to a decrease in wetland discharge and DOC outflow (Schindler et al. 1996b, Clair et al. 1998). Conversely, climate change may also lead to increased DOC due to declining wetland area and the exposure of wetland sediments to aeration due to low water levels (Oni et al. 2012). The condition of wetlands as a carbon sink or source will likely change (Wrona et al. 2006).

Box 3: Terrestrial and aquatic carbon sources

Carbon provides the fundamental building block for organic compounds and photosynthesis. Organic carbon is created from the decomposition of plants and animals. In soils and sediments, organic carbon ranges from freshly deposited litter to highly decomposed humus. Carbon is found in different sizes, configurations and amounts in aquatic ecosystems, such as larger sized particulate organic carbon and smaller sized dissolved organic carbon (DOC). DOC is important because: (1) it is a source of energy (e.g., a food source for micro-organisms); (2) it is part of the acid-base chemistry of many low-alkaline weakly buffered freshwater systems; (3) it combines with trace metals to form water-soluble molecules that can be transported and taken up or consumed by organisms; and (4) it affects light penetration in aquatic ecosystems and reduces the effects of UV-B radiation.

Carbon is available from allochthonous and autochthonous sources. Allochthonous carbon comes from soils and vegetation in the surrounding area and, in reaction with water, can form several aqueous compounds (e.g., carbonic acid, bicarbonate and minerals) that affect biogeochemical cycling. Autochthonous carbon is derived in the lake from respiration by organisms, such as algae and macrophytes, and through oxidation of organic matter (e.g., detritus) on the bottom of lakes once these organisms die (Wetzel 1975, Upchurch 1976). Allochthonous detrital inputs are primary energy sources in streams and rivers. Coarse particulate organic matter (>1mm diameter), fine particulate organic matter (0.5µm to 1mm), and dissolved organic matter (<0.5µm) are major energy resources for stream ecosystems because they provide a large proportion of the fixed carbon that is metabolized by stream biota (Cummins 1974, Smith 1980, Cummins et al. 1983).

3.2.3. Pollutants

Noyes et al. (2009) provide a thorough review of the toxicology of climate change. Climate change could alter the environmental distribution and toxicity of chemical pollutants. Increased temperature could enhance toxicity and volatility of pollutants and contaminants, while changes in precipitation resulting from climate change could also alter the fate and behaviour of chemicals by changing wet deposition and enhanced degradation. Secondary impacts could also occur, such as changes in the distribution of agriculture and pest species which could alter pesticide use. In addition altered species migratory pathways could alter the transport of persistent, bioaccumulative and toxic pollutants (PBTs). Rising temperatures also increases the bioavailability and toxicity of PBTs in terrestrial and aquatic wildlife (Magnuson et al. 1997), furthermore populations at/or near the edge of their physiological tolerance range may be more vulnerable to the dual stresses of climate change and contaminants (Noyes et al. 2009).

Data confidence

Mercury and Other Organohalogens

Mercury is a chemical element that occurs naturally and is also redistributed into ecosystems through industrial processes. Mercury is found in trace amounts in rocks and soil, and enters terrestrial and aquatic ecosystems as a result of the weathering of rocks and volcanic activity (Goldwater 1971). Historically, artificial sources around the world have included: (1) waste from the manufacture of vinyl chloride; (2) the use of mercury compounds on agricultural seeds to inhibit fungal growth; (3) the use as a slimicide in the paper manufacturing industry; and (4) as a by-product of coal combustion to generate electricity (Goldwater 1971, Hodges 1977, Sorensen 1991). Organic forms of mercury, such as methylmercury, are more dangerous for fish and wildlife compared with inorganic mercury (Sorensen 1991). For example, seeds treated with methylmercury as a fungicide were found to poison birds and other wildlife in Sweden in the 1960s (Goldwater 1971). Various forms of mercury can become methylated by bacteria when discharged into water (Goldwater 1971). The biomagnification of mercury up the food chain is evident in the Laurentian Great Lakes, despite declines in mercury in recent years based on emission controls. In top predator fish, such as Lake Trout and Walleye, mercury levels are increasing in Lake Superior and Lake Erie, and decreasing in Lake Ontario, Lake Huron, and Lake Michigan. Compared with historic concentrations however, all of the Great Lakes show elevated mercury concentrations in fish (Murray and Holmes 2004, Zananski et al. 2011).

Climate change will influence how mercury behaves in aquatic ecosystems. Oxygen binds with mercury to form insoluble compounds that sink to the bottom and remain trapped in the sediments. However, as oxygen levels decrease and conditions become anoxic, this trapped mercury will be released and taken up by aquatic organisms (Yediler and Jacobs 1995). Additionally, warmer water temperatures increase the rate of methylation of mercury allowing more methylmercury to be incorporated into fish tissue, thereby, increasing the presence of mercury in the food chain (Monson 2009, Mackey 2012). Increased rainfall, runoff and resulting water level fluctuations will increase the mobilization of mercury into aquatic ecosystems (Monson 2009).

Other organohalogens that are PBTs, such as polychlorinated biphenyl (PCBs), polybrominated biphenyl (PBBs), polybrominated diphenyl ether (PBDEs,) and other pesticides are expected to show similar changes and risks as mercury. These chemicals may be similarly affected by climate change, but the data confidence is extremely limited (Noyes et al. 2009). Increased temperatures in the Great Lakes Basin from 1990-2000 led to increased volatility and atmospheric concentrations of hexachlorobenzene (HCB) and PCBs (Ma et al. 2004).

3.3. Ecological Effects and Biodiversity

Climate change will affect individual species, communities and ecosystems in unique and diverse ways, and is projected to generate novel biotic communities and ecosystems. Nituch and Bowman (2013) summarized the literature on the known response of 181 vertebrate species, many of which inhabit the Great Lakes Basin. Examples of terrestrial species currently undergoing range expansion in response to climate change include the American Bullfrog (*Rana* *catesbeiana*), Northern Leopard Frog (*R. pipiens*), American Woodcock (*Scolopax minor*), Fisher (*Martes pennanti*), and the Red Fox (*Vulpes vulpes*). Species currently undergoing range contraction include the Painted Turtle (*Chrysemys picta*), Alder Flycatcher (*Empidonax alnorum*), Canada Lynx (*Lynx canadensis*), and Northern Flying Squirrel (*Glaucomys sabrinus*).

While the number of species inhabiting an area tends to correlate with air temperature (Minns and Moore 1995, Kerr and Packer 1998), it is unclear how climate change will affect species richness in the Great Lakes Basin. At relatively local scales, warmer temperatures may result in higher species richness in some habitats. For example, Minns and Moore (1995) projected that a temperature increase of 4.5 to 5^{o}C would increase fish species richness from 12 to 60 fish species in Ontario's 137 tertiary watersheds. An increase of 10 species within the tertiary watersheds corresponds to about one new species per lake (Minns 1989). However, global diversity is projected to decline because habitat for colder-adapted species is disappearing and other habitats are changing (Woodward 1992, Kerr and Packer 1998, Warren et al. 2013).

Given the variety of local responses by species to climate change in the Great Lakes Basin, it is unlikely that species distribution, abundance and richness will respond uniformly. Given the unique combinations of limiting physical conditions (e.g., barriers to movement) and biological processes (e.g., reduced access to food), it is likely that species response will result in a patchwork of increasing and decreasing species richness and productivity, changing with time throughout the Great Lakes Basin and across the country (Nantel et al. 2014). Some species will disperse to new suitable habitats, withstand the changes through phenotypic plasticity (ability of an individual to modify behaviour, morphology or physiology), adapt through genetic change or disappear. New species will join the community resulting in community reassembly (Nituch and Bowman 2013).

3.3.1. Species Range Shifts

The distributions of many organisms are shifting in latitude or elevation in response to changing climate. A recent global analysis estimated that terrestrial species have shifted to higher elevations at a median rate of 11.0 meters per decade, and to higher latitudes at a median rate of 16.9 kilometers per decade – rates that are 2 to 3 times faster than previously reported (Chen et al. 2011). However, such rates are likely to be unattainable for many species, especially in highly fragmented or modified landscapes, such as the Great Lakes Basin and in aquatic systems with limited connectivity. When species are mobile and suitable habitat is present in the right location, range shifts may represent a viable response to changing conditions. However, species that are not able to disperse will have to confront the stress of climatic conditions that are increasingly unfavourable, as well as new species moving into their range that may compete for resources and may bring diseases and parasites. Birds and butterflies tend to be highly mobile, while plants species are immobile and, therefore, more susceptible to climate change (Ste. Marie et al. 2011). Small species with shorter life cycles are more likely to adapt to climate change (Bronson 2009). Given that ecosystems are complex assemblages of species, and the response of individual species will affect how ecosystems respond as a whole, range and abundance shifts are expected to occur independently of shifts of other species, creating new novel interactions. A global modelling study of 48,000 common and widespread species showed that, without significant reductions in greenhouse gas emissions in the next few decades, about 60% of plants and 35% of animals will lose 50% or more of their current range by 2080 (Warren et al. 2013).

Data confidence

Aquatic Species

Climate change will result in changes to water temperature and chemistry, which will alter ecosystem composition, including the distribution of freshwater fish species (Dove-Thompson et al. 2011). Northern range boundaries of fish species have shifted significantly northward (Comte et al. 2013). Over the past 30 years fish have moved northward at a rate of 12 to 17 km per decade in Ontario (Alofs et al. 2014) and could move further north by 500-600 km in the Great Lakes Basin (Magnuson et al. 1997). A fish's body temperature is essentially the temperature of the water in which it lives. Each species has a preferred temperature range, called a "thermal guild," which varies from about 10°C to 30°C +/- 5°C in the Great Lakes (Kling et al. 2003). Climate change projections show increased thermally suitable habitat within the Great Lakes Basin, though where these habitats occur are projected to shift (Lynch et al. 2010). Coldwater fishes will seek refuge further north and deeper in the water column whereas warmwater fishes will move into the vacated habitats in the warmer regions of the lakes (Lynch et al. 2010). As temperatures warm, coldwater fish, such as Lake Trout, Brook Trout (*Salvelinus fontinalis*), and Lake Whitefish (*Coregonus clupeaformis*), will face longer periods in summer confined to ever smaller suitable thermal spaces (Minns and Moore 1992, Stefan et al. 1995, Kling et al. 2003, Chu et al. 2005, Minns et al. 2014b). Coolwater fish, such as Walleye (*Sander vitreus*), will gain more seasonal habitat space in northern Ontario and loose habitat space in southern areas (Stefan et al. 1995, Shuter et al. 2002, Kling et al. 2003, Chu et al. 2005, Comte et al. 2013, Minns et al. 2014b). Warmwater fish, such as Smallmouth Bass (*Micropterus dolomieu*), will expand northward and access more suitable habitat space (Stefan et al. 1995, Kling et al. 2003, Sharma et al. 2007, Comte et al. 2013, Minns et al. 2014b), although even they will eventually be limited by climate change as warming reaches the upper bounds of physiological tolerance projected by some climate model-scenarios (Minns et al. 2014b).

Due to range expansions and contractions, competition and predation between various species, as well as within species, will be altered. For example, interspecies competition is already being observed in inland lakes where Smallmouth Bass are competing with Lake Trout for minnows. When Smallmouth Bass are absent, minnows compose 60% of the diet of Lake Trout; when Smallmouth Bass are present this decreases to 20% (Dove-Thompson et al. 2011). Prey consumption and growth of stream-dwelling Smallmouth Bass is predicted to increase by 3 to 17% by 2060 if sufficient food is available (Pease and Paukert 2014). Climate change will also lead to increased intraspecific predation. The deepening of lake thermoclines means that adult and juvenile Lake Trout will be occupying space closer together in the water column which will increase the chance of adult Lake Trout preying on juvenile Lake Trout (Dove-Thompson et al. 2011).

In a natural ecosystem, stream and river networks are connected systems in which organisms can move and migrate during periods of change (Allan et al. 2005). For example, during previous periods of climatic change, access to new habitats was critical to the survival of fishes (Briggs 1986) and aquatic invertebrates (Zwick 1981). In the contemporary landscape, rivers are fragmented by human activities, and species and populations are less able to move to new suitable habitats (Allan et al. 2005). This isolation poses one of the most significant threats to aquatic biodiversity in a changing climate (Poff et al. 2001, Poff and Day 2002). Many types of land use in the Great Lakes Basin will exacerbate the effects of climate change on streams and rivers, including the expansion of urban and industrial areas and agricultural practices.

Data confidence

Tree and Plants Species

Since ecosystem structure and function are influenced by climatic patterns, a fundamental effect of climate change on forests across the Great Lakes Basin will be potential shifts in the distribution of vegetation. Many of the dominant species in the basin may not be able to establish and reproduce under altered temperature and precipitation patterns, while other species may flourish and become dominant. Particularly in the northern region of the basin, but projected to varying degrees across all of the Great Lakes Basin, models project that the climatic niche for each species will dissipate and perhaps shift north (McKenney et al. 2010). Temperature may increase more rapidly than species are able to respond, thereby driving species range contraction.

Factors, including species-specific migration rates, soil types, migratory pathways and the presence of pollinator species, will combine to alter ecosystem composition, structure and function (Davis 1989, Roberts 1989). For some species, this will reduce population growth at the centre of their current range, and increase growth at the northern extent. Species that are not able to adapt quickly enough may be extirpated (Ste. Marie et al. 2011). Trees species whose southern edge lies within the Great Lakes Basin, such as White Pine (*Pinus strobus*), Trembling Aspen (*Populus tremuloides*), Jack Pine (*Pinus banksiana*), Red Pine (*Pinus resinosa*), and Yellow Birch (*Betula alleghaniensis*), will likely experience reduced growth rates, reproductive failure, and increased disease and mortality (Walker et al. 2002). Similarly, Joyce and Rehfeldt (2013) identified potential stress impacts on White Pine associated with climate change. Handler et al. (2012) reported on observed and projected change in tree species ranges across the United States, with deciduous forests replacing the cool mixed forests in the southern Great Lakes Basin; however, it is also predicted that most trees are expected to shift more slowly than necessary given the changes in climate.

A key milestone in climate change research has been the development of climatic niche (or climate envelope) modelling that can project the future distributions of current climate niches (i.e., climatically suitable habitats) for both ecosystems and species (McKenney et al. 2007, 2011b, Wang et al. 2012b). Models of the projected climatic suitability of several important tree species in the Great Lakes Basin have concluded that there is a general pattern of northward movement of optimal climate, accompanied by a loss of optimal climate in southern areas (Walker et al. 2002, McKenney et al. 2010, Joyce and Rehfeldt 2013, Duveneck et al. 2014). As the century progresses, the zones of suitable climate are projected to disappear across most of the Great Lakes Basin with suitable habitat occurring only in the northern upper Great Lakes for boreal species including Black Spruce (*Picea mariana*), Jack Pine, White Spruce (*Picea glauca*), Balsam Fir (*Abies balsamea*), and Trembling Aspen. For tree species in the Great Lakes-St Lawrence forest region including White Pine, Red Pine, Sugar Maple (*Acer saccharum*), and Red Oak, the amount of suitable habitat is projected to increase. Similarly, deciduous Carolinian species, such as Tulip Tree (*Liriodendron tulipifera*) and Shagbark Hickory (*Carya ovate*), are also projected to experience gains in the Great Lakes Basin. In the Lake Simcoe tertiary watershed, models project that after 2040, the northwestern quaternary watersheds may provide a more stable habitat for White Pine, while Sugar Maple populations will remain stable until 2071, after which they will sharply decline (Walker et al. 2002, McKenney et al. 2010, Puric-Mladenovic et al. *in review*). Species with current ranges in the southern Great Lakes Basin, such as Shellbark Hickory (*Carya laciniosa*), Red Mulberry (*Morus rubra*), Black Gum (*Nyssa sylvatica*), and Swamp White Oak (*Quercus bicolor*) are expected to find suitable habitat in the Lake Simcoe watershed, while others such as the Tulip Tree and Cucumber Tree (*Magnolia acuminate*) may not (Puric-Mladenovic et al. *in review*). In the northwest part of the Great Lakes

Basin, Frelich and Reich (2010) projected a broad shift from forest to savannah along the prairie-forest border. Wisconsin is likely to experience reduction in evergreen tree cover and increase in deciduous tree cover with climate change; moreover the zone between southern and northern forest types is expected to shift northward, potentially out of the state by the end of the century (Notaro et al. 2013). Stankowski and Parker (2011) showed that species that vary across time periods such as willows (*Salix* species) are difficult to model as the variability within the species models greatly influenced the direction and magnitude of projected distributional change. Beyond climate niche models, some studies have incorporated other key factors that influence species distributions and shifts such as microclimates and species migration rates (Matthews et al. 2011, Fisichelli et al. 2013). A model of 63 native tree species suggests that 13 new reserves should be added to the existing reserve network in Ontario to mitigate potential migration due to climate change (Crowe and Parker 2011). However, in the United States portion of the Great Lakes Basin, the expanded reserve strategy was not effective under a high emission scenario (Duveneck et al. 2014).

Species distribution models have also been developed that depict habitat changes for 134 tree species across the eastern United States (Prasad et al. 2007, Iverson et al. 2008). Studies using species distribution models have projected that tree species in the eastern USA have a low probability of colonizing habitat beyond their existing ranges over the next 100 years (Iverson et al. 2004). Forest fragmentation, particularly across the southern portions of the Great Lakes Basin, means that widespread tree migration will be less likely to occur in response to climate change (Iverson et al. 2004).

Due to projected increases in the occurrence of large fires, pest outbreaks and extreme storm events, these factors may become the driving force for change in forest species composition (Price et al. 2013). Increased natural disturbance may favour pioneer deciduous broadleaves or early successional ecosystems that are dominated by fire-adapted species (Hogg and Bernier 2005, Flannigan et al. 2005, Price et al. 2013). These conditions could alter biodiversity to reflect more fire-origin forest stands and younger forests (Weber and Flannigan 1997). The effects of changes due to fire dynamics could potentially overshadow the direct effects of climate change on the distribution and abundance of tree species (Weber and Flannigan 1997). Changes in species composition of forest in the Great Lakes Basin over time could also have an influence on future forest fire frequency and intensity. Forests dominated by deciduous trees are less prone to fires due to the lower flammability of deciduous trees (Terrier et al. 2013). With projected increases in prevalence of deciduous species, such as sugar maple, the predicted increase in fire frequency due to climate change could potentially be offset by changing species composition (Terrier et al. 2013). These projected changes to species composition and distribution will have consequences on forest ecosystem services (Matthews et al. 2014).

Data confidence

Wildlife Species

Some animals will shift their distribution and increase their abundance. Other species, with a narrow range of temperature and precipitation requirements, or with specific habitat requirements, will most likely experience declines, local extirpations or extinction (Varrin et al. 2007, Price et al. 2013). As northern latitudes warm, temperature-limited species at the northern extent of their current ranges may shift further north, though some may encounter significant barriers, such as the Great Lakes. Wildlife inhabiting the southern edges of their current ranges may encounter increased biotic (e.g., parasites, competition) and physiological stresses that will result in range contraction (Bowman et al. 2005, Varrin et al. 2007). In the Great Lakes Basin, landscape fragmentation may impede migration and, consequently, reduce the ability of species to respond to a changing climate (Walpole and Bowman 2011). Furthermore, the speed at which climate niches are projected to shift, along with barriers such as the Great Lakes, exceed the movement potential of small mammals (Francl et al. 2010).

Climate change may promote an increase in ‘generalist’ species and a decrease in ‘specialist’ species, leading to a decline in species diversity (Walpole and Bowman 2011). Examples of species showing range and abundance changes in the Great Lakes are growing. Bowman et al. (2005) documented rapid northern shifts of Southern Flying Squirrels (*Glaucomys volansin*) from the southern Great Lakes into Ontario over a series of years with relatively warm winters and higher availability of food (tree mast, such as acorns, nuts and other seeds), followed by range contraction to its historical limit after a very cold winter and mast failure. Moose (*Alces alces*) and White Tailed Deer (*Odocoileus virginianus*) populations are projected to increase in parts of their range as the climate warms, which will result in increased Grey Wolf (*Canis lupus*) density (Rempel 2012). For birds, which are clearly very mobile, several recent papers document range shifts, with changes dominated by northern shifts over a range of distances, as well as some evidence for shifts in other directions (Hitch and Leberg 2007, LaSorte and Thompson 2007, Zuckerberg et al. 2009). National Audubon Society (2014) projected an average loss of 76% loss in summer range and a 45% loss in winter range for 90 climate-threatened bird species in the Great Lakes Basin.

3.3.2. Genetics Changes

The ability of local and regional populations of species to cope over the short term and potentially adapt to altered environmental conditions will depend on the type and extent of genetic variation within local populations. Increasingly, research is looking at genetic influences, as well as the role of genetic diversity in populations. Although results suggest that some species may be able to respond quickly to changes, many others may lack the genetic variation that might allow selection, and thus adaptation, to occur.

Data confidence

Aquatic Species

Very little is currently known about the scope and variation of thermal tolerances and adaptive potential within and among populations and evolutionary lineages of important Great Lakes Basin fish species. A long-term study has shown that both ice-out and smallmouth bass spawning season have advanced by 2 days per decade (M.S. Ridgway, pers. Comm.). Several studies have been conducted on the thermal physiology and genetic diversity of Great Lakes Basin Lake Trout and Brook Trout (McDermid et al. 2012, 2013, Stitt et al. 2014, Kelly et al. 2014). McDermid et al. (2007) examined the environmental and genetic influences on the life history traits of Lake Trout and found that both local adaptation and phenotypic plasticity will have an impact on life history variation. Many factors, such as temperature, habitat and predation, have been found to influence life history traits (Halbisen and Wilson 2009, McDermid et al. 2010). Climate is strongly linked with rate traits, such as pre-maturation growth, age at maturity and maximum age, but not size traits, such as length at maturity and maximum size (McDermid et al. 2010). Climate change is expected to have an impact on the life history traits of Lake Trout (i.e., faster pre-maturation growth, earlier age at maturity and decreased longevity), and effects are likely to vary on a local scale (McDermid et al. 2010). Brook Trout show greater phenotypic plasticity and local adaptation in thermal physiology (McDermid et al. 2012, Stitt et al. 2014) than Lake Trout which have limited variation within and among populations (McDermid et al. 2013, Kelly et al. 2014). Brook Trout from southern populations have increased tolerance for warmer temperatures than northern populations (McDermid et al. 2012, Stitt et al. 2014).

Data confidence

Tree and Plants Species

Genetic and physiological mechanisms linked to superior growth and adaptability of important Great Lakes Basin tree species in diverse climatic habitats are largely unknown, and information, such as genetic diversity and allele richness, is limited. Lu et al. (2014) describe analysis of adaptive capacity and growth potential of White Spruce. Tree growth for seed sources from south-central Ontario and southwestern Quebec outperformed even local provenances at spatially and climatically heterogeneous sites across Ontario, suggesting these species possess a promising candidate genetic base for intraspecific assisted migration. They theorize that White Spruce species colonizing these locations migrated from two glacial refugia rather than one, resulting in a broader genetic base and the expression of genetic alleles for superior tree growth and climatic adaptability.

Genetic climatic niche modelling, such as that conducted for White Pine by Joyce and Rehfeldt (2013) can be used to assess the relative spatial and temporal vulnerability of forests, tree species and populations to climate change. By modelling the response of genetically derived species attributes of provenances, such as phenology, growth potential and cold hardiness, to 34 climatic variables, Joyce and Rehfeldt (2013) determined that maximum temperature and interactions between precipitation and temperature dominated the overall model; however, they caution that the real adaptation of populations is a function of seasonal temperature regimes. Thomson et al. (2009) also demonstrated the temperature dependency of seed source growth for Black Spruce, though the relationship was less apparent for precipitation.

Projected redistributions incorporating both the climate and ecological genetic profile suggest that White Pine is one of many species poorly equipped to persist in its contemporary zone (Joyce and Rehfeldt 2013). Thomson and Parker (2008) and Thomson et al. (2009) found that maximum growth for Jack Pine and Black Spruce originated from their central interior ranged-seed sources; whereas seed sources north of the Great Lakes Basin will benefit in terms of height growth with increased temperatures. For the most southerly regions of Black Spruce distributions, there are no best matched seed sources available. Thomson et al. (2009) postulate that the genotypes that favour the persistence of species in the harsher conditions of their southern and northern limits may not correspond to the genotypes that select for superior growth. Thomson et al. (2010) found that shifts in optimal breeding zones for White Spruce differed depending on the climate change model used in analyses. Using the HaDCM3 and CGCM2 there was little change in breeding zones by 2041-2070, whereas breeding zones were much narrower using the CSIRO model.

Data confidence

Wildlife Species

In the short term, phenotypic change will likely be a more important mechanism for coping with changing habitat conditions; but as climate change accelerates, plastic responses may be inadequate for providing long-term solutions to species survival (Nituch and Bowman 2013).

Genetic diversity enhances species ability to respond to climate change, and the loss of genetic diversity can lead to demographic collapse and reduced fitness (Spielman et al. 2004, Hoffmann and Sgro 2011). For example, in the last 40 years, Canada Lynx populations have contracted at the southern range edge by almost 200 km and current populations along the contracting edge exhibit lower genetic variability than core Canada Lynx populations, the result of warmer winter temperatures and possibly changes in forest species composition (Koen et al. 2014a,b). Climate change can alter genetic connectivity among populations and many populations are projected to decrease as a consequence of climate change, increasing the risk of losing genetic variation due to genetic drift (Nituch and Bowman 2013). The rapid northward expansion of some species may lead to new or renewed contact between species resulting in increased incidence of hybridization, such as between the Carolina Chickadee (*Poecile carolinensis*) and Black-capped Chickadee (*Poecile atricapillus*; Varrin et al. 2007) and between the Northern Flying Squirrel and the Southern Flying Squirrel (Bowman et al. 2005). While hybridization can result in a decrease in diversity and fitness (e.g., Carolina and Black-capped Chickadee), there can also be positive outcomes in terms of genetic variation. New combinations of genes can facilitate rapid evolutionary adaptation, putting new and emerging species at an advantage. Hybridized Darwin's finches (*Geospiza spp.*) are demonstrating morphological changes that are better suited to their new climatic niches (Grant and Grant 2010). Fishers are also exhibiting hybrid vigour in recolonizing populations (Nituch and Bowman 2013).

3.3.3. Altered Phenology

For many species, seasonal changes in temperature trigger transitions in seasonal life cycle events. In addition to direct impacts on changes in phenology (the relationship between climate and periodic biological phenomena, such as bird migration or plant flowering), warming temperatures can indirectly influence other seasonal cycles that affect species (e.g., lake stratification), both of which can lead to asynchrony. Asynchrony is the discordance between or among ecological processes, and climatic changes can reduce synchrony between interacting species (Parmesan 2006). Based on ecological studies in parts of Canada and the United States, phenological changes include the timing of bloom, bud and leaf emergence, which would be influenced by temperature and heat accumulation (Beaubien and Freeland 2000), as well as the timing of breeding, migration and stages of development for invertebrates, mammals, amphibians and reptiles (Mortsch et al. 2003). Implications of changes in phenology are in many cases unclear, but there is a growing body of work documenting these changes.

Data confidence

Aquatic Species

Although photoperiod, an ecological cue, will not change, water temperature, which influences the timing of spawning events and the growth and survival of biota, will change with climate (Reist et al. 2006, Wrona et al. 2006). Photoperiod is a key driver in the timing of the life history of fishes. For some species, such as Lake Trout, decoupling of ecological cues is expected to significantly impact population processes (Shuter et al. 2012). Asynchrony caused by a mismatch between photoperiod and flow and temperature in rivers can increase egg and larval mortality and change interspecific interactions (Jones et al. *in review*). Recent work by Schneider et al. (2010) suggests that both ice-out and Walleye spawning are occurring earlier in the Great Lakes Basin. Increases in winter and spring temperatures at mid-to-high latitudes caused earlier spring phenologies for amphibians (Schwartz et al. 2006, Coristine and Kerr 2011), such as earlier shifts in the onset and breadth of breeding in southern Ontario (Walpole and Bowman 2011, Walpole et al. 2012). Over a four-decade period, from 1970 to 2010, first date of emergence for the Northern Leopard Frog has shifted 22 days earlier, and the initiation of calling has shifted 37 days earlier (Klaus and Lougheed 2013). The American Toad (*Bufo americanus*) has also started calling 19 days earlier in response to warmer spring temperatures (Klaus and Lougheed 2013).

Data confidence

Tree and Plant Species

Decoupling of ecological cues used by plants likely will occur, but the extent and significance is not well understood (Wrona et al. 2006). Studies have found that vegetation in the northern hemisphere's mid-to-high latitudes is particularly sensitive to changes in spring temperatures (Fang et al. 2014). Earlier warming in spring and later cooling in autumn contribute to an earlier start for plant growth and a longer growing season (Mortsch et al. 2003, Schwartz et al. 2006). If other factors, such as nutrients, water availability and sunlight, are not limited, plant productivity is expected to increase (Mortsch et al. 2003). McKenney et al. (2010, 2011b) discuss that climate niches will become increasingly small and scattered or may even disappear as a result of asynchrony between major climate gradients of temperature and precipitation, with an end result potentially being novel climate combinations for large portions of Ontario.

Data confidence

Wildlife Species

Increases in winter and spring temperatures have caused earlier occupation of breeding habitat and emergence of hatchlings by bird species (Waite and Strickland 2006). Given that the timing of spring life-cycle stages of many insect and plant species has already advanced in response to warmer temperatures (Harrington et al. 2001, Logan et al. 2003), a potential consequence for migratory birds is a phenological mismatch between seasonal peaks in plant or insect biomass and hatchling growth and development (e.g., Rodenhouse et al. 2009, Knudsen et al. 2011). For example, the North American Wood Warbler preys upon Eastern Spruce Budworm, which is emerging earlier in the season in response to climate change; however, Wood Warblers are not breeding and migrating earlier, leading to asynchrony between the species (Nituch and Bowman 2013). Predator-prey and parasite-host relationships may be disrupted or decoupled, and important species may disappear from local habitats (National Assessment Synthesis Team 2001). For example, the Canada Lynx-Snowshoe Hare (*Lepus americanus*) cycle may be decoupled with climate warming (Stenseth et al. 2002, 2004). Canada Lynx are specialized hunters that prey almost exclusively on snowshoe hare. Therefore, Lynx population size is closely tied to Snowshoe Hare distribution and abundance, where synchrony is greatest during cold periods and tends to break down during warm periods (Scott and Craine 1993). Accordingly, the North Atlantic Oscillation significantly affects the synchronous relationship between Canada Lynx and Snowshoe Hare because of its influence on snow depth and structure, which in turn affects the distribution and abundance of Lynx competitors such as the Coyote (*Canis latrans*), Fisher, and Bobcat (*Lynx rufus*; Stenseth et al. 2002). Unlike its competitors, the Canada Lynx is a highly effective deep snow hunter, and less snow cover could create more competition for Lynx. In addition, Bobcats, Coyotes, and Fishers prey on a more diverse range of species and, therefore, are better equipped to adapt to changing climate than specialists such as the Canada Lynx. Long-lived mammals may experience suboptimal reproductive and hibernation schedules as these events are often controlled by photoperiod rather than temperature, whereas this will be less of an issue for small rodents (Bronson 2009).

3.3.4. Habitat Alteration

Evidence suggests that the synergistic effects of habitat fragmentation, habitat loss and climate change will contribute significantly to a decline in biological diversity (Opdam and Wascher 2004, McLaughlin et al. 2005, Brooke et al. 2008, Nituch and Bowman 2013). These effects will generate an asymmetric response by species throughout the Great Lakes Basin. For example, in some cases the negative effects of habitat fragmentation may be overshadowed by the positive effects of increased temperatures for some species. In the Great Lakes Basin, the northward expansion of the Hooded Warbler (*Wilsonia citrina*) and the Southern Flying Squirrel appears to have been simultaneously facilitated by increased temperatures and limited by habitat fragmentation (Bowman et al. 2005, Melles et al. 2011).

Data confidence

Aquatic Species

Many studies project that habitat for warm-, cool- and coldwater fish will increase in some of the deep stratified lakes if dissolved oxygen concentrations do not become limiting (Mortsch et al. 2003). For example, in large deep lakes, such as Lake Huron, Lake Superior and Lake Michigan, a warming of 3.5^{o}C is expected to increase available thermal habitat for warmwater fishes that occupy the epilimnion during summer (Allan et al. 2005). And cold- and coolwater fishes are also expected to benefit because this level of warming will not exceed thermal tolerance and will promote metabolic activity (Magnuson et al. 1997).

In contrast, smaller and shallower lakes may experience a significant loss of cold hypolimnetic volume and, consequently, coldwater fish may lose habitat (Allan et al. 2005, Magnuson et al. 1997). Lake Trout will likely disappear from a number of the shallower lakes in Ontario as temperatures rise. Jackson (2007) found that end of summer thermoclines typically reach 15m in the Atikokan area of northwestern Ontario. Lakes with maximum depths of less than 20m were assessed as having high risk of losing Lake Trout populations due to hypolimnion habitat loss associated with warming, whereas lakes with maximum depths 20 to 25m were considered at moderate risk of losing Lake Trout populations (Jackson 2007). Minns et al. (2009) project that by 2100 Lake Trout habitat in Ontario will be reduced by about 30%, with steep declines (up to 60%) in the south and east only partly offset by increases (>30%) in the northwest.

Coldwater stream and river habitat for some fish species will decrease as surface water and groundwater temperatures increase (Mortsch et al. 2003). With climate change, nearly 50% of the cold- and coolwater stream habitat could be lost in the United States (Eaton and Scheller 1996). Meisner (1990) projected a 30% and 42% decline in total Brook Trout habitat, and fragmentation of that habitat in two southern Ontario streams in response to a climate change scenario that projected a 4.1^{o}C increase in water temperature. But concentrating on temperature alone may not provide the true picture of the effects of climate change on river ecology (Jager et al. 1999). For example, fall spawning Brook Trout and Brown Trout (*Salmo trutta*) demonstrate a strong negative relationship with high flow frequency in winter, likely due to redd scour (the scouring of redds or nests in the gravel; Wenger et al. 2011), while Jager et al. (1999) noted that while scouring mortality does happen it may be offset by the seasonal shift in flow that reduces the dewatering of redds.

One of the most significant effects of climate change on wetland ecosystems will be on the distribution and abundance of vegetation. For example, in locations where water levels decline or are inconsistent, wetland vegetation communities requiring little water, such as sedges, grasses, wet meadows and trees, will replace emergent and submergent species (Mortsch et al. 2003).

Effects on wetland faunal diversity will be significant. For example, Doka et al. (2006) assessed the vulnerability of 99 fish species inhabiting coastal wetlands in the lower Great Lakes to climate change and reported that vulnerable species included coolwater and warmwater spring spawning species that use shallow, vegetated water. Less vulnerable species included coldwater fall spawners (such as Lake Trout and Lake Whitefish) that use deeper, more open water habitats to spawn. Avifauna will be impacted as well. For example, the number of spring-time wetlands is related to the annual waterfowl production and breeding pair density, and the water conditions in May play a critical role in waterfowl breeding success. The quality of breeding habitat depends on the type, quality and permanence of wetland complexes because the persistence of wetlands through the waterfowl breeding season is important for brood survival (Clair et al. 1998).

Mortsh et al. (2006) developed the Hydrological Vulnerability Index to examine the vulnerability of wetland-dependent bird species due to climate change; the Index ranks species based on life history characteristics, such as marsh dependency, nesting habitat, nest location and foraging habitat. Chu (*in review*) modelled two species – the American Coot (*Fulica americana*) and Pied-billed Grebe (*Podilymbus podiceps*), which are sensitive to hydrological changes in Great Lakes Basin wetlands. The habitat alterations due to climate change for these species will vary across the five basins. In the Lake Huron basin, under an A2 scenario, ~70% of the American Coot habitat and ~50% of wetlands with Pied-billed Grebe may have mid-to- high vulnerability by 2071-2100. In the Lake Erie basin, nearly all of the habitat for both species may have mid or high vulnerability under an A2 scenario by 2071-2100. Changes in precipitation and temperature due to climate change in the Upper St. Lawrence basin may greatly reduce habitat for both species (Chu *in review*).

Data confidence

Trees, Plants and Wildlife Terrestrial Species

Given that some species will fail to shift their range in response to changing climatic niches because of habitat fragmentation (Taylor et al. 1993), the risk of extirpation is increased (Travis 2003, Inkley et al. 2004, Opdam and Wascher 2004). For example, many forest plant species inhabiting highly fragmented landscapes show limited, if any, ability to colonize new habitat patches (Varrin et al. 2009). Successful colonization is higher in more contiguous and connected landscapes and waterscapes (Honnay et al. 2002, Nantel et al. 2014). This climate change-habitat fragmentation synergy (see Box 4) is a significant problem in southern Ontario because habitat fragmentation is severe (Varrin et al. 2009). For example, the Southern Flying Squirrel, a forest-obligate species, has spread north only through the contiguous habitats of the Precambrian shield in eastern Ontario, but not through the fragmented forests of the southwest (Bowman et al. 2005).

Drying soil resulting from warming air temperatures is projected to reduce tree cover across southern and western Wisconsin, establishing a more prairie-like environment (Notaro et al. 2013). Productivity in the Great Lakes forests are likely to switch from being temperature- to water-limited by the end of the century (Peters et al. 2013).

Box 4: Synergy

Synergy denotes the interaction of processes whereby the total effect is greater than each process acting independently. It is anticipated that the synergistic effects of habitat fragmentation, habitat loss and climate change will contribute to the decline of biological diversity. Populations in fragmented landscapes are more susceptible to ecological stressors, such as climate change, than those in connected landscapes, and reduced population connectivity increases the risk of extinction (Nituch and Bowman 2013). Species inhabiting regions with intensive land development and significant landscape fragmentation, as seen in the Great Lakes Basin, are particularly at risk. Similar synergies can occur between climate change and pathogens, or climate change and invasives, or combinations of both (Nituch and Bowman 2013, Nantel et al. 2014).

3.3.5. Pathogens and Parasites

Pathogens and their vectors are sensitive to changes in temperature, rainfall and humidity (Harvell et al. 2002) and, therefore, climate change affects the distribution, seasonality and severity of diseases (Le Conte and Navajas 2008). Given that most pathogens and vectors are limited by temperature, warmer temperatures could increase the incidence of disease by increasing vector population size and distribution and increasing the length of exposure time (Lemprière et al. 2008, Nituch and Bowman 2013). Climate change may also affect the pesticides and biocides used to prevent outbreaks, as well as the timing and intensity of chemical application, thus creating further potential chemical impacts on the ecosystem (Coakley et al. 1999, Bloomfield et al. 2006, Schiedek et al. 2007, Noyes et al. 2009).

Data confidence

Aquatic Species

Warmer water temperatures may result in suboptimal thermal regimes that are stressful for fish and can render their immune systems more vulnerable to parasites and diseases (Barton and Iwama 1991). This will result in decreased growth and productivity, as well as increased incidence of mortality (Wrona et al. 2006). For example, as southern species migrate northward, they could carry with them diseases not currently found at northern latitudes (Wrona et al. 2006). Climate change may also promote the establishment of new parasites through the accidental or intentional introduction of non-native invasive species.

Opportunities for parasite infection can result from a change in habitat (e.g., higher temperatures and shorter cold periods can accelerate parasite development) or through the host fish (e.g., shifts in fish feeding affecting parasite development, Greifenhagen and Noland 2003). Climate change may also lead to alterations in parasite-host interactions due to phenological changes (Paull and Johnson 2014). Higher parasite development rates may increase burdens on fish hosts, which are likely to result in poorer health and decreased productivity of the population (Marcogliese 2001). Shifts in thermal regimes that result in increased local densities of hosts, especially intermediate hosts such as planktonic or benthic invertebrates, are also likely to increase parasite species diversity (Marcogliese 2001).

Data confidence

Tree and Plants Species

Late spring frosts are known to play a key role in terminating disease outbreaks such as Dutch Elm disease (*Ophiostoma* spp.). However with climate change, late spring frosts are projected to become less frequent, which could have significant implications for disease outbreaks. Dukes et al. (2009) suggest that it is more difficult to anticipate the response of forest pathogens under a warmer future due to complex modes of infection, transmission, survival and tree response.

Data confidence

Wildlife Species

Climate change will expose wildlife to new or increasing parasite loads. Moose, for example, are already experiencing health effects (e.g., increased heart rate and weight loss) due to heat stress caused by recent climate warming (Lenarz et al. 2009) and, therefore, may be at greater risk of contracting parasitic and infectious diseases (Murray et al. 2009). In some cases, invasive species will transmit deadly diseases and parasites to indigenous species. For example, along the central and northwestern regions of the Great Lakes Basin, Moose population could decline in response to increased interaction with the highly invasive White-tailed Deer (Thompson et al. 1998, Rempel 2012), which transmits the deadly Brain Worm (*Parelaphostrongylus tenuis*) to Moose through an intermediate host. Coupled with increased predation by Grey Wolves, these complex interactions will cumulatively affect the distribution of Moose (Rempel 2012).

Lyme disease is a significant threat to human health caused by a pathogen introduced by some species of ticks. Until recently, ticks have been restricted to localized areas along the north shore of Lake Erie, Lake Ontario and the St Lawrence River due to temperature limitations. However, due to longer growing seasons resulting from increased temperatures and decreased tick mortality during milder winters, ticks are projected to spread beyond their current range by ~200 km by 2020 and to the entire Great Lakes Basin and beyond by mid-century (Ogden et al. 2006). In North America, other tick-borne diseases such as babesiosis, anaplasmosis and Powassan encephalitis, as well as mosquito-borne diseases such as dengue and West Nile virus, may also expand their ranges if there is a northern expansion of vector populations (Epstein 2001, Greer et al. 2008).

3.3.6. Invasive Species

Invasive species have been defined as species beyond their natural range that have negative economic, environmental and/or human health effects. Due to climate change, native species are likely to become more poorly adapted to the local environment, whereas non-native species may be more competitive under a new climate (Walther et al. 2009). Climate change is likely to interact with and affect the distribution, spread, abundance and effects of invasive species (Gritti et al. 2006, Walther et al. 2009).

Climate change and invasive species are often treated as independent problems yet they interact and can reinforce each other (Pyke et al. 2008, Walther et al. 2009, Smith et al. 2012). Invasive species may also influence the rate and impact of climate change on ecosystem function through the alteration of natural processes, such as fire cycles and carbon sinks (Pyke et al. 2008, Smith et al. 2012). This positive feedback loop occurs whereby climate change creates new habitat for invasive species and those invasive species make ecosystems more susceptible to the impacts of climate change (McNeely 2000). Together, climate change and invasive species could compromise the fitness of native species (Mainka and Howard 2010) and alter species relationships and community composition (Tylianakis et al. 2008). Changes in invasive species also affect changes in pesticide and biocide uses, thus creating a chemical impact on the ecosystem. The effectiveness of pesticides and biocides used to control invasive species may decrease (Hellmann et al. 2008). This decreased effectiveness could occur for many reasons, including increased tolerance of invasive species or decoupling of biocontrol agents and their targets (Hellmann et al. 2008).

Data confidence

Aquatic Species

For decades, invasive species have impacted the ecology and economy of the Great Lakes Basin; climate change will likely exacerbate these effects. Aquatic invasive species have entered the Great Lakes through bilge water discharge by ocean-going vessels on the St. Lawrence Seaway and by accidental and deliberate introduction of fish and other species (Taylor et al. 2006). As of 2009, 186 aquatic invasive species were present in the Great Lakes Basin (Ontario Biodiversity Council 2010). Warmer waters, reduced ice cover and altered stream flows may increase the chances of establishment of invasive species in the Great Lakes and inland waters of Ontario (Rahel and Olden 2008). Native zooplankton and fishes could become threatened by invasive species, such as bloody-red mysid shrimp (*Hemimysis anomala*; Pagnucco et al. 2015). Species currently limited to more southerly aquatic ecosystems in the United States may be able to extend their range northward in warming waters through intentional (e.g., disposal of bait fish) or accidental releases (e.g., bilge water). For example, most Ponto-Caspian invasive species originate in warmer waters, which provide them a competitive advantage over cool- and coldwater species inhabiting the Great Lakes (Schindler 2001). Some current invaders, such as the spiny waterflea (*Bythotrphes longimanus*), may actually decline as water temperatures increase because of their coolwater preference (Pagnucco et al. 2015).

Natural invasion through connected waterbodies is also likely as temperatures increase and become suitable for warmwater species as was the case for White Perch (*Morone americana*) in the Great Lakes (Comte et al. 2013). As lake and river waters warm, the distribution of cool- and coldwater fish species will be reduced. In some rivers and lakes there will be a significant increase in the distribution and abundance of warmwater species (Casselman 2002, Casselman and Scott 2002, Kling et al. 2003, Shuter and Lester 2004, Chu et al. 2005). Mandrak (1989) identified 27 species common in the United States that could move northward into Ontario with climate change. These species include non-native fish species that are currently restricted to the lower Great Lakes and that could expand their ranges (Mandrak 1989). It has been suggested that warming associated with a doubling of atmospheric CO_2 could result in a 500-600 km northward shift in the zoogeographical boundary of freshwater fish species (Magnuson et al. 1997). For example, it is estimated that a 4^oC warming results in a 640 km northward latitudinal shift in thermal regimes for macroinvertebrates (Sweeney et al. 1992) and a 500 km northward shift for Smallmouth Bass and Yellow Perch (Allan et al. 2005). The northern expansion of Smallmouth Bass would result in the extirpation of many native minnow species, as well as adversely impacting Lake Trout, a native top predator (Jackson and Mandrak 2002, Vander Zanden et al. 2004, Pease and Paukert 2014). Climate and connectivity modelling was used to assess the invasion potential of cool- and warmwater invaders in the Canadian Great Lakes Basin and found that southern Ontario drainage basins and northern watersheds in the Lake Superior drainage basin were most vulnerable to aquatic invasive species (Melles et al. 2015). Climate change could improve conditions for wetland plant invaders, such as Purple Loosestrife

(*Lythrum salicaria*) and Phragmites (*Phragmites australis*; Koslow 2010). Warmer winter temperatures are also expected to increase the northern range edges of bird species (Cadman et al. 2007), including the range of the invasive Mute Swan (*Cygnus olor*; Weaver 2012). It is important to note that while birds, many aquatic insects and plants can disperse aerially, fish and other aquatic organisms do not and may not be able to migrate due to the isolated nature of some lakes and the presence of dams on some waterways (Allan et al. 2005).

Data confidence

Trees, Plants and Wildlife Terrestrial Species

Climate change will affect the distribution and abundance of terrestrial invasive species in a number of ways. Warming will provide new habitat, while allowing some species to extend their reproduction period and expand their northern range limits (Walther et al. 2002). The White-footed Mouse (*Peromyscus leucopus*) has been expanding its range northward with warmer winter conditions, and this trend is likely to continue into the future according to climate models (Roy-Dufresne et al. 2013). The White-footed Mouse is an important host for the pathogen responsible for Lyme disease, which would move northward along with its host. The northern range boundary of the Virginia Opossum (*Didelphis virginiana*) coincides with the -12°C January minimum temperature isotherm (1970-1993; Ontario Atlas of Mammals), and its expansion northward has been linked to climate warming (Myers et al. 2009). Using climate modelling, Bradley et al. (2010) found that two of the three most dominant and aggressive invasive plants in the southern United States, Privet (*Ligustrum sinense; L. vulgare*) and Kudzu (*Pueraria lobata*), pose an invasion risk to the southern Great Lakes by 2100.

Forests across the Great Lakes Basin are already under considerable stress from invasive pests, including the Gypsy Moth (*Lymantria dispar dispar*), Spruce Budworm (*Choristoneura* spp.), and the Asian Long-horned Beetle (*Anoplophora glabripennis*). Available moisture has a strong impact upon a tree’s susceptibility. For example, Spruce Budworm outbreaks could occur more frequently in the warmer margins of the host tree's range, and have already been identified as being associated with periods of drought (Chiotti and Lavender 2008). As climate changes, length and frequency of drought are projected to increase, which could have significant implications for vulnerability of trees to infestations.

Dukes et al. (2009) concluded that there would be more insect pest damage in northeastern North America due to increased metabolic activity in active periods and increased winter survival. There is growing concern about the potential arrival of the Mountain Pine Beetle (*Dendroctonus ponderosae*) in Ontario (Logan et al. 2003, Lemprière et al. 2008). Dukes et al. (2009) also suggest that it is more difficult to anticipate the response of forest pathogens under a warmer future due to complex modes of infection, transmission, survival and tree response. Climate change will increase the amount of climatically suitable habitat for the Gypsy Moth, allowing it to invade further west (Régnière et al. 2009). For example, there is a strong association between patterns of emergence of the Gypsy Moth, climatic suitability and defoliation, which is expected to threaten hardwood forest resources as warmer temperatures enable the Gypsy Moth to spread further north and west (Régnière et al. 2009). Higher winter temperatures are interfering with the diapause portion of the Gypsy Moth life cycle, resulting in a low hatch rate of eggs in the spring and, thereby causing a northward range shift due to higher hatching success rates (Régnière et al. 2012). Warmer nocturnal temperatures increase flight activity of invasive Pine Processionary Moth (*Thaumetopoea pityocampa*) females, enabling them to disperse over greater distances

(Battisti et al. 2006). Increasing temperatures could enable an additional generation of this invasive moth each year (Walther et al. 2002). Climate change will allow the Bean Leaf Beetle (*Cerotoma trifurcata*) to expand its distribution in the Great Lakes Basin and become an increasingly severe pest (Berzitis et al. 2014). The historic range of Mountain Pine Beetle has been limited by climate, but warmer temperatures have allowed it to complete its life cycle in one year instead of two and rapidly spread eastward into new habitats in Canada to now threaten Jack Pine and other pine species (Logan and Powell 2001, Lemprière et al. 2008, Sambaraju et al. 2011). Models have predicted that the Spruce Budworm is likely to shift northward over the next 50 years due to climate change; however, the spread is limited by the range of host plants (Candau and Fleming 2011, Régnière et al. 2012).

3.4. Summary of Community and Human Impacts of Climate Change in the Great Lakes

In addition to ecological and physical effects, climate change has both direct and indirect implications for the well-being of communities in the Great Lakes Basin. As the climate changes and the health of the Basin is affected, so will the ecosystem services provided (TEEB 2011; MEA 2005). Likewise, climate change will directly impact social, economic, cultural and human health aspects of communities (IPCC 2014), which in turn influences the management of the Basin. While a full assessment of the state of the science related to socio-economic, cultural and human health impacts of climate change was beyond the scope of this report, a few prominent studies did surface during the review process and are reported on here. This section therefore, provides a limited synthesis of major implications of previously mentioned ecosystem-based climate change impacts for socio-economics and human health within Great Lakes communities.

The Great Lakes Basin is of importance to a range of industries, as well as the recreation, tourism and agricultural sectors, many of which will be impacted by climate change. A 2014 report by the Mowatt Centre estimated that low water levels due to climate variability and change are expected to cost over $9.6 billion in economic losses (Schlozberg et al. 2014). The International Upper Great Lakes Study (IUGLS, 2012) assessed the plausible impact of climate change on water levels and flows using multiple climate change scenarios in the context of ranking the robustness of alternative regulation plans for the outflows for Lake Superior and the implications to domestic, municipal and industrial water uses, commercial navigation, hydroelectric generation, shoreline property, recreational boating and tourism as well as ecosystem response. In the case of agriculture, Cabas et al. (2010) report potential increases in average crop yield despite increased temperature and rainfall variability in Ontario. DeLaporte (2014) explored the potential yields and costs of growing energy crops, such as switchgrass and miscanthus, in Ontario. The results indicated yield increases or decreases depending on the climate model and scenario used. Similarly, Berzitis et al. 2014 applied bioclimatic envelope models to examine the possible changes in the range of the Bean Leaf Beetle pest and soybean, its most important agronomic host plant, in North America. The findings show that projected changes in range suitability depend on the choice of GCM for both the beetle and soybean; however, some models project more suitability for the pest and soybean. Dominguez-Faus et al. (2013) report that climate change may increase rainfall intensity, as well as irrigation requirements, of corn ethanol in the Great Lakes Basin, which may require infrastructure development to increase water catchment capacity. These impacts to agriculture have significant implications for land and water use in the Basin, along with changing the profile of risks associated with agricultural runoff and shipping.

The extensive use of Great Lakes waterways for shipping, hydroelectric power generation, recreation and tourism will also be impacted by climate change due to fluctuations in both water levels and decreasing ice cover (Schlozberg et al. 2014). In a study focusing on grain shipping in the United States, Attavanich et al. (2013) project a growing importance for Great Lakes routes due to crop mix shifts and a longer shipping season. Several macroeconomic analyses of impacts of climate change and water level variability in the Great Lakes suggest that trade routes, access to ports and marinas and the host of downstream economic consequences are increasingly important considerations due to climate change and variability (Schlozberg et al. 2014, Seelbach et al. 2014). Schlozberg et al (2014) estimated costs of over $1.9 and $2.9 billion in losses for commercial shipping and hydroelectric sectors, respectively.

Another key economic impact associated with the Great Lakes is the shifting profile of natural hazard risks that pertain to both public and private assets. Many of these assets are not insured against certain natural hazards, namely overland flooding, thus making many economic sectors vulnerable to losses as extreme climate becomes more severe. While it is beyond the scope of this report to provide a detailed review of insurance-related vulnerabilities, many local and regional climate change vulnerability assessments have defined these risks in more detail. Such work is described in studies, such as Wuebbles (2010), Feltmate and Thistlewaite (2012), and many staff reports to local city councils across the Great Lakes Basin. Other important considerations include property value loss if shorelines recede, legal battles driven by variable lake levels, shoreline erosion and public and private infrastructure impacts, port management and dredging considerations (IUGLS 2012).

The health of ecosystems in the Great Lakes Basin is of great importance to Great Lakes recreational and tourism sectors. Climate change presents risks and opportunities for nature-based tourism due to changes in ecosystem function in natural heritage areas. For instance, the Lake Simcoe watershed is expected to experience decreased ice fishing, skiing and snowmobiling seasons, while spring and fall seasons will lengthen possibly increasing provincial park usage (Lemieux et al. 2012). Research in the Great Lakes Basin has also explored other tourism sectors, such as golfing, downhill skiing and popular local events such as Winterlude in Ottawa (Scott et al. 2002, Scott et al. 2005, Scott and Jones 2007).

Several studies have explored climate change impacts on human health in the Great Lakes Basin, including changes to the seasonality and range of infectious diseases and increases in non-communicable diseases, such as heat illnesses. Patz et al. (2008) link increases in extreme precipitation events due to climate change to overflows from combined sewer systems, which can threaten human health and recreation activities in the Basin. Using statistically downscaled climate models, Vavrus and Van Dorn (2010) explored human health impacts in Chicago and also report an increase in the frequency of heavy precipitation due to climate change, which may increase the risk of waterborne disease outbreaks. They further report an increase in the frequency, duration and intensity of heat waves that threaten human health, and a decrease in frequency and intensity of extreme cold. Climate change also has the potential to expand the range of zoonotic disease; for instance, climate projections suggest Lyme disease will spread northward due to increasing temperatures that create suitable conditions for ticks (Odgen et al. 2006). Greater incidence of West Nile virus, which is carried by mosquito vectors, has been linked to warmer temperatures, elevated humidity and heavy precipitation in the United States (Wellenius et al. 2009). In addition, warmer temperatures have been linked to increased enteric infections from *Salmonella*, pathogenic *E. coli* and *Campylobacter* (Fleury et al. 2006). While more difficult to attribute, climate change is also expected to impact pollen seasons and contribute to other types of air contaminants, such as those linked to large wildfires (Kinney 2008).

Heat-related illnesses are also a leading concern for many municipalities, and Great Lakes shorelines are often cited as assets for communities to cope with such events (Paterson et al., 2012). There are also many cascading effects of extreme weather events on the infrastructure and public health systems upon which communities rely. A recent example is the contamination of Toledo’s drinking water supply due to blue-green algae blooms in Western Lake Earie associated with concurrent high levels of agricultural runoff and hotter than normal temperatures, conditions that can both be expected to increase in frequency due to climate change. Other waterborne diseases, such as *E. coli*, can also lead to beach closures, reduced access to shoreline recreation and impacts on water treatment systems (Bush et al. 2014).

While it was beyond the scope of this report to provide a comprehensive treatment of the social, economic and human health impacts of climate change in the Great Lakes Basin, it is evident from the limited review conducted that many important effects to communities due to climate are mediated by ecosystems. As such, continuing to understand and manage ecological impacts of climate change is critical to ensuring ecosystems are functional and able to provide the services relied upon by communities.

PART 4. KNOWLEDGE GAPS

There is a growing body of literature that addresses a range of ecological, physical and socio-economic effects of climate change in the Great Lakes Basin. However, given the complexity of climate change and diversity of topics of interest to this discussion, many knowledge gaps remain. In some instances, the literature cited in this report identified knowledge gaps. In others, an analysis of the research completed to date and insights collected from subject matter experts revealed significant knowledge gaps. The identification of knowledge gaps will help in assigning priority for the future research needed to support climate change vulnerability, impact, and adaptation assessments.

4.1. Advancing Climate Modelling and Analysis in the Great Lakes Basin

The complex and uncertain nature of climate models and the challenge of integrating these with ecological models remains one of the main challenges for ecologically-focused climate change science in the Great Lakes Basin and beyond. Climate models continually need updating with new data and knowledge to reduce uncertainties.

Advancing local-scale climate modelling and analysis: Most existing research in the Great Lakes Basin employs raw or downscaled GCM output as the basis for understanding climate change impacts on species, biophysical processes, hydrologic systems and overall ecology. Additionally, climate modelling and downscaling of GCM projections represent important opportunities to better understand the role of local-scale features in influencing climate regimes across the Great Lakes Basin. This includes the role of feedbacks between the land uses, open water and the atmosphere. Understanding these feedbacks and the influence of different scenarios on the earth system at a more refined scale is critical to an overall improved understanding of climate change impacts. The fundamental processes affecting local climate across the Great Lakes Basin require greater understanding to help refine how earth systems are captured/portrayed in regional climate models to advance understandings of climate change.

Importance of uncertainty analysis and communicating confidence: Defining both the climate and its effects in a particular location, particularly one as diverse as the Great Lakes Basin, is an inherently uncertain science due to natural temporal and spatial variability and the complexity of the earth-atmosphere system. Climate change greatly increases that level of uncertainty due to the inherent unpredictability of the future, and variability in estimates of future climate that result from the many climate projection datasets available. A robust uncertainty analysis is critical when using climate projections to generate information about more specific impacts within the Basin. The IPCC increasingly makes use of ensembles of projection datasets, including downscaled ones, and communicates sources of uncertainty and this provides a good example for the Great Lakes Basin.

Advancing emerging model scenarios: Prior to 2014, researchers used the Special Report on Emission Scenarios (SRES), which represented state-of-the-art climate science, to project future climate change. The IPCC's fifth assessment report (AR5) introduced a new approach to scenarios. That report focused on four emissions trajectories, known as Representative Concentration Pathways (RCPs), that each produce different levels of heat energy at the end of the century – 8.5, 6, 4.5 and 2.6 Watts/m^2. While the new RCPs are not directly comparable with the SRES scenarios, some general qualitative comparisons between the emission scenarios may be needed in the Great Lakes Basin to build on existing research and aid practitioners in understanding the existing knowledge base.

Validation and hindcasting: Climate model performance can be assessed by conducting prognostic and retrospective diagnostic analyses. For example, models can be tested and validated by statistically comparing spatial and temporal modelled results with observed trends over the recent past (i.e., hindcasting). These comparisons can be used to characterize any uncertainty in interpreting model projections.

Improved climatological and climate impact monitoring: To better understand climate change and its impacts in the Great Lakes Basin, it is necessary to have high quality records of both atmospheric conditions and climate impacts across the Great Lakes Basin. Such information is of great value for better characterizing impacts, defining system thresholds and responses, and understanding local profiles of risk and opportunity with respect to climate change. Improved observational data also assist with the refinement of climate models. Many areas of the Great Lakes Basin are poorly covered by climate stations, and as such it is necessary to identify those specific gaps, for example, there is a significant gap in station density and coverage between the United States and Canada, with Canada lagging significantly behind (WMO 1995; Environment Canada 2013). Improved linkages between observation networks, the placement of observing stations in remote unregulated watersheds, and a more expansive network in the remote areas (where impacts are expected to be greater) would help to close existing knowledge gaps and better ascertain the causes and effects, as well as the scale, of climatic impacts (IUGLS 2012; Environment Canada 2013). In addition, on-going and enhanced ecological monitoring would help validate ecological thresholds and refine ecosystem-based climate modelling and research efforts (Mackey 2012). Critical monitoring gaps for specific areas of ecological research are identified in following sections.

Communicating climate information assumptions: Through the preparation of this report, it was evident that many studies inconsistently or insufficiently communicate the types of climate information used in non-climatological applications. For example, some ecological studies may describe the GCM or ESM from which projections were derived, without acknowledging whether those data were downscaled. In several instances, we discovered that studies that initially indicated they had used GCMs were in fact using downscaled or bias-corrected GCM output. Clear communication on sources of climate information, in particular the GCMs, downscaling methods, emission scenarios, baseline datasets, and periods of analysis will advance climate change science. Communication is also important to identify potential sources of uncertainty in climate information and the effect that has on ultimate study findings and information confidence.

4.2. Water Temperature

Spatial dynamics of lake water temperature: Differences in lake temperature will occur offshore versus inshore. Water temperatures will also be impacted by extreme events, upwellings, seiches and groundwater inputs. These factors have not been incorporated into lake temperature models for climate change.

Forecasting lake thermal profiles: Climate projections of lake water temperature have largely focused on surface water temperatures. Modelling and monitoring of thermal profiles would be beneficial to better understand thermal habitat distribution within lakes.

Wind in ice dynamic models: Changes in wind (speed and direction) due to climate change will impact freeze-up and break-up and, therefore, are important considerations for incorporation into ice dynamic models.

Wetland water temperature projections: Wetlands are among the most biologically diverse ecosystems, serving as home to a wide range of plant and animal life. Temperature and water levels are key determinants in the distribution, productivity and functioning of wetland ecosystems. The paucity of information on wetland water temperatures and how these temperatures are projected to change with climate is an important knowledge gap and could impact the functioning of the ecosystem and the species dependent on these systems.

4.3. Water Levels and Surface Hydrology

Improved understanding of precipitation vs. evaporation and evapotranspiration: The difference between precipitation and evaporation and evapotranspiration ultimately governs water levels. Long-term direct measurements of these components are needed to better understand, model and predict water level fluctuations. Projections have demonstrated excessive sensitivity of overlake evaporation and evapotranspiration to climate. Therefore, uncertainty and variability of projections should be incorporated when managing water resources (Lofgren and Gronewold 2012). As water temperature and wind speed increases, and ice cover declines, evaporation is predicted to increase over the Great Lakes. Observational studies have shown increased overlake evaporation in summer, but decreased evaporation in winter (Lenters et al. 2013). However, Music et al. (2015) showed that evaporation over the lake is expected to increase in winter by the 2050s.

Lakes

Great Lakes water level projections: Questions remain about the causes of historic prolonged decline in Great Lakes water levels. There is limited consensus about the likely near and medium-term projections of water levels. Some of the uncertainty derives from the unique nature of the Great Lakes Basin as a highly dynamic and adaptive natural and human system, with multiple factors that are continually changing, including water supplies and outflows. The analysis of moisture and energy budgets of the lakes would benefit from a better understanding of the interplay of hydroclimatic factors (such as fluxes of water vapor, trace gases and sensible heat flux from the Great Lakes) (Lofgren and Gronewold 2012).

Characterize diversity of inland lake types: Inland lake types are diverse and their physical characteristics, water quality and the species they maintain have not been well characterized (Lofgren and Gronewold 2012, Minns et al. 2014b).

Rivers

Projected changes to stream flow, timing and discharge volume: There is substantial modelling and research on river temperatures in the Great Lakes Basin. However, there is little integration of additional factors that affect river conditions, such as stream flows, timing of events and discharge volumes. Some information from St. Lawrence tributaries is available on bed material transport rates, the number of transport events and the number of days in the year when sediment transport occurs (Verhaar et al. 2011). Estimating how runoff from tributaries will be altered by climate change will contribute to river and lake water level estimates.

Integration of land use and management: Other factors, such as stream regulation, surrounding land use and change in land cover (Nejadhashemi et al. 2012), have not been integrated into the projections of stream temperature, water levels and habitat analyses, even though these factors influence species distributions in rivers.

Wetlands

Patterns of wetland drying: Wetlands are particularly vulnerable to climatic changes. However, information that describes the climate change vulnerability of wetlands is lacking. For example, patterns of wetland drying due to climate change needs further study. Existing studies treat each wetland uniformly due to limited data. However, it is recognized that wetlands will not dry uniformly; rather, drying or shrinking may occur around the edges of the wetland leaving the middle intact (Chu *in review*). More detailed projections of how the wetland will change (e.g., spatial extent and plant community composition) would improve studies on shifts in wetland bird distributions with climate change.

Water budgets: Improving our understanding of wetland hydrology is critical. How climate change may influence water budgets of various wetland types is not well understood. Each type of wetland will be moderated with different water influxes; for example, the dominant influxes of water for marshes come from precipitation and surface water, whereas fens are groundwater-driven. Characterization and projections for surface and groundwater hydrology in the Great Lakes Basin are fundamental information needs for advancing wetland climate research.

Monitoring and evaluation: Wetland monitoring programs are currently limited and there is limited 'point-in-time' data provided by other monitoring programs, such as the ecological land classification component of the Forest Resource Inventory. Extensive data has recently been collected for wetlands along the shoreline of the Great Lakes through a comprehensive and binational Great Lakes coastal wetland monitoring program (Uzarski and Sherman 2012). To advance research on climate change effects on wetlands, wetland monitoring should include: groundwater levels, remote sensing, aerial photography, vegetation and wildlife inventories, and fixed points for recurrent photography. Ecosystem service valuation of wetlands for floods and droughts will be important, as well as understanding how wetlands may help mitigate the negative impacts of climate change on nearby terrestrial and aquatic ecosystems.

4.4. Groundwater

Recharge and discharge: There is a knowledge gap related to groundwater recharge and the interactions between shallow aquifers and surface water. A focus on discharge is important, including identifying significant discharge zones, because it is difficult to measure recharge.

Groundwater mapping: The majority of the freshwater in the world lies underground and provides many important ecological and ecosystem services. Increased population pressures and shifting hydrological regimes demand improved understanding of aquifer and groundwater inventories and characterization at the regional scale. Conducting an inventory of groundwater sources could also identify possible coldwater thermal refuges.

Groundwater modelling: Existing groundwater models are generally only available at a local scale. Larger regional groundwater models that are linked temporally and spatially with surface hydrologic modelling, needed to improve the understanding of the groundwater to surface water interaction across the Great Lakes Basin, are not widely available.

Monitoring: The IPCC (2007) stated that a lack of data has made it impossible to determine the magnitude and direction of groundwater change due solely to climate change. The existing 25-40 years of groundwater level data, and groundwater monitoring stations are not well aligned with stream flow and climate stations. Records of groundwater withdrawal that is accompanied by observational data would help differentiate between climatic and pumping impacts (Environment Canada 2013).

4.5. Precipitation and Extreme Events

Flooding, precipitation and drought: Improved and detailed modelling of the intensity, duration and frequency of precipitation and extreme weather events is needed to improve the understanding of how such events relate to flooding and climate change. Floodplain mapping and the theory and methods of floodplain mapping in the Great Lakes Basin have not been updated to take into account a changing climate. Given the increasing trend in droughts over the past 60 years and the costly implications of prolonged droughts, identifying indicators for drought would help target monitoring and assessment of drought impacts.

Consequences of disturbance regimes: The role of altered disturbance regimes (e.g., fires and drought) in shaping plant and animal distributions are not well understood.

4.6. Chemical Effects

Improved understanding of the interaction between climate and chemical/pollutant dynamics: The vulnerability assessment of chemicals to climate change would benefit from a better fundamental understanding of the interaction of climate and surface water and water column chemistry (e.g., oxygen levels, carbon, nitrogen, and phosphorous dynamics) of the Great Lakes and inland lakes. Knowledge and data on the direct effects of climate change on chemical exposure, fate and transport are also limited.

Improved projections: Improved projections of how climate change influences the chemistry (e.g., oxygen levels, carbon, nitrogen, and phosphorous) and other pollutant dynamics (e.g., PBT chemical substances, biocides, pesticides, etc.), of the Great Lakes and inland lakes in the Basin are needed. This would include future scenarios that consider surface and ground water, water quality issues, pollutants and agricultural runoff.

Carbon dioxide fertilization: The extent of the CO_2 fertilization effect for primary productivity is not well incorporated into carbon cycle modelling. A recent study has found that CO_2 fertilization is underestimated in current models, and the new figures should be used to improve the carbon-climate feedbacks (Sun et al. 2014).

Monitoring: It may be important to better monitor the chemical changes in the waters of the Great Lakes Basin. In addition, monitoring and testing of chemical and pesticide uses and applications to the waters is important. A carbonate chemistry and acidification monitoring program implemented in the Great Lakes Basin, in addition to a more rigorous chemical of mutual concern and nutrient monitoring program, that could assist in both monitoring and modelling these expected changes over time would be beneficial.

Changes in chemical use and application: The use and application of pesticides and biocides are likely to change as distributions of species and changes in growing conditions occur. These changes have not been factored into models of chemical effects resulting from climate change.

4.7. Beyond Single Species Range Shifts

Integrated ecological modelling: The complex interconnections of ecosystem responses to climate change challenge our ability to accurately project the diverse potential changes and prescribe adaptive measures. To date, the majority of research and modelling efforts have examined species-level responses, while species interactions (such as competition, predation, disease, disturbance regimes and interspecies synergies) are often not well integrated. For example, the sensitivity of forest ecosystems to climate raises questions about increased mortality, the speed and ability of species to migrate northward, and how climate change may affect disturbance regimes. Shifts in forest composition will, in part, be determined by how individual species respond to heat or drought stress, increased pest activity, and the role of other stressors directly or indirectly impacted by climate (such as fires). Furthermore, forest shifts will also depend on how other important variables, such as overstory composition and understory biota, shift with a changing climate (Fisichelli et al. 2013).

The coupling of biotic and abiotic factors and the integration of community dynamics into climate models would be useful in revealing novel pressures on and/or opportunities for species, including extinction risks and their adaptive capacity. For example, climate niche models that predict range expansions typically do not account for dispersal limitations (e.g., geographical barriers, soil type, or habitat connectivity) and genetic influences. As a result, the projections may over-estimate range expansions outside the plausible bounds for certain species (Nantel et al. 2014). In many cases, however, the paucity of long-term data and the complexity of developing integrated ecological modelling hinder the development or power of such hybrid models. Some examples include:

- Individual species models have been completed for aquatic thermal guilds and some species (e.g., Lake Trout and Walleye). Community models could incorporate competitive advantages among species.
- Climate niche models have projected terrestrial range shifts for the majority of Ontario tree species (e.g., White Pine, White Spruce). However, only one or two examples of efforts to integrate other limitations exist, such as genetic adaptive capacity. Disturbance projections (e.g., fire, drought) and limitations to movement and establishment (e.g., geographical barriers, soil type, and connectivity) are currently not incorporated.
- Relatively few aquatic ecosystem climate change studies have analyzed changes in lake depth temperature profiles, summer lake stratification, and habitat changes to the metalimnion and hypolimnion. Models could benefit from expanding the seasonal temperature profiles for lakes and the associated implications of climate change on the thermal habitat space for fish species. The earlier freshets and increased frequency of high flow events into predictive models of aquatic ecosystems have not been incorporated.

In addition, better understanding in the following areas would be beneficial:

- How winter conditions affect overwintering of early life stages (e.g., egg development and survival upon hatching);
- relating thermal habitat to primary and secondary productivity;
- mapping of aquatic connectivity to identify migratory pathways and barriers to inform potential movement and management options;
- effects in vernal pools and how changes in these systems will impact amphibians; and
- the importance of snow cover to small mammals near the base of the food change (changes in snow cover could occur at the local scale and confound more broad scale modelling effects).

Local-scale considerations: Climatic niche models can be used to project species occurrence over broad ranges; however at local scales, other abiotic and biotic factors may have greater impact. Climate model resolutions are often too coarse to capture specialist or at-risk species that may occupy areas with localized microclimates. These species might persevere or be at risk of extinction due to changes in climate. Furthermore, coupled species distribution and climate models tend not to account for novel localized climatic niches that will form based on topography, soil texture or other factors (Wang et al. 2012b).

Coastal ecosystems: Research is limited on the impacts of climate change on coastal ecosystems, including impacts on coastal wetlands, dunes, bluffs, wave power, etc.

Monitoring: Ongoing monitoring of species and community level changes is necessary to refine hybrid models, which will lead to a better understanding of the reconfiguration of ecosystems in Ontario (Nituch and Bowman 2013, Nantel et al. 2014). Such monitoring may also inform changes in chemical and pesticide use intended to address species and ecosystem changes over time.

4.8. Genetic and Phenologic Change

Genetics of fitness-related traits that will impact adaptation to climate change: For both aquatic and terrestrial ecosystems, there is a gap in research identifying specific genetic climatic thresholds for climate sensitive species. Functional genetic research to examine the adaptive capacity of tree, aquatic and wildlife species is currently limited to selected species. Additionally, long-term monitoring of how climate change is affecting other species attributes, such as phenology (e.g., breeding patterns) and life history traits, could strengthen the power of model predictions (Hoffman and Sgro 2011, Klaus and Lougheed 2013).

Assisted migration: Assisted migration of species as a climate change adaptation measure is a topic of current research and debate. Various knowledge gaps exist, including political, ethical, operational and scientific challenges. Research in this area would be benefitial before the implementation of assisted migration is considered (Ste. Marie et al. 2011).

Genetic matching: Research in this field could reveal genotypes that are best suited to future climates based on their adaptive potential. Genetic research and DNA sequencing to determine genes that select for local adaption is currently a growing science, particularly for tree species. In 2011, Genome Canada awarded $4.7 million to the University of British Columbia to fund tree species DNA sequencing for this purpose (Ste. Marie et al. 2011). High-density functional gene arrays are an emerging genomic tool to determine the genetic origin of species that perform best in provenance trials outside of their natural range (Lu et al. 2014).

Asynchronies resulting from phenological changes: Research examining the cascading effects of shifts in phenology on species and ecosystems is limited.

4.9. Invasive Species, Parasites and Pathogens

Integration of invasive species: There is limited integrated research on climate change and invasive species. Existing research in the Great Lakes Basin focuses on inland lakes and, primarily, on modelling current invasive species threats, rather than predicting future threats that may arrive from other areas. Additional consideration to unique characteristics and drivers of the spread of new and existing invasive species in the Great Lakes Basin would be benefitial.

Parasites and pathogens: There is little research on identifying aquatic, tree and wildlife parasites and pathogens that may expand into the Great Lakes Basin with climate change.

Monitoring: Ongoing monitoring of species and community level changes would help refine hybrid models which could lead to a better understanding of the reconfiguration process of ecosystems in Ontario that will also address issues related to invasive species, parasites and pathogens. Such monitoring may also inform changes in chemical and pesticide use intended to address species and ecosystem changes over time.

4.10. Integration of Land Use

The altered state of the Great Lakes Basin makes it particularly important to consider land use in climate change modelling. Land use could modify the magnitude and even direction of climate change impacts on aquatic and terrestrial ecosystems in the Great Lakes Basin. For instance, using land cover projections in the Upper Mississippi River foodplain, DeJager (2013) reported potential transition of some forest, marshland and agricultural lands to open water by 2050. However, uncertainty about future technological developments is a challenge in improving land-use models.

4.11. Cumulative Effects

Integration of cumulative effects: Human-induced climate change is itself a cumulative impact of multiple human activities. Projecting the local magnitude, style and timing of climate changes and how the many influences on climate interact is not well understood. These are complex systems in which the impacts of multiple stressors are not only additive but can also interact, change ecosystem functions and cross thresholds. Cumulative effects assessments that examine multiple environmental stressors (including climate change) have to date been limited in the Great Lakes Basin. Cumulative effects of 34 environmental and human-induced stressors (e.g., pollution, invasive species, coastal development, exploitation, ecosystem services and climate change) were recently examined by a collaborative research team as part of the Great Lakes Environmental Assessment and Mapping Project (GLEAM). The GLEAM analysis found that most areas in the Great Lakes are highly influenced by 10 to 15 different environmental stressors, with near-shore areas experiencing significantly more stressors than offshore areas (Allan et al. 2013). Research led by MNRF scientists is exploring the interface between the climate-induced spread of suitable habitat for aquatic invasive species in inland lakes across the Basin with the role humans play in the spread of invasive species through access to lakes via angling. In Lake Erie and Lake Ontario the combined effects of a changing climate, invasive species, and nutrient loadings collectively have generated water quality impairments and harmful algal blooms (Michalak et al. 2013). Similarly, research that explores habitat fragmentation and the vulnerability of furbearing species in the Great Lakes Basin build such influences as the connectivity of landscapes into the analysis. These types of research help fill a critical need to integrate climate change impact analysis in with other environmental stressors.

4.12. Climate Change in the Great Lakes Basin and its Impacts on Humans

This report focuses almost exclusively on the ecological effects of climate change in the Great Lakes Basin. This focus was taken in order to align with the ecological emphasis in the GLWQA and COA, and the recognition that ecosystems are the basis for human wellbeing in the Basin.

Nevertheless, there are numerous human impacts associated with climate change that both mediate and are influenced by the ecological effects identified in this report. As such, these human aspects must be factored into the development of research strategies for Great Lakes Climate Change Science. In particular, a synthesis of the state of science related to social, cultural, economic, health, built infrastructure, and political effects of climate change would complement the research presented in this report.

4.13. Accessibility and Effective Use of Science for Adaptive Management

Tools and strategies for increased access and usability of information: The development of tools and strategies would ensure decision makers can access and effectively use scientific research on climate change, its impacts and the effectiveness of adaptation measures in the Great Lakes Basin. Ensuring access and effective use of scientific information will go a long way to support adaptive management in the Basin. While there are many current barriers to and opportunities for advancing adaptive management in the Basin, access and effective use of scientific information is identified as one critical element (IPCC 2014; IUGLS 2012). As was described in the introduction to this report, adaptive management relies heavily on scientific information at various stages, including identification of adaptation alternatives, planning for implementation, ongoing monitoring and evaluation, and continual assessment of risk and vulnerability. As such, it is critical that decision makers have access to this information, and to the tools, to enable them to use the information effectively. Open dialogue with the research community is also needed to ensure priority questions are being identified and addressed. There is a very active community of researchers focused on strategies for advancing adaptive management, and the development of a definitive set of tools and strategies would ensure the work of these scientists is incorporated into decision making. Key tools include:

- Evaluation and decision tools needed for the ongoing evaluation of the performance of potential responses to climate change over time (IGLSLR AMTT 2013)
- Adaptation facilitated by boundary organizations and through strengthened knowledge networks (see Kalafatis et al. 2015; Lemos et al. 2014; Lemos et al. 2012)
- Enhanced use of visualizations and plain-language narratives for communicating with stakeholders (see Clites et al. 2014; Gronewold et al. 2013; Veloz et al. 2012)
- Technical guidance to inform specific decision making processes, such as regulatory approvals, investments and development plans (e.g., see Douglas 2014; EBNFLO and AquaResource 2011).

Leadership on evidence-based adaptive management: There are currently two major binational decision making frameworks designed to support adaptive management of climate change impacts in the Great Lakes, namely the Annex sub-committees for the GLWQA and the IJC's Great Lakes-St. Lawrence River Adaptive Management (GLAM) Committee. These groups represent significant opportunities to advance adaptive management through proactive leadership and by developing integrated strategies for evidence-based decision making among all the key players in the Basin. There are also a host of other organizations and initiatives active at the local scale across the Basin that support the adoption of adaptive management, including state, provincial, and municipal governments, watershed planning and protection agencies, industry, and civil society. Given the complexities of climate change and its impacts, agents could benefit from common access to the same base of information opportunities to discuss implications for management, and processes to identify and pursue emerging research questions. The Annex sub-committees of GLWQA and the IJC GLAM committee represent bodies where many of the interest groups in the Great Lakes Basin are represented. Thus, these groups are in a unique position to advance the adoption of adaptive management frameworks across the basin, develop strategies for dialogue between decision makers and researchers, and ensure dissemination of key guidance and information on climate change, its impacts, and adaptive strategies.

III. CLOSING REMARKS

This report provided an analysis of current trends in the use of climate science in the Great Lakes Basin, a synthesis of key ecosystem vulnerabilities relevant to the ecosystem-based management frameworks governing the Basin, and a series of identified gaps and potential priorities for research. Thirteen themes of key gaps have been identified, and together, help identify the scientific information available that can improve overall adaptive management in the Great Lakes Basin. As climate change research continues to evolve, knowledge gaps will be filled and data confidence should improve. It will therefore be critical to track this progress and identify new priorities and research avenues as we continue to address adaptation of ecosystems to climate change.

REFERENCES

Abdel-Fattah, S. and G. Krantzberg. 2014. Commentary: Climate change adaptive management in the Great Lakes. J. Great Lakes Res. 40: 578-580.

Adamowski, J., K. Adamowski and A. Prokoph. 2013. Quantifying the spatial temporal variability of annual streamflow and meteorological changes in eastern Ontario and southwestern Quebec using wavelet analysis and GIS. J. Hydrol. 499: 27-40.

Allan, J.D., M. Palmer and N.L. Poff. 2005. Climate change and freshwater ecosystems. pp. 274-290 in T.E. Lovejoy and L. Hannah (eds.). Climate Change and Biodiversity. Yale University Press, New Haven, CT. 418p.

Allan, J.D., P.B. McIntyre, S.D.P. Smith, B.S. Halpern, G.L. Boyer, A. Buchsbaum, G.A. Burton, L.M. Campbell, W.L. Chadderton, J.J.H. Ciborowski, P.J. Doran, T. Eder, D.M. Infante, L.B. Johnson, C.A. Joseph, A.L. Marino, A. Prusevich, J.G. Read, J.B. Rose, E.S. Rutherford, S.P. Sowa and A.D. Steinman. 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. **Proc. Natl. Acad. Sci. U.S.A.** 110: 372-377.

Alofs, K.M., D.A. Jackson and N.P. Lester. 2014. Ontario freshwater fishes demonstrate differing range-boundary shifts in a warming climate. Divers. Distrib. 20: 1-14.

Amiro, B.D., A. Cantin, M.D. Flannigan and W.J. de Groot. 2009. Future emissions from Canadian boreal forest fires. Can. J. For. Res. 39: 383-395.

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

AquaResources Inc. and EBNFLO Environmental. 2011. Future Climate Datasets Guide. Ontario Ministry of Natural Resources. Available at http://waterbudget.ca.

Assel, R. and D. Robertson. 1995. Changes in winter air temperatures near Lake Michigan, 1851-1993, as determined from regional lake ice records. Limn. and Oceanogr. 40: 165-176.

Assel, R., D. Robertson, M. Hoff and J. Selgeby. 1995. Climatic-change implications for the long-term (1823-1994) ice records for the Laurentian Great Lakes. Annals of Glaciol. 21: 383-386.

Assel, R., K. Cronk and D. Norton. 2003. Recent trends in Laurentian Great Lakes ice cover. Clim. Chang. 57: 185-204.

Atilla, N., G.A. McKinley, V. Bennington, M. Baehr, N. Urban, M. DeGrandpre, A.R. Desai and C. Wu. 2011. Observed variability of Lake Superior pCO_2. Limnol. Oceanogr. 56: 775-786.

Attavanich, W., B.A. McCarl , Z. Ahmedov, S.W. Fuller and D.V. Vedenov. 2013. Effects of climate change on US grain transport. Nature Clim. Change 3: 638-643.

Austin, J.A. and S.M. Colman. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophys. Res. Lett. 34, L06604.

Austin, J.A. and S.M. Colman. 2008. A century of temperature variability in Lake Superior. Limnol. Oceanogr. 53: 2724-2730.

Austin J.A. and A. Joshua. 2011. Sensitivity of summer Lake Superior thermal structure to meteorological forcing, Limnology and Oceanography. 56.

Ayres, M.P. and M.J. Lombardero. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci. Total Environ. 262: 263-286.

BaMasoud, A. and M. Byrne. 2011. Analysis of shoreline changes (1959 – 2004) in Point Pelee National Park, Canada. J. Coastal Res. 27: 839 – 846.

Barnett, T.P., J.C. Adam and D.P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438: 303-309.

Barton, B.A. and G.K. Iwama. 1991. Physiological changes in fish from stress in aquaculture with emphasis on the response and effects of corticosteroids. Ann. Rev. Fish. Dis. 1: 3-26.

Battisti, A., M. Stastny, E. Buffo and S. Larsson. 2006. A rapid altitudinal range expansion in the processionary moth produced by the 2003 climatic anomaly. Glob. Change Biol. 12: 662-671.

Beaubien, E.G. and H.J. Freeland. 2000. Spring phenology trends in Alberta, Canada: Links to ocean temperature. Int. J. Biometeorol. 44: 53-59.

Bedford, K. 1992. The physical effects of the Great Lakes on tributaries and wetlands. J. Great Lakes Res. 18: 571-589.

Beltaos, S. and T. Prowse. 2009. River-ice hydrology in a shrinking cryosphere. Hydrol. Process. 23: 122-144.

Bergeron, Y., D. Cyr, M.P. Girardin and C. Carcaillet. 2010. Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: collating global climate model experiments with sedimentary charcoal data. Int. J. Wildland Fire 19: 1127-1139.

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

Bekele, E. and V. Knapp. 2010. Watershed Modeling to Assessing Impacts of Potential Climate Change on Water Supply Availability. University of Illinois Urbana–Champaign.

Berzitis, E.A., J.N. Minigan, R.H. Hallett, and J.A. Newman. 2014. Climate and host plant availability impact the future distribution of the bean leaf beetle (*Cerotoma trifurcata*). Global change biology.

Bidwell, D., T. Dietz, and D. Scavia. 2013. Fostering knowledge networks for climate adaptation. Nature Clim. Change 3: 610-611.

Bilby, R.E. 1984. Characteristics and frequency of cool-water areas in a western Washington stream. J. Freshwater Ecol. 2: 593-602.

Bizikova, L., T.L. Neale and I. Burton. 2008. Canadian Communities' Guidebook for Adaptation to Climate Change: Including an Approach to Generate Mitigation Co-benefits in the Context of Sustainable Development. Adaptation and Impacts Research Division, Environment Canada.

Blanken, P.D., C. Spence, N. Hedstrom, and J. Lenters. 2011. Evaporation from Lake Superior: 1. Physical controls and processes. J. of Great Lakes Res. 37: 707-716.

Bloomfield, J.P., R.J. Williams, D.C. Gooddy, J.N. Cape and P. Guha. 2006. Impacts of climate change on the fate and behaviour of pesticidesin surface and groundwater – a UK perspective. Sci. Total Environ. 369: 163–177.

Bonsal, B.R., E.E. Wheaton, A.C. Chipsnshi, C. Lin, D.J. Sauchyn and L. Wen. 2011. Drought research in Canada: A review. Atmos.-Ocean Syst. 49: 303-319.

Bootsma, J. 2001. Response to Question 5. Question and Answer Panel Discussion: Morning Session. In Climate Change and the Great Lakes Water Ecology: What Are The Potential Impacts and What Can We Say? Milwaukee, MN.

Booty, W., D. Lam, G. Bowen, O. Resler and L. Leon. 2005. Modelling changes in stream water quality due to climate change in a southern Ontario watershed. Can. Water Resour. J. 30: 211-226.

Boyer, C., D. Chaumont, I. Chartier and A.G. Roy. 2010a. Impact of Climate Change on the Hydrology of St. Lawrence Tributaries. Université de Montréal, Concordia.

Boyer, C., P.M. Verhaar, A.G. Roy, P.M. Biron and J. Morin. 2010b. Impacts of environmental changes on the hydrology and sedimentary processes at the confluence of St. Lawrence tributaries: potential effects on fluvial ecosystems. Universite´ de Montreal, Concordia.

Boulanger, Y., S. Gauthier, D.R. Gray, H. Le Goff, P. Lefort and J. Morissette. 2013. Fire regime zonation under current and future climate over eastern Canada. Ecol. Appl. 23: 904-923.

Bowman, J., G.L. Holloway, J.R. Malcolm, K.R. Middel and P.J. Wilson. 2005. Northern range boundary dynamics of southern flying squirrels: Evidence of an energetic bottleneck. Can. J. Zool. 83: 1486-1494.

Bradley, B.A., D.S. Wilcove and M. Oppenheimer. 2010. Climate change increases risk of plant invasion in the Eastern United States. Biol. Invasion 12: 1855-1872.

Branfireum, B.A., N.T. Roulet, C.A. Kelly and J.W. Rudd. 1999. In situ sulphate stimulation of mercury methylation in a boreal peatland: Toward a link between acid rain and methyl-mercury contamination in remote environments. Global Biogeochem. Cycles 13: 743-750.

Breffle, W.S., D. Muralidharan, R.P. Donovan, F. Liu, A. Mukherjee and Y. Jin. 2013. Socioeconomic evaluation of the impact of natural resource stressors on human-use services in the Great Lakes environment: A Lake Michigan case study. Resour Policy 38: 152-161.

Briggs, J.C. 1986. Introduction to zoogeography of North American fishes. pp. 1-16 in C.H. Hocutt and E.O. Wiley (eds.). The Zoogeography of North American Freshwater Fishes. John Wiley and Sons, New York, NY. 866p.

Brommit, A.G., N. Charbonneau, T.A. Contreras and L. Fahrig. 2004. Crown loss and subsequent branch sprouting of forest trees in response to a major ice storm. J. Torrey Bot. Soc. 131: 169-176.

Bronson, F.H. 2009. Climate change and seasonal reproduction in mammals. Phil. Trans. R. Soc. B 364: 3331-3340.

Brooke, M. de L., S.H.M. Butchart, S.T. Garnett, G.M. Crowley, N.B. Mantilla-Beniers and A. J. Stattersfield. 2008. How fast are threatened bird species moving towards extinction? Conservation Biology 22: 417-427.

Brooks, A.S. and J.C. Zastrow. 2003. The potential influence of climate change on offshore primary production in Lake Michigan. J. Great Lakes Res. 28(4): 597-607.

Brown, L.C. and C.R. Duguay. 2010. The response and role of ice cover in lake-climate interactions. Prog. Phys. Geog. 34: 671-704.

Brown, C. and R.L. Wilby 2012. An alternate approach to assessing climate risks. Eos Trans. AGU, 93: 401.

Brown, C., W. Werick, W. Leger, and D. Fay. 2011. A Decision-Analytic approach to managing climate risks: Application to the upper Great Lakes. J Am Water Resour. 47: 524-534.

Burnett, A.W., M.E. Kirby, H.T. Mullins and W.P. Patterson. 2003. Increasing great Kaje-effect snowfall during the twentieth century: A regional response to global warming? J. Climate 16: 3535-3542.

Bush, K.F., C.L. Fossani, S. Li, B. Mukherjee, C.J. Gronlund and M.S. O'Neill. 2014. Extreme precipitation and beach closures in the great lakes region: Evaluating risk among the elderly. International journal of environmental research and public health, 11(2).

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

Cabas, J., A. Weersink and E. Olale. 2010. Crop yield response to economic, site and climatic variables. Clim. Change 101: 599-616.

Cadman, M.D., D.A. Sutherland, G.G. Beck, D. Lepagem and A.R. Couturier (eds.). 2007. Atlas of the Breeding Birds of Ontario, 2001-2005. Bird Studies Canada, Environment Canada, Ontario Field Ornithologists, Ontario Ministry of Natural Resources, and Ontario Nature, Toronto. 728p.

Canadian Council of Professional Engineers. 2011. Public Infrastructure Envineering Vulenrability Committee Engineering Protocol, Version 10. Engineers Canada, Ottawa, ON.

Candau, Jn-N. and R.A. Fleming. 2011. Forecasting the response of spruce budworm defoliation to climate change in Ontario. Can. J. For. Res. 41: 1948-1960.

Casselman, J.M. 2002. Effects of temperature, global extremes, and climate change on year-class production of warmwater, coolwater, and coldwater fishes in the Great Lakes Basin. Am. Fish. Soc. Symp. 32: 39-60.

Casselman, J.M. and K.A. Scott. 2002. Fish-community dynamics of Lake Ontario – long-term trends in the fish populations of eastern Lake Ontario and the Bay of Quinte. pp. 349-383 in M. Munawar (ed.). State of Lake Ontario: Past, Present and Future. Ecovision World Monogr. Ser., Aquat. Ecosyst. Health Mgmt. Soc., Stuttgart, Germany. 684p.

Changnon, S.A. and K.E. Kunkel. 2006. Severe storms in the Midwest. Informational/Educational Material 2006-06. Illinois State Water Survey. Champaign, IL. 74p.

Charron, I. 2014. A Guidebook on Climate Scenarios: Using Climate Information to Guide Adaptation Research and Decisions. Ouranos, 66p.

Chen, I.C., J.K. Hill, R. Ohlemuller, D.B. Roy and C.D. Thomas. 2011. Rapid range shifts of species associated with high levels of climate warming. Science 333: 1024-1026.

Cheng, C.S., H. Auld, G. Li, J. Klaassen and Q. Li. 2007. Possible impacts of climate change on freezing rain in south-central Canada using downscaled future climate scenarios. Nat. Hazards Earth Syst. Sci. 7: 71-87.

Cheng, C.S., G. Li and H. Auld. 2011. Possible impacts of climate change on freezing rain using downscaled future climate scenarios: Updated for eastern Canada. Atmosphere-Ocean 49: 8-21.

Cheng, C.S., G. Li, Q. Li and H. Auld. 2012a. Climate change and heavy rainfall-related water damage insurance claims and losses in Ontario, Canada. J. Water Resour. Prot. 4: 49-62.

Cheng, C.S., G. Li, Q. Li, H. Auld and C. Fu. 2012b. Possible impacts of climate change on wind gusts under downscaled future climate conditions over Ontario, Canada. J. Climate 25: 3390-3408.

Cheng, C.S., H. Auld, L. Qian and L. Guilong. 2012c. Possible impacts of climate change on extreme weather events at local scale in south–central Canada. Climatic change 112, no. 3-4: 963-979.

Cherkauer, K.A. and T. Sinha. 2010. Hydrologic impacts of projected future climate change in the Lake Michigan region. Purdue University.

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

Chu, C. In review. Climate Change Vulnerability Assessment for Aquatic Ecosystems in the Great Lakes Basin, Ontario.

Chu, C., C.K. Minns, J.E. Moore and E.S. Millard. 2004. Impact of oligotrophication, temperature and water levels on walleye habitat in the Bay of Quinte, Lake Ontario. T. Am. Fish. Soc. 133: 868-879.

Chu, C., N.E. Mandrak and C.K. Minns. 2005. Potential impacts of climate change on the distributions of several common and rare freshwater fishes in Canada. Divers. Distrib. 11: 299-310.

Chu, C., N.E. Jones, N.E. Mandrak, A.R. Piggott and C.K. Minns. 2008. The influence of air temperature, groundwater discharge and climate change on the thermal diversity of stream fishes in southern Ontario watershed. Can. J. Fish. Aquat. Sci. 65: 297-308.

Chu, C., N.E. Jones and L. Allin. 2010. Linking the thermal regimes of streams in the Great Lakes Basin, Ontario, to landscape and climate variables. River. Res. Applic. 26: 221-241.

Clair, T.A., B.G. Warner, R. Robarts, H. Murkin, J. Lilley, L. Mortsch and C. Rubec. 1998. Climate change and Canadian inland wetlands. pp. 189-218 in G. Koshida and W. Avis (eds.). The Canada Country Study: Climate Impacts and Adaptation, National Sectoral Volume. Env. Can., Ottawa, ON.

Cleland, D.R., T.R. Crow, S.C. Saunders, D.I. Dickmann, A.L. Maclean, J.K. Jordan, R.L. Watson, A.M. Sloan and K.D. Brosofske. 2004. Characterizing historical and modern fire regimes in Michigan (USA): A landscape ecosystem approach. Landscape Eco. 19: 311-325.

Clites, A.H., J.P. Smith, T.S. Hunter and A.D. Gronewold. 2014. Visualizing relationships between hydrology, climate, and water level fluctuations on Earth's largest system of lakes. Journal of Great Lakes Research, 40: 807-811

Coakley, S.M., H. Scherm, and S. Chakrabort, 1999. Climate change and plant disease management. Annu. Rev. Phytopathol. 37: 399-426.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner. 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K.Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Colombo, S.J. 2008. Forests and Forestry in a Changing Climate. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-12. 21p.

Colombo, S.J., D.W. McKenney, K.M. Lawrence and P.A. Gray. 2007. Climate Change Projections for Ontario: Practical Information for Policymakers and Planners. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-05. 37p. + CD-ROM.

Committee on Environment and Natural Resources. 2010. Scientific Assessment of Hypoxia in U.S. Coastal Waters. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

Comte, L., L. Buisson, M. Daufresne and G. Grenouillet. 2013. Climate-induced changes in the distribution of freshwater fish: observed and predicted trends. Freshwater Biol. 58: 625-639.

Coristine, L.E. and J.T. Kerr. 2011. Habitat loss, climate change, and emerging conservation challenges in Canada. Can. J. Zool. 89: 435-451.

Crins, W.J., P.A. Gray, P.W.C. Uhlig and M.C. Wester. 2009. The ecosystems of Ontario. Part 1. Ecozones and ecoregions. Ont. Min. Nat. Resour., Inventory, Monitoring Assessment, Peterborough, ON. SIB TER IMA TR-01. 71p.

Croley, T.E. II. 1990. Laurentian Great lakes double-CO2 climate change hydrological impacts. Clim. Chang. 17: 27-47.

Croley, T.E., and C.L. Luukkonen. 2003. Potential effects of climate change on ground water in lansing, michigan, J. Am. Water Resour. As. 39: 149–163.

Crossman, J., M.N. Futter, S.K. Oni, P.G. Whitehead, L. Jin, D. Butterfield, H.M. Baulch and P.J. Dillon. 2013. Impacts of climate change on hydrology and water quality: Future proofing management strategies in the Lake Simcoe watershed. Canada. J. Great Lakes Res. 39: 19-32.

Crowder, A., J. Smol, R. Dalrymple, R. Gilbert, A. Mathers and J. Price. 1996. Rates of natural and anthropogenic change in shoreline habitats in the Kingston Basin, Lake Ontario. Can. J. Fish. Aquat. Sci. 53: 121-135.

Crowe, K.A. and W.H. Parker. 2011. Conserving the diversity of Ontario tree species under multiple uncertain climatic futures. Can. J. Forest Res. 41: 533-542.

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

Cummins, K.W. 1974. Structure and function of stream ecosystems. BioScience 24: 631-641.

Cummins, K.W., J.R. Sedell, F.J. Swanson, G.H. Minshall, S.G. Fisher, C.E. Cushing, R.C. Petersen and R.L. Vannote. 1983. Organic matter budgets from stream ecosystems. pp. 299-353 in J.R. Barnes and G.W. Minshall (eds.). Stream Ecology: Application and Testing of General Ecological Theory. Plenum, New York, NY.

Cunderlik, J.M. and S.P. Simonovic. 2007. Inverse flood risk modelling under changing climatic conditions. Hydrol. Process. 21: 563-577.

Cunderlik, J.M. and T.B.M.J. Ouarda. 2009. Trends in the timing and magnitude of floods in Canada. J. Hydrol. 375: 471-480.

Cunjak, R.A. and G. Power. 1987. The feeding and energetics of stream-resident trout in winter. J. Fish Biol. 31: 493-511.

Dadfar, H., S.E. Allaire, E.V. Bochove, J.T. Denault, G. Thériault and A. Charles. 2010. Likelihood of burrow flow in Canadian agricultural lands. J. Hydrol. 386: 142-159.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks and B.M. Wotton. 2001. Climate change and forest disturbances. J. Bioscience 51: 723-734.

Davis, M.B. 1989. Lags in vegetation response to climate change. Clim. Change 15: 75-80.

de Elía, R. and H. Côté , 2010: Climate and climate change sensitivity to model configuration in the Canadian RCM over North America. Meteorol. Z. 19: 325-339.

DeGaetano, A.T. 2009. Time-dependent changes in extreme-precipitation return-period amounts in the continental United States. J. Appl. Meteor. Climatol. 48: 2086–2099.

De Jager, N.R., J.J. Rohweder and J.C. Nelson. 2013. Past and predicted future changes in the land cover of the upper Mississippi river floodplain, USA. River Res. Appl. 29: 608-618.

De Laporte, A.V., A.J. Weersink and D.W. McKenney. 2014. A spatial model of climate change effects on yields and break-even prices of switchgrass and miscanthus in Ontario, Canada. GCB Bioenergy, 6(4), 390-400.

Derecki, J.A. 1976. Hydrometeorology: Climate and hydrology of the Great Lakes. pp. 71-104 in Limnology Working Group. Great Lakes Basin Framework Study, Appendix 4, Limnology of Lakes and Embayments. Great Lakes Basin Commission, Ann Arbor, Michigan. 441p.

Desai, A.R., J.A. Austin, V. Bennington and G.A. McKinley. 2009. Stronger winds over a large lake in response to weakening air-to-lake temperature gradient. Nat. Geosci. 2: 855-858.

Devito, K.J., A.R. Hill and P.J. Dillon. 1999. Episodic sulphate export from wetlands in acidified headwater catchments: Prediction at the landscape scale. Biogeochem. 44: 187-203.

Dillon, P.J., N.D. Yan and H.H. Harvey. 1984. Acidic deposition: Effects on aquatic ecosystems. Crit. Rev. Env. Contr. 13: 167-194.

Disch, J., P. Kay and L. Mortsch. 2012. A Resiliency Assessment of Ontario's Low-water Response Mechanism: Implications for Addressing Management of Low-water Under Potential Future Climate Change. University of Waterloo

Dobiesz, N.E. and N.P. Lester. 2009. Changes in mid-summer water temperature and clarity across the Great Lakes between 1968 and 2002. J. Great Lakes Res. 35: 371-384.

Dobbyn, J.S., J. Eger and N. Wilson. 1994. Atlas of the Mammals of Ontario. pp. 120. Toronto, ON, Canada: Federation of Ontario Naturalists.

Doka, S.E., M.L. Mallory, D.K. McNicol, I. Wong, C.K. Minns and N.D. Yan. 2003. Assessing potential for recovery of biotic richness and indicator species due to changes in acidic deposition and lake ph in five areas of southeastern Canada. Environ. Monitor. and Assess. 88: 53-101.

Doka, S., C. Bakelaar and L. Bouvier. 2006. Coastal wetland fish community assessment of climate change in the lower Great Lakes. pp. 101-127 in L. Mortsch, J. Ingram, A. Hebb and S. Doka (eds.). Great Lakes Coastal Wetland Communities: Vulnerabilities to Climate Change and Response to Adaptation Strategies. Env. Can., Fish. and Oceans Can., Univ. Waterloo, and Snell and Cecil Environmental Research. 247 p + Appen.

Dominguez-Faus, R., C. Folberth, J. Liu, A.M. Jaffe and P.J. Alvarez. 2013. Climate change would increase the water intensity of irrigated corn ethanol. Environ. Sci. and Technol., 47(11), 6030-6037.

D'Orgeville, M., W.R. Peltier, A.R. Erler and J. Gula, 2014: Climate change impacts on Great Lakes Basin precipitation extremes. J. of Geophys. Res.: Atm. 119: 10799–10812.

Douglas, A., C. Lemiuex, G. Nielsen, P. Gray, V. Anderson and S. MacRitchie. 2014. Responding to the Effects of Climate Change in the Lake Simcoe Watershed. Ont. Min. Nat. Resour., Science and. Res. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-37. 25p.

Douglas, S. 2014. Assessing Extreme Events and Climate Change in the Coastal Environment: New Technical Guidance from the FHWA. Proceedings of the National Hydrologic Engineering Conference, August 21 2014, University of South Alabama.

Dove-Thompson, D., C. Lewis, P.A. Gray, C. Chu and W.I. Dunlop. 2011. A summary of the effects of climate change on Ontario's aquatic ecosystems. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-11. 68p.

Dukes, J.S., J. Pontius, D. Orwig, J.R. Garnas, V.L. Rodgers, N. Brazee, B. Cooke, K.A. Theoharides, E.E. Stange, R. Harrington, J. Ehrenfeld, J. Gurevitch, M. Lerdau, K. Stinson, R. Wick and M. Ayres. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? Can. J. Forest Res. 39: 231-248.

Duveneck, M.J., R.M. Scheller, M.A. White, S.D. Handler and C. Ravenscroft. 2014. Climate change effects on northern Great Lake (USA) forests: A case for preserving diversity. Ecosphere 5: 23. doi:10.1890/ES13-00370.1.

Eaton, J.G. and R.M. Scheller. 1996. Effects of climate warming on fish thermal habitat in streams of the United States. Limnol. Oceanogr. 41: 1109-1115.

Edsall, T. and M. Charlton. 1997. Nearshore waters of the Great Lakes. State of the lakes Ecosystem Conference, 1996. Environmental Protection Agency, Washington, DC.

Environment Canada. 1988. The Potential of Soils and Bedrock to Reduce the Acidity of Atmospheric Deposition in Canada. Environmental Fact Sheet 88-1, Inland Waters and Lands Directorate, Environ. Can., Hull, QC.

Environment Canada. 2001. Threats to Sources of Drinking Water and Aquatic Ecosystem Health in Canada. Nation. Water Res. Inst., Burlington, ON, NWRI Assess. Rep. Ser. No. 1. 72p.

Environment Canada. 2013. Climate variability and change – wetlands. Available at: http://www.ec.gc.ca/inre-nwri/default.asp?lang=En&n=0CD66675-1&offset=18&toc=show.

Environment Canada and U.S. Environmental Protection Agency. 2011. State of the Great Lakes 2011 Highlights.

Epstein, P.R. 2001. Climate change and emerging infectious diseases. Microbes Infect. 3: 747-754.

EBNFLO Environmental, AquaResource Inc., 2010. Guide for Assessment of Hydrologic Effects of Climate Change in Ontario.

Fang, X. and H.G. Stefan. 1998. Potential climate warming effects on ice covers of small lakes in the contiguous US. Cold Regions. Sci. and Tech. 27: 119-140.

Fang, X., Q. Zhu, H. Chen, Z. Ma, W. Wang, X. Song, P. Zhao and C. Peng. 2014. Analysis of vegetation dynamics and climatic variability impacts on greenness across Canada using remotely sensed data from 2000 to 2009. Journal of Applied Remote Sensing 8: 083666-1-083666-14.

Feltmate, B. and J. Thistlethwaite. 2012. Climate change adaptation: a priorities plan for Canada. Climate Change Adaptation Project. *Intact Insurance.*

Ficke, A.A., C.A. Meyrick and L.J. Hansen. 2007. Potential impacts of global climate change on freshwater fisheries. Rev. Fish. Biol. Fisheries 17: 518-613.

Fisichelli, N.A., L.E. Frelich and P.B. Reich. 2013. Climate and interrelated tree regeneration drivers in mixed temperate–boreal forests. Landscape Ecol. 28: 149-159.

Flannigan, M.D. and C.E. Van Wagner. 1991. Climate change and wildfire. Canada. Can. J. For. Res. 21: 66-72.

Flannigan, M.D., Y. Bergeron, O. Engelmark and B.M. Wotton. 1998. Future wildfire in circumboreal forests in relation to global warming. J. Veg. Sci. 9: 469-476.

Flannigan, M.D., B.J. Stocks and B.M. Wotton. 2000. Climate change and forest fires. Sci. Total Environ. 262: 221-229.

Flannigan, M.D., K.A. Logan, B.D. Amiro, W.R. Skinner and B.J. Stocks. 2005. Future area burned in Canada. Clim. Chang. 72: 1-16.

Flato, G.M., G.J. Boer, W.G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader and A.J. Weaver. 2000. The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate. Clim. Dyn.16: 451-467.

Fleming, R.A., J.N. Candau and R.S. McAlpine. 2002. Landscape-scale analysis of interactions between insect defoliation and forest fire in central Canada. Clim. Change 55: 251-272.

Fleury, M., D.F. Charron, J.D. Holt, O.B. Allen and A.R. Maarouf. 2006. A time series analysis of the relationship of ambient temperature and common bacterial enteric infections in two Canadian provinces. Int. J. Biometeorol. 50: 385-391.

Fracz, A. and Chow-Fraser, P. 2013. Impacts of declining water levels on the quantity of fish habitat in coastal wetlands of eastern Georgian Bay, Lake Huron. Hydrobiologia 702: 151-169.

Francis, M., P. Hodge, R. Lidster, S. McGowan and S. Young. 2011. Major forest disturbances. pp. 11-32 in T.A. Scarr, K.L. Ryall and P. Hodge (eds.). Forest Health Conditons in Ontario 2011. Ont. Min. Nat. Resour., Sault Ste. Marie, ON. 100p.

Francl, K.E., K. Hayhoe, M. Saunders and E.P. Maurer. 2010. Ecosystem adaptation to climate change: Small mammal migration pathways in the Great Lakes states. J. Great Lakes Res. 36:86-93.

Frelich, L.E. and P.B. Reich. 2010. Will environmental changes reinforce the impact of global warming on the prairie-forest border of central North America? Front. Ecol. Environ. 8: 371-378.

Fuss, S., J.G. Canadell, G.P. Peters, M. Tavoni, R.M. Andrew, P. Ciais, R.B. Jackson, C.D. Jones, F. Kraxner, N. Nakicenovic, C. Le Quéré, M.R. Raupach, A. Sharifi, P. Smith and Y. Yamagata. 2014. Betting on negative emissions. Nature Climate Change, 4: 850-853.

Gao, Y., J.S. Fu, J.B. Drake, Y. Liu and J.F. Lamarque. 2012. Projected changes of extreme weather events in the eastern United States based on a high resolution climate modeling system. Environmental Research Letters, 7: 044025.

Garroway, C.J., J. Bowman, G.L. Holloway, J.R. Malcolm and P.J. Wilson. 2011. The genetic signature of rapid range expansion by flying squirrels in response to contemporary climate warming. Glob. Change Biol. 17: 1760-1769.

Gay, D.A. and R.E. Davis. 1993. Freezing rain and sleet climatology of the southeastern USA. Climate Research 3: 209–220.

Giorgi, F., C. Jones and G. Asrar. 2009. Addressing Climate information needs at the regional level: the CORDEX Framework. WMO Bulletin July 2009. 58, 175-183.

Girardin, M.P., A.A. Ali, C. Carcaillet, S. Gauthier, C. Hély, H. Le Goff, A. Terrier and Y. Bergeron. 2013. Fire in managed forests of eastern Canada: Risks and options. 294: 238-249.

Gleeson, J., P. Gray, A. Douglas, C.J. Lemieux and G. Nielsen. 2011. A practitioner's guide to climate change adaptation in Ontario's ecosystems. Ontario Centre for Climate Impacts and Adaptation Resources.

Gober, P. 2013. Getting Outside the Water Box: The Need for New Approaches to Water Planning and Policy. Water Resour Manage 27: 955–957.

Goldwater, L.J. 1971. Mercury in the environment. Sci. Am. 224: 15-21.

Government of Ontario. 2012. Ontario’s Great Lakes Strategy. Toronto, ON. 71p.

Grannemann, R., J. Hunt, J.R. Nicholas, T.E. Reilly and T.C. Winter. 2000. The Importance of Ground Water in the Great Lakes Region. Water Resources Investigations Report 00-048, U.S. Geol. Surv., Michigan, USA. 14p.

Grant, P.R. and B.R. Grant. 2010.Conspecific versus heterospecific gene exchange between populations of Darwin’s finches. Phil. Trans. R. Soc. Lond. B364: 1065-1076.

Green, T.R., M. Taniguchi, H. Kooi, J.J. Gurdak, D.M. Allen, K.M. Hiscock, H. Treidel and A. Aureli. 2011. Beneath the surface of global change: Impacts of climate change on groundwater. J. Hydrol. 405: 532-560.

Greer, A., V. Ng and D. Fisman. 2008. Climate change and infectious diseases in North America: the road ahead. Can. Med. Assoc. J. 178: 715-722.

Gregg, R.M., K.M. Feifel, J.M. Kershner and J.L. Hitt. 2012. The state of climate change adaptation in the Great Lakes Region. EcoAdapt. Bainbridge Island, WA.

Greifenhagen, S. and T.L. Noland. Compilers. 2003. A Synopsis of Known and Potential Diseases and Parasites Associated With Climate Change. For. Res. Inf. Pap. No. 154, Ont. For. Res. Inst., Ont. Min. Nat. Res., Sault Ste Marie, ON. 200p.

Grillakis, M.G., A.G. Koutroulis and I.K. Tsanis. 2011. Climate Change Impact on the Hydrology of Spencer Creek Watershed in Southern Ontario, Canada. Technical University of Crete.

Gritti, E.S., B. Smith and M.T. Sykes. 2006. Vulnerability of Mediterranean Basin ecosystems to climate change and invasion by exotic plant species. J. Biogeogr. 33: 145-157.

Gronewold, A.D., A.H. Clites, J.P. Smith and T.S. Hunter. 2013. A dynamic graphical interface for visualizing projected, measured, and reconstructed surface water elevations on the earth's largest lakes.Environmental Modelling and Software, 49, 34-39.

Gula, J. and W.R. Peltier. 2012. Dynamical Downscaling over the Great Lakes Basin of North America using the WRF Regional Climate Model: The impact of the Great Lakes system on regional greenhouse warming. J. Climate 25: 7723-7742.

Halbisen, M.A. and C.C. Wilson. 2009. Variable introgression from supplemental stocking in southern Ontario populations of lake trout. T. Am. Fish. Soc. 137: 699-719.

Handler, S.D., C.W. Swanston, P.R. Butler, L.A. Brandt, M.K. Janowiak, M.D. Powers and P.D. Shannon. 2012. Climate change vulnerabilities within the forestry sector for the Midwestern United States. pp. 1-22 in J. Winkler, J. Andresen, J. Hatfield, D. Biwell and D. Brown (eds.). U.S. National Climate Assessment Midwest Technical Input Report. Available at: http://glisa.msu.edu/docs/NCA/MTIT_Forestry.pdf.

Harrington, R., R.A. Fleming and I.P. Woiwod. 2001. Climate change impacts on insect management and conservation in temperate regions: Can they be predicted? Agric. Forest Entomol. 3: 233-240.

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

Hauer, F.R. and W.R. Hill. 1996. Temperature, light, and oxygen. pp. 93-106 in F.R. Hauer and G.A. Lambert (eds.). Methods in Stream Ecology. Academic Press Inc., New York, NY. 674p.

Hayhoe, K., C. Wake, T. Huntington, L. Luo, M. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. Troy and D. Wolfe. 2006. Past and future changes in climate and hydrological indicators in the U.S. Northeast. Climate Dynamics 28: 381-407.

Hayhoe, K., J. VanDorn, T. Croley, II, N. Schlegal and D. Wuebbles. 2010. Regional climate change projections for Chicago and the Great Lakes. J. Great Lakes Res. 26: 7-21.

Hebb, A.J., L.D. Mortsch, P.J. Deadman and R. Cabrera. 2013. Modelling Wetland Vegetation Response to Water-level Fluctuations at Long Point, Ontario. J. Great Lakes Res. 39: 191–200.

Hellmann, J.J., J.E. Byers, B.G. Bierwagen and J.S. Dukes. 2008. Five potential consequences of climate change for invasive species. Conserv. Biol. 22: 534-543.

Hitch, A.T. and P.L. Leberg. 2007. Breeding distributions of North American bird species moving north as a result of climate change. Conserv. Biol. 21: 534-539.

Hodges, L. 1977. Environmental Pollution. Holt, Reinhart and Winston, Toronto, ON. 496p.

Hoffman, A.A. and C.M. Sgro. 2011. Climate change and evolutionary adaptation. Nature 470: 479-485.

Hogg, E.H. and P.Y. Bernier. 2005. Climate change impacts on drought-prone forests in western Canada. The Forestry Chronicle 81: 675-682.

Honnay, O., K. Verheyen, J. Butaye, H. Jacquemyn, B. Bossuyt and M. Hermy. 2002. Possible effects of habitat fragmentation and climate change on the range of forest plant species. Ecol. Lett. 5: 525-530.

Horton, R., G. Yohe, W. Easterling, R. Kates, M. Ruth, E. Sussman, A. Whelchel, D. Wolfe and F. Lipschultz. 2014. Ch. 16: Northeast. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 16-1-nn

Hostetler, S. and E. Small. 1999. Response of North American freshwater lakes to simulated future climates. J. Am. Water Resour. Assoc. 35: 1625-1637.

Howk, F. 2009. Changes in Lake Superior ice cover at Bayfield, Wisconsin. J. Great Lakes Res. 35: 159-162.

Huff, A. and A. Thomas. 2014. Lake Superior Climate Change Impacts and Adaptation. Prepared for the Lake Superior Lakewide Action and Management Plan – Superior Work Group. Available at: http://www.epa.gov/glnpo/lakesuperior/index.html

Hynes, H.B.N. 1970. The Ecology of Running Waters. Univ. Toronto Press, Toronto, ON. 555p.

ICLEI Canada. 2010. Changing Climate, Changing Communities: Guide and Workbook for Municipal Climate Adaptation. Available online: http://www.icleicanada.org/component/k2/item/3-changing-climate-changing-communities

[IGLSLR-AMTT] International Great Lakes-St. Lawrence River Adaptive Management Task Team, 2013. Building Collaboration Across the Great Lakes – St. Lawrence River System: An Adaptive Management Plan for Addressing Extreme Water Levels - Breakdown of Roles, Responsibilities and Proposed Tasks. Final report to the International Joint Commission, May 30, 2013

Inkley, D.B., M.G. Anderson, A.R. Blaustein, V.R. Burkett, B. Felzer, B. Griffith, J. Price and T.L. Root. 2004. Global climate change and wildlife in North America. Bethesda, Maryland, Technical Review 4-2.

[IPCC] Intergovernmental Panel on Climate Change. 2000. Special Report on Emissions Scenarios (SRES), Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries,J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, et al., Special Report on Emissions Scenarios, Working Group III, Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, 595p.

[IPCC] Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: The Physical Science Basis: Summary for Policymakers. A Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland. 996p.

[IPCC] Intergovernmental Panel on Climate Change. 2014. Summary for Policymakers. pp. 1-32 in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Fields, C.D., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastradrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.). Cambridge University Press, Cambridge, UK.

Irland, L.C. 2000. Ice storms and forest impacts. Sci. Total Environ. 262: 231-242.

[IUGLS] International Upper Great Lakes Study. 2009. Impacts of Upper Great Lakes water levels: St. Clair River. Final report to the International Joint Commission, December 2009.

[IUGLS] International Upper Great Lakes Study. 2012. Lake Superior regulation: Addressing uncertainty in Upper Great Lakes water levels. Final report to the International Joint Commission, March 2012.

Iverson, L.R., M.W. Schwartz and A.M. Prasad. 2004. How fast and far might tree species migrate in the eastern United States due to climate change? Global Ecol. Biogeogr. 13: 209-219.

Iverson, L.R., A.M. Prasad and S. Matthews. 2008. Modeling potential climate change impacts on the trees of the northeastern United States. Mitig. Adapt. Strategies Glob. Chang. 13: 487-516.

Iverson, L. R., S.N. Matthews, A.M. Prasad, M.P. Peters and G. Yohe. 2012. Development of risk matrices for evaluating climatic change responses of forested habitats. Clim. Chang. 114: 231-243.

Jackson, B. 2007. Potential Effects of Climate Change on Lake Trout in Atikokan Area. 2007. Climate Change Res. Infor. Note No. 4, Ont. Min. Nat. Resour., Sault Ste Marie, ON, Canada. 4p.

Jackson, D.A. and N.E. Mandrak. 2002. Changing fish biodiversity: Predicting the loss of cyprinid biodiversity due to global climate change. Am. Fish. Soc. Symp. 32: 89-98.

Jager, H.I., V.W. Winkle and B.D. Holcomb. 1999. Would hydrologic climate changes in Sierra Nevada streams influence trout persistence? T. Am. Fish. Soc. 128: 222-240.

Jeong, D.I,, L. Sushama and M.N. Khaliq. 2014. The role of temperature in drought projections over North America. Climatic Change 127: 289–303.

Jeppesen, E., B. Kronvang, M. Meerhoff, M. Søndergaard, K.M. Hansen, H.E. Anderson, T.L. Lauridsen, L. Liboriussen, M. Beklioglu, A. Özen and J.E. Olesen. 2009. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, potential adaptations. J. Environ. Qual. 38: 1930-1941.

Jones, N.E., I.C. Petreman and B.J. Schmidt. In press. High flows and freshet timing in Canada: Observed trends.

Joyce, D.G. and G.E. Rehfeldt. 2013. Climatic niche, ecological genetics, and impact of climate change on eastern white pine (*Pinus strobus* L.): Guidelines for land managers. Forest Ecol. Manag. 295: 173-192.

Jyrkama, M.I. and J.F. Sykes. 2007. The impact of climate change on spatially varying groundwater recharge in the Grand River watershed (Ontario). J. Hydrol. 338: 237-250.

Kalafatis, S. E., M.C. Lemos, Y.J. Lo and K.A. Frank. 2015. Increasing information usability for climate adaptation: The role of knowledge networks and communities of practice. Global Environmental Change, 32, 30-39

Karl, T.R., J.M. Melillo and T.C. Peterson (eds.). 2009. Global climate change impacts in the United States. Cambridge University Press., NY, USA.

Kaya, C.M., L.R. Kaeding and D.E. Burkhalter. 1977. Use of a cold-water refuge by rainbow and brook trout in a geothermal heated stream. Prog. Fish-Cult. 39: 37-39.

Keller, W. 2009. Limnology in northestern Ontario: From acidification to multiple stressors. Can. J. Fish. Aquat. Sci. 66: 1189-1198.

Kelly, N.I., G. Burness, J.L. McDermid and C.C. Wilson. 2014. Ice age fish in a warming world: Minimal variation in thermal acclimation capacity among lake trout (*Salvelinus namaycush*) populations. Conserv. Physiol. 2: 1-14.

Kerr, J. and L. Packer. 1998. The impact of climate change on mammal diversity in Canada. Environ. Monit. Assess. 49: 263-270.

Kerry, M., G. Kelk, D. Etkin, I. Burton and S. Kalhok. 1999. Glazed over: Canada copes with the ice storm of 1998. Environment 41: 6-11.

Khairy, M., D. Muir, C. Teixeira and R. Lohmann. 2014. Spatial trends, sources, and air–water exchange of organochlorine pesticides in the Great Lakes basin using low density polyethylene passive samplers. Environ. Sci. Technol. 48: 9315-9324.

Kinney, P. L. 2008. Climate change, air quality, and human health. Am. J. Prev. Med. 35: 459-467.

Kirchmeier, M.C., D.J. Lorenz and D.J. Vimont. 2014. Statistical Downscaling of Daily Wind Speed Variations. Journal of Applied Meteorology and Climatology 53: 660-675.

Klaus, S.P. and S.C. Lougheed. 2013. Changes in breeding phenology of eastern Ontario frogs over four decades. Ecol. Evol. 3: 835-845.

Kling, G.W., K. Hayhoe, L.B. Johnson, J.J. Magnuson, S. Polasky, S.K. Robinson, B.J. Shuter, M.M. Wander, D.J. Wuebbles and D.R. Zak. 2003. Confronting Climate Change in the Great Lakes Region: Impacts on Our Communities and Ecosystems A Report of the Union of Concerned Scientists and Ecol. Soc. Am., USC Publications, Cambridge, Mass. 92p.

Knudsen, E., A. Lindén, C. Both, N. Jonzén, F. Pulido, N. Saino, W.J. Sutherland, L.A. Bach, T. Coppack, T. Ergon, P. Gienapp, J.A. Gill, O. Gordo, A. Hedenström, E. Lehikoinen, P.P. Marra, A.P. Møller, A.L.K. Nilsson, G. Péron, E. Ranta, D. Rubolini, T.H. Sparks, F. Spina, C.E. Studds, S.A. Sæther, P. Tryanowski and N.C. Stenseth. 2011. Challenging claims in the study of migratory birds and climate change. Biol. Rev. 86: 928-946.

Koen, E.L., J. Bowman, J.L. Lalor and P.J. Wilson. 2014a. Continental-scale assessment of the hybrid zone between bobcat and Canada lynx. Biological Conservation 178: 107-115.

Koen, E.L., J. Bowman, D.L. Murray and P.J. Wilson. 2014b. Climate change reduces genetic diversity of Canada lynx at the trailing range edge. Ecography 37: 1-9.

Koonce, J.F., W. Busch and T. Czapia. 1996. Restoration of Lake Erie: Contribution of water quality and natural resource management. Can. J. Fish. Aquat. Sci. 53910: 105-112.

Koshida, G. and W. Avis (eds.). 1998. Canada Country Study: Climate Impacts and Adaptation. Government of Canada. Available at: http://www.climatechange.gc.ca/english/publications/ccs/.

Koslow, M. 2010. Improving the odds: using climate-readiness planning to reduce the impacts of climate change on the Great Lakes ecosystem. National Wildlife Federation. http://www.nwf.org/~/media/PDFs/Global-Warming/Reports/Great-Lakes-Adaptation.ashx

Krantzberg, G. and C. de Boer. 2006. A Valuation of Ecological Services in the Great Lakes Basin Ecosystem to Sustain Healthy Communities and a Dynamic Economy. Technical Report: Ontario Ministry of Natural Resources, 98 pages.

Kundzewicz, Z.W. and L.J. Mata. 2007. Freshwater resources and their management. pp. 173-210 in M.L. Parry, O.F. Canziana, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University press, Cambridge, U.K. 976p.

La Sorte, F.A. and F.R. Thompson III. 2007. Poleward shifts in winter ranges of North American birds. Ecology 88: 1803-1812.

Lambert, S.J. and B.K. Hansen. 2011. Simulated changes in the freezing rain climatology of North America under global warming using a coupled climate model. Atmosphere-ocean 49: 289-295.

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

Le Conte, Y. and M. Navajas. 2008. Climate change: impact on honey bee populations and diseases. Rev Sci Tech− Office International des Epizooties 27: 499-510.

Le Goff, H., M.D. Flannigan and Y. Bergeron. 2009. Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change. Can. J. For. Res. 39: 2369-2380.

Lecomte, E.L., A.W. Pang and J.W. Russell. 1998. Ice Storm '98. Institute for Catastrophic Loss Reduction Research Paper Series No. 1.

Lee, C.C. 2012. Utilizing Synoptic Climatological Methods to Assess the Impacts of Climate Change on Future Tornado-Favorable Environments. Natural Hazards 62 (2): 325-343.

Lehman, J.T. 2002. Mixing patterns and plankton biomass of the St. Lawrence Great Lakes under climate change scenarios. J. Great Lakes Res. 28: 583-596.

Lemieux, C.J., D.J. Scott, P.A. Gray and R.G. Davis. 2007. Climate Change and Ontario's Provincial Parks: Towards an Adaptation Strategy. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-06.

Lemmen, D.S. and F.J. Warren. 2004. Climate change impacts and adaptation: A Canadian perspective. Nat. Res. Can., Ottawa, ON.

Lemos, M. C., C.J. Kirchhoff, S.E. Kalafatis, D. Scavia and R.B. Rood. 2014. Moving climate information off the shelf: Boundary Chains and the role of RISAs as adaptive organizations. Weather Clim Soc. 6: 273-285.

Lemos, M. C., C.J. Kirchhoff and V. Ramprasad. 2012. Narrowing the climate information usability gap. Nature Climate Change, 2: 789-794.

Lemprière, T.C., P.Y. Bernier, A.L. Carroll, M.D. Flannigan, R.P. Gilsenan, D.W. McKenney, E.H. Hogg, J.H. Pedlar and D. Blain. 2008. The importance of forest sector adaptation to climate change. Nat. Res. Can., Edmonton, AB. 78p.

Lenarz, M.S., M.E. Nelson, M. Schrage and A.J. Edwards. 2009. Temperature mediated moose survival in Northeastern Minnesota. J. Wildl. Manage. 73: 503-510.

Lenters, J.D., J.B. Anderton, P. Blanken, C. Spence and A.E. Suyker. 2013. Assessing the Impacts of Climate Variability and Change on Great Lakes Evaporation. pp. 1-11 in D. Brown, D. Bidwell and L. Briley (eds.). 2011 Project Reports. Available at: http://glisaclimate.org/media/GLISA_Lake_Evaporation.pdf

Lim, B., E. Spanger-Siegfried, I. Burton, E. Malone and S. Huq. 2005. Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies, and Measures. http://www.preventionweb.net/files/7995_APF.pdf.

Lishawa, S.C., A.A. Dennis and N.C. Tuchman. 2010. Water level decline promotes *Typha X glauca* establishment and vegetation change in the Great Lakes coastal wetlands. Wetlands 30: 1085-1096.

Lofgren B.M., T.S. Hunter and J. Wilbarger. 2011. Effects of using air temperature as a proxy for potential evapotranspiration in climate change scenarios of Great Lakes basin hydrology. J Great Lakes Res 37: 744–752.

Lofgren, B.M. and T.S. Hunter. 2011. Comparative Analysis of Net Basin Supply Components and Climate Change Impact on the Upper Great Lakes. NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan.

Lofgren, B.M., F.H. Quinn, A.H. Clites, R.A. Assel, A.J. Eberhardt and C.L. Luukkonen. 2002. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. J. Great Lakes Res. 28: 537-554.

Lofgren, B.M. and A. Gronewold. 2012. Water Resources. pp. 1-12 in J. Winkler, J. Andresen, J. Hatfield, D. Bidwell, and D. Brown (eds.). U.S. National Climate Assessment Midwest

Technical Input Report. Available at: http://glisa.msu.edu/docs/NCA/MTIT_WaterResources.pdf

Logan, J.A. and J.A. Powell. 2001. Ghost forests, global warming, and the mountain pine beetle. Am. Entomol. 47: 160-173.

Logan, J.A., J. Régnière and J.A. Powell. 2003. Assessing the impacts of global warming on forest pest dynamics. Front. Ecol. Environ. 1: 130-137.

Lu, P., W.H. Parker, M. Cherry, S. Colombo, W.C. Parker, R. Man and N. Roubal. 2014. Survival and growth patterns of white spruce (*Picea glauca* [Moench] Voss) rangewide provenances and their implications for climate change adaptation. Ecol. Evol. 4: 2360-2374.

Lynch, A.J., W.W. Taylor and K.D. Smith. 2010. The influence of changing climate on the ecology and management of selected Laurentian Great Lakes fisheries. J. Fish Biol. 77: 1764-1782.

Ma, J., H. Hung and P. Blanchard. 2004. How do climate fluctuations affect persistent organic pollutant distribution in North America? Evidence from a decade of air monitoring. Environ. Sci. Technol. 38: 2538-2543.

MacDonald, N.W., A.J. Burton, M.F. Jurgensen, J.W. McLaughlin and G.D. Mroz. 1991. Variation in forest soil properties along a Great Lakes air pollution gradient. Soil Science Society of America Journal 55: 1709-1715.

MacKay, M. and F. Segleneiks. 2010. Simulating Net Basin Supply and Lake Levels for the Upper Great Lakes Part II. Environment Canada, Report for the Hydroclimatic Technical Work Group.

MacKay, M. and F. Segleneiks. 2013. On the simulation of Laurentian Great Lakes water levels under projections of global climate change. Clim. Chang. 117: 55-67.

Mackey, S.D. 2012. Great Lakes Nearshore and Coastal Systems. pp. 1-14 in J. Winkler, J. Andresen, J. Hatfield, D. Bidwell, and D. Brown (eds.). U.S. National Climate Assessment Midwest Technical Input Report. Available at: http://glisa.msu.edu/docs/NCA/MTIT_Coastal.pdf

Magnuson, J. 1998. Regional Climate Change and Fresh Water Ecology. Upper Great Lakes Regional Climate Change Impacts Workshop. May, University of Michigan. Available at: http://www.geo.msu.edu/glra/PDF_files/workshop%20report/05.%20Appendices/Appendix%201-%20Invited%20talks/06.%20Magnuson.pdf

Magnuson, J.J., K.E. Webster, R.A. Assel, C.J. Browser, P.J. Dillon, J.G. Eaton, H.E. Evans, E.J. Fee, R.I. Hall, L.R. Mortsch, D.W. Schindler and F.H. Quinn. 1997. Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian Shield Region. Hydrol. Process. 11: 825-871.

Magnuson, J.J., D. Robertson, B. Benson, R. Wynee, D. Livingstone, T. Arai, R. Assel, R. Barry, V. Card, E. Kuusisto, N. Granin, T.Y. Prowse, K. Stewart and V. Vuglinski. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. Science 289: 1743-1746.

Mailhot, A., I. Beauregard, G. Talbot, D. Caya and S. Biner. 2012. Future changes in intense precipitation over Canada assessed from multi-model NARCCAP ensemble simulations. International Journal of Climatology. 32: 1151-1163.

Mainka, S.A. and G.W. Howard. 2010. Climate change and invasive species: double jeopardy. Integr. Zool. 5: 102-111.

Malmaeus, J.M., T. Blenckner, H. Markensten and I. Persson. 2006. Lake phosphorus dynamics and climate warming: A mechanistic model approach. Ecol. Model. 190: 1-14.

Mandrak, N.E. 1989. Potential invasion of the Great Lakes by fish species associated with climatic warming. J. Great Lakes Res. 15: 306-316.

Marcogliese, D.J. 2001. Implications of climate change for parasitism of animals in the aquatic environment. Can. J. Zool. 79: 1331-1352.

Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Fram, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G-K. Plattner, G.W. Yohe and F.W. Zwiers. 2010. Guidance note for lead authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties. Intergovernmental Panel on Climate Change (IPCC). Available at: http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf

Matthews, S.N., L.R. Iverson, A.M. Prasad, M.P. Peters and P.G. Rodewald. 2011. Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history-factors." Forest Ecol. Manage. 262: 1460-1472.

Matthews, S.N., L.R. Iverson, M.P. Peters, A.M. Prasad and S. Subburayalu. 2014. Assessing and comparing risk to climate changes among forested locations: implications for ecosystem services. Landscape Ecol. 29: 213-228.

McBean, E. and Motiee, H. 2008. Assessment of impact of climate change on water resources: a long term analysis of the Great Lakes of North America. Hydrol. and Earth Syst. Sci. 12: 239-255.

McCombie, A.M. 1959. Some relations between air temperatures and the surface water temperature of lakes. Limnol. Oceanog. 4: 252-258.

McDermid, J.L., P.E. Ihssen, W.N. Sloan and B.J. Shuter. 2007. Genetic and environmental influences on life history traits in lake trout. T. Am. Fish. Soc. 136: 1018-1029.

McDermid, J.L., B.J. Shuter and N.P. Lester. 2010. Life history differences parallel environmental differences among North American lake trout (*Salvelinus namaycush*) populations. Can. J. Fish. Aquat. Sci. 67: 314-325.

McDermid, J.L., C.C. Wilson, W.N. Sloan and B.J. Shuter. 2013. Intraspecific differences in thermal biology among inland lake trout populations. T. Am. Fish. Soc. 142: 756-766.

McDermid, J.L., F.A. Fischer, M. Alshamlih, W.N. Sloan, N.E. Jones and C.C. Wilson. 2012. Variation in acute thermal tolerance within and among hatchery strains of brook trout, Salvelinus fontinalis. T. Am. Fish. Soc. 141: 1230-1235.

McKenney, D.W., J.H. Pedlar, K. Lawrence, K. Campbell and M.F. Hutchinson. 2007. Beyond traditional hardiness zones: Using climate envelopes to map plant range limit. Bioscience 57: 929-937.

McKenney, D.W., J.H. Pedlar, K. Lawrence, P.A. Gray, S.J. Colombo and W.J. Crins. 2010. Current and Projected Future Climatic Conditions for Ecoregions and Selected Natural Heritage Areas in Ontario. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-16. 42p.

McKenney, D.W., M.F. Hutchinson, P. Papadopol, K. Kawrence, J.H. Pedlar, K. Campbell and T. Owen. 2011a. Customized spatial climate models for North America. American Meteorological Society: 1611-1622.

McKenney, D.W., J.H. Pedlar, R.B. Rood and D. Price. 2011b. Revisiting projected shifts in climate envelopes of North American trees using updated general circulation models. Glob. Chan. Biol. 17:2720-2730.

McLachlan, J.S., J.S. Clark and P.S. Manos. 2005. Molecular indicators of tree migration capacity under rapid climate change. Ecology 86: 2088-2098.

McNeely, J.A. 2000. The future of alien invasive species: Changing social views. pp. 171-190 in H.A. Mooney and R.J. Hobbs (eds.). Invasive species in a changing world. Island Press, Washington, DC.

[MEA] Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Meadows, G.A., S.D. Mackey, R.R. Goforth, D.M. Mickelson, T.B. Edil, J. Fuller, D.E. Jr. Guy, L.A. Meadows, E. Brown, S.M. Carman and D.L Liebenthal. 2005. Cumulative Impacts of Nearshore Engineering. pp. 90-112 in S.D. Mackey and R.R. Goforth (eds.). Great Lakes Nearshore and Coastal Habitats: Special Issue. J. Great Lakes Res. 31: 90-112.

Mearns, L.O., W.J. Gutowski, R. Jones, L-Y. Leung, S. McGinnis, A.M.B. Nunes and Y. Qian. 2009. A regional climate change assessment program for North America. *EOS*. 90: 311-312. http://www.agu.org/pubs/eos/eo0936.shtml

Medeiros, A.S. and L.A. Molot. 2006. Trends in iron and phosphorus loading to Lake Ontario from waste water treatment plants in Hamilton and Toronto. J. Great Lakes Res. 32: 788-797.

Meisner, J.D. 1990. Potential loss of thermal habitat for Brook Trout due to climate warming, in two southern Ontario streams. T. Am. Fish. Soc. 119: 282-291.

Meisner, J.D., J.S. Rosenfeld and H.A. Regier. 1988. The role of groundwater on the impact of climate warming on stream salmoninds. Fisheries 13: 2-8.

Melillo, J., M.T.C. Richmond and G.W. Yohe. 2014. Highlights of Climate Change Impacts in the United States: The Third National Climate Assessment. US Global Change Research Program. 148p.

Melles, S.J., C. Chu, K.M. Alofs and D.A. Jackson. 2015. Potential spread of Great Lakes fishes given climate change and proposed dams: an approach using circuit theory to evaluate invasion risk. Landscape Ecol. 30:919-935.

Melles, S.J., M-J. Fortin, K. Lindsay and D. Badzinski. 2011. Expanding northward: Influence of climate change, forest connectivity, and population processes on a threatened species' range shift. Glob. Change Biol. 17: 17-31.

Michalak, A. M., E. J. Anderson, D. Beletsky, S. Boland, N.S. Bosch, T.B. Bridgeman, J.D. Chaffin, K. Cho, R. Confesor, I. Daloğlu, J.V. DePinto, M.A. Evans, G.L. Fahnenstiel, L. He, J.C. Ho, L. Jenkins, T.H. Johengen, K.C. Kuo, E. LaPorte, X. Liu, M.R. McWilliams, M.R. Moore, D.J. Posselt, R.P. Richards, D. Scavia, A.L. Steiner, E. Verhamme, D.M. Wright and M.A. Zagorski. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proceedings of the National Academy of Sciences 110: 6448-6452.

Minns, C.K. 1989. Factors affecting fish species richness in Ontario lakes. T. Am. Fish. Soc. 118: 533-545.

Minns, C.K., J.E. Moore, D.W. Schindler and M.L. Jones. 1990. Assessing the potential extent of damage to inland lakes in eastern Canada due to acidic deposition: III Predicted impacts on species richness in seven groups of aquatic biota. Can. J. Fish. Aquat. Sci. 47: 821-830.

Minns, C.K. and J.E. Moore. 1992. Predicting the impact of climate change on the spatial pattern of freshwater fish yield capability in eastern Canada. Clim. Chang. 22: 327-346.

Minns, C.K. and J.E. Moore. 1995. Factors limiting the distributions of Ontario's freshwater fishes: The role of climate and other variables, and the potential impacts of climate change. Can. Spec. Publ. Fish. Aquat. Sci. 121: 137-160.

Minns, C.K., B.J. Shuter and J.L. McDermid. 2009. Regional Projections of Climate Change Effects on Ontario Lake Trout (*Salvelinus namaycush*) Populations. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-14. 10p.

Minns, C. K., E.J Moore, S.E. Doka and M.A. St. John. 2011. Temporal trends and spatial patterns in the temperature and oxygen regimes in the Bay of Quinte, Lake Ontario, 1972-2008. Aquat. Ecosys. Health Manage. 4: 9-20.

Minns, C.K., B.J. Shuter and S.R. Fung. 2014a. Regional projections of climate change effects on ice cover and open-water duration for Ontario lakes using updated ice-date models. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-40. 41p.

Minns, C.K., BJ. Shuter and S.R. Fung. 2014b. Regional projections of climate change effects on thermal habitat space for fisheries in stratified Ontario lakes. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-41. 21p.

Minshall, L. 2000. Adapting to Climate Change in the Grand River Watershed Progress Report. Climate Change Action FGGund – Impacts and Adaptation Project A093. 3p. (Unpublished Report).

Mishra, V., K.A. Cherkauer, L.C. Bowling and M. Huber. 2011. Lake ice phenology of small lakes: Impacts of climate variability in the Great Lakes region. Global Planet. Change 76: 166-185.

Moiseenko, T.I. 2005. Effects of acidification on aquatic ecosystems. Russian J.Ecol. 36: 93-102.

Monson, B.A. 2009. Trend reversal of mercury concentrations in piscivorous fish from Minnesota Lakes: 1982-2006. Environ. Sci. Technol. 43: 1750-1755.

Moore, S.K., V.L. Trainer, N.J. Mantua, M.S. Parker, E.A. Laws, L.C. Backer and L.E. Fleming. 2008. Impacts of climate variability and future climate change on harmful algal blooms and human health. Environ. Health 7: S4.

Moore, T.R., J.A. Trofymow, B. Taylor, C. Prescott, C. Camire, L. Duschene, J. Fyles, L. Kozak, M. Kranabetter, I. Morrison, M. Siltanen, S. Smith, B. Titus, S. Visser, R. Wein and S. Zoltai. 1999. Litter decomposition rates in Canadian forests. Global Change Biol. 5: 75-82.

Mortsch, L.D. and F.H. Quinn. 1996. Climate change scenarios for Great Lakes Basin ecosystem studies. Limnology and oceanography 41: 903-911.

Mortsch, L. 1998. Assessing the impacts of climate change on the Great Lakes shoreline wetlands. Clim. Chang. 40: 391-416.

Mortsch, L., H. Hengeveld, M. Lister, L. Wenger, B. Lofgren, F. Quinn and M. Slivitzky. 2000. Climate change impacts on the hydrology of the Great Lakes-St. Lawrence system. Canadian Water Resources Journal 25: 153-179.

Mortsch, L., M. Alden and J.D. Scheraga. 2003. Climate Change and Water Quality in the Great Lakes Region: Risks, Opportunities and Responses. A Report Prepared for the Great Lakes Water Quality Board of the International Joint Commission.135p.

Mortsch, L., J. Ingram, A. Hebb and S. Doka. 2006. Great Lakes Coastal Wetland Communities: Vulnerabilities to Climate Change and Response to Adaptation Strategies. Final Report submitted to the Climate Change Impacts and Adaptation Program, Natural Resources Canada. Environ. Can. and the Dept. Fish. and Ocean., Toronto, ON. 251 p.+appendices.

Mortsch, L.D. 2010. Multiple Dimensions of Vulnerability and its Influence on Adaptation Planning and Decision Making. pp 67-88 in Climate: Global Change and Local Adaptation. Linkov, I. and S. Todd (eds.). Springer, Netherlands.

Moulton, R.J. and D.R. Cuthbert. 2000. Cumulative impacts/risk assessment of water removal or loss from the Great Lakes-St. Lawrence River system. Can. Water Resour. J. 25: 181-208.

Moyle, P.B. and B. Vondracek. 1985. Persistence and structure of the fish assemblage in a small California stream. Ecol. 66: 1-13.

Murray, D.L., E.W. Cox, W.B. Ballard, H.A. Whitlaw, M.S. Lenarz, T.W. Custer, T. Barnett and T.K. Fuller. 2009. Pathogens, nutritional deficiency, and climate influences on a declining moose population. Wildlife Monogr. 166: 1-30.

Murray, M. and S.A. Holmes. 2004. Assessment of mercury emissions inventories for the Great Lakes states." Environ. Res. 95: 282-297.

Music, B., A. Frigon, B. Lofgren, R. Turcotte and J-F. Cyr. 2015. Present and future Laurentian : Great Lakes hydroclimatic conditions as simulated by regional climate models with an emphasis on Lake Michigan-Huron. Climatic Change. DOI: 10.1007/s10584-015-1348-8.

Music, B. and D. Caya. 2007: Evaluation of the Hydrological Cycle over the Mississippi River Basin as Simulated by the Canadian Regional Climate Model (CRCM). J. Hydromet. 8: 969-988.

Myers, P., B.L. Lundrigan, S.M.G. Hoffman, A.P. Haraminac and S.H.Seto. 2009. Climate-induced changes in the small mammal communities of the Northern Great Lakes Region. Global Change Biol. 15: 1434-1454.

Nantel, P., M.G. Pellatt, K. Keenleyside and P.A. Gray. 2014. Biodiversity and protected areas. pp. 159-190 in Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation. F.J. Warren and D.S. Lemmen (eds.). Government of Canada, Ottawa, ON. 286p.

National Assessment Synthesis Team. 2001. Climate Change Impacts on the United States: The Potential Consequences of Climate variability and Change. Cambridge University Press, New York, NY. 620p.

National Audubon Society. 2014. Audubon’s Birds and Climate Change Report: A Primer for Practitioners. National Audubon Society, New York. Contributors: Gary Langham, Justin Schuetz, Candan Soykan, Chad Wilsey, Tom Auer, Geoff LeBaron, Connie Sanchez, Trish Distler. Version 1.2.

Natural Resources Canada. 2000. Sensitivities to Climate Change in Canada. Natural Resources Canada, Ottawa, ON. 29p.

Nejadhashemi, A.P., B.J. Wardynski and J.D. Munoz, J.D. 2012. Large-Scale Hydrologic Modeling of the Michigan and Wisconsin Agricultural Regions to Study Impacts of Land use Changes. Michigan State University.

Nituch, L.A. and J. Bowman. 2013. Community-level effects of climate change on Ontario’s biodiversity. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-36. 57p.

[NOAA] National Oceanic and Atmospheric Administration. 2010. NOAA Ocean and Great Lakes Acidification Research Plan. NOAA Special Report. 143p.

Nohara, D., A. Kitoh, M. Hosaka and T. Oki. 2006. Impact of climate change on river discharge projected by multimodel ensemble. J. Hydrometerol. 7: 1076-1089.

Notaro, M., J.W. Williams and D. Lorenz. 2013. Vegetation and land carbon projections for Wisconsin, USA, in the 21st century. Climate Res. 54: 149-165.

Notaro, M, D. Lorenz, C. Hoving and M. Schummer. 2014. Twenty-First-Century Projections of Snowfall and Winter Severity across Central-Eastern North America. J. Climate 27: 6526-6550.

Notaro, M., D.J. Lorenz, D. Vimont, S. Vavrus, C. Kucharik and K. Franz. 2011. 21st Century Wisconsin Snow Projections Based on an Operational Snow Model Driven by Statistically Downscaled Climate Data. International Journal of Climatology 31: 1615-1633.

Notaro, M., V. Bennington and S. Vavrus. 2015. Dynamically Downscaled Projections of Lake-Effect Snow in the Great Lakes Basin. J. Climate 28: 1661–1684.

Noyes, P.D., M.K. McElwee, H.D. Miller, B.W. Clark, L.A. Van Tiem, K.C. Walcott, K.N. Erwin and E.D. Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environment International 35: 971-986.

Ogden, N.H., A. Maarouf, I.K. Barker, M. Bigras-Poulin, L.R. Lindsay, M.G. Morshed, C.J. O'Callaghan, F. Ramay, D. Waltner-Toews and D.F. Charron. 2006. Climate change and the potential for range expansion of the Lyme disease vector Ixodes scapularis in Canada. Int. J. Parasitol. 36: 63-70.

Oni, S.K., M.N. Futter, L.A. Molot and P.J. Dillion. 2012. Modelling the long term impact of climate change on the carbon budget of Lake Simcoe, Ontario using INCA-C. Sci. Total Environ. 414: 387-403.

Oni, S.K., P.J. Dillon, R.A. Metcalfe and M.N. Futter. 2012. Dynamic Modelling of the Impact of Climate Change and Power Flow Management Options using STELLA: Application to the Steephill Falls Reservoir, Ontario, Canada. Can Water Resour J. 37: 125-148.

Ontario Biodiversity Council. 2010. State of Ontario's biodiversity 2010. A report of the Ontario Biodiversity Council, Peterborough, ON.

Opdam, P. and D. Wascher. 2004. Climate change meets habitat fragmentation: linking landscape and biogeographical scale levels in research and conservation. Biol. Conserv. 117: 285-297.

Pagnucco, K.S., G.A. Maynard, S.A. Fera, N.D. Yan, T.F. Nalepa and A. Ricciardi. 2015. The future of species invasions in the Great Lakes-St. Lawrence River basin. J. Great Lakes Res. 41: 96-107.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. Ann. Rev. Ecol. Evol. Syst. 37: 637-669.

Paterson, J.A., D.J. Ford, L.B. Ford, A. Lesnikowski, P. Berry, P., Henderson and J. Heymann. 2012. Adaptation to climate change in the Ontario public health sector. BMC public health, 12(1), 452.

Patz, J.A., S.J. Vavrus, C.K. Uejio and S.L. McLellan. 2008. Climate change and waterborne disease risk in the Great Lakes region of the US. Am. J. Prev. Med. 35: 451-458.

Paull, S.H. and P.T.J. Johnson. 2014. Experimental warming drives a seasonal shift in the timing of host-parasite dynamics with consequences for disease risk. Ecol. Lett. 17: 445-453.

[PCIC] Pacific Climate Impacts Consortium. (2014. Statistically Downscaled Climate Scenarios. *University of Victoria.* Available at: http://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios.

Pease, A.A. and C.P. Paukert. 2014. Potential impacts of climate change on growth and prey consumption of stream-dwelling smallmouth bass in the central United States. Ecol. Freshw. Fish 23: 336-346.

Peck, A., P. Prodanovic and S.P. Simonovic. 2012. Rainfall intensity duration frequency curves under climate change: city of London, Ontario, Canada. Can. Water Resour. J. 37: 177-189.

Peters, E.B., K.R. Wythers, S. Zhang, J.B. Bradford and P.B. Reich. 2013. Potential climate change impacts on temperate forest ecosystem processes. Can. J. Forest Res. 43: 939-950.

Petersen, B., K.H. Hall, K. Kahl and P.J. Doran. 2013. In Their Own Words: Perceptions of Climate Change Adaptation from the Great Lakes Region's Resource Management Community. Environmental Practice 15: 377-392.

Piggott, A., B. Mills and S. Moin. 2005. Groundwater and climate change: Impacts and adaptation in southern Ontario. Can. J. Civil Eng. 22: 14-17.

Podur, J. and M. Wotton. 2010. Will climate change overwhelm fire management capacity? Ecological Modelling 221: 1301–1309.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks and J.C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. BioScience 47: 769-784.

Poff, N.L., P.A. Angermeier, S.D. Cooper, P.S. Lake, K.D. Fausch, K.O. Winemiller, L.A.K. Mertes, M.W. Oswood, J. Reynolds and F.J. Rahel. 2001. Fish diversity in streams and rivers. pp. 315-350 in F.S. Chapin III, O.E. Sala and E. Huber-Sannwald (eds.). Global Biodiversity in a Changing Environment: Scenarios for the 21st century. Springer-Verlag, New York, NY.

Poff, L.M. and B.J. Day. 2002. Aquatic Ecosystems and Global Climate Change: Potential Impacts on Inland Freshwater and Coastal Wetland Ecosystems in the United States. Prepared for the Pew Centre on Global Climate Change. Available at: http://www.pewclimate.org/projects/aquatic.pdf

Power, G., R.S. Brown and J.G. Imhof. 1999. Groundwater and fish – insights from northern North America. Hydrol. Process. 13: 401-422.

Prasad, A.M., L.R. Iverson, S. Matthews and M. Peters. 2007. A climate change atlas for 134 forest tree species of the eastern United States [database]. US Department of Agriculture, Forest Service. Available at: http://www. nrs. fs. fed. us/atlas/tree.

Price, D.T., D.W. McKenney, L.A. Joyce, R.M. Siltanen, P. Papadopol and K. Lawrence. 2011. High resolution interpolation of IPCC AR4 GCM climate scenarios for Canada. Nat. Resour. Can., Can. For. Serv. North. For. Cent. Edmonton, Alta. Inf. Rep. NOR-X-421.

Price, J., J. Silbernagel, N. Miller, R. Swaty, M. White and K. Nixon. 2012. Eliciting expert knowledge to inform landscape modeling of conservation scenarios. Ecol Model. 229: 76-87.

Price, D.T., R.I. Alfaro, K.J. Brown, M.D. Flannigan, R.A. Fleming, E.H. Hogg, M.P. Girardin, T. Lakusta, M. Johnston, D.W. McKenney, J.H. Pedlar, T. Stratton, R.N. Sturrock, I.D. Thompson, J.A. Trofymow and L.A. Venier. 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environmental Reviews 21:322-365.

Prowse, T. and S. Beltaos. 2002. Climatic control of river-ice hydrology: A review. Hydrol. Process. 16: 805-822.

Prowse, T.D., F.J. Wrona, J.D. Reist, J.E. Hobbie, L.M.J. Lévesque and W.F. Vincent. 2006a. General features of the Arctic relevant to climate change in freshwater ecosystems. Ambio 35: 330-338.

Prowse, T.D., F.J. Wrona, J.D. Reist, J.J. Gibson, J.E. Hobbie, L.M.J. Lévesque and W.F. Vincent. 2006b. Climate change effects on hydroecology of Arctic freshwater ecosystems. Ambio 35: 347-358.

Pryor, S.C., D. Scavia, C. Downer, M. Gaden, L. Iverson, R. Nordstrom, J. Patz and G. P. Robertson. 2014: Ch. 18: Mid-west. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 418-440

Pryor, S.C. and R.J. Barthelmie. 2010. Climate change impacts on wind energy: A review. Renew. Sust. Energ. Rev. 14: 430-437.

Puric-Mladenovic, D., J. Malcolm, H. She, S. Stobl and J. Buck. In review. An analysis of the vulnerabilities of terrestrial ecosystems/vegetation cover to climate change in the Lake Simcoe watershed.

Pyke, C.R., R. Thomas, R.D. Porter, J.J. Hellmann, J.S. Dukes, D.M. Lodge and G. Chavarria. 2008. Current practices and future opportunities for policy on climate change and invasive species. Conserv. Biol. 22: 585-592.

Quinn, F.H., B.M. Lofgren, A.H. Clites, R.A. Assel, A. Eberhardt and Y.T. Hunter. 1999. Great Lakes Water Resources Sector Report. Great Lakes Environ. Res. Lab., Ann Arbor, MI. 6p.

Rahel, F.J. and J.D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. Conserv. Biol. 22: 521-533.

Rahman, M., T. Bolisetti and R. Balachandar. 2012. Hydrologic modelling to assess the climate change impacts in a Southern Ontario watershed. Can. J. Civil Eng. 39: 91-103.

Rahman, M., T. Bolisetti and R. Balachandar. 2010. Effect of Climate Change on Low-Flow Conditions in the Ruscom River Watershed, Ontario. University of Windsor.

Randall, D. 2011. The Evolution of Complexity in General Circulation Models. In: Leo Donner, Wayne Schubert, and Richard Somerville (Eds.), The Development of Atmospheric General Circulation Models: Complexity, Synthesis, and Computation, Cambridge University Press, 202-221

Reclamation. 2013. Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information, and Summary of User Needs. *U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center*. Denver, Colorado: 47p.

Régnière, J., V. Nealis and K. Porter. 2009. Climate suitability and management of the gypsy moth invasion into Canada. Biol. Invasions. 11: 135-148.

Régnière, J., R. St-Amant and P. Duval. 2012. Predicting insect distributions under climate change from physiological responses: spruce budworm as an example. Biol. Invasions 14: 1571-1586.

Reist, J.D., F.J. Wrona, T.D. Prowse, M. Power, J.B. Dempson, R.J. Beamish, J.R. King, T.J. Carmichael and C.D. Sawatzky. 2006. General effects of climate change on Artic fishes and fish populations. Ambio 35: 370-380.

Rempel, R.S. 2012. Effects of climate change on moose populations: A vulnerability analysis for the clay belt ecodistrict (3E-1) in northeastern Ontario. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-26. 26p.

Roberts, L. 1989. How fast can tress migrate? If the climate models are correct, greenhouse warming will spell doom for many forests across the United States. Science 243: 735-737.

Rodenhouse, N.L., L.M. Christenson, D. Parry and L.E. Green. 2009. Climate change effects on native fauna of northeastern forests. Can. J. Forest Res. 39: 249-263.

Roy-Dufresne, E., T. Logan, J.A. Simon, G.L. Chmura and V. Millien. 2013. Poleward expansion of the white-footed mouse (*Peromyscus leucopus)* under climate change: implications for the spread of lyme disease. PLoS ONE 8: e80724. doi:10.1371/journal.pone.0080724

Rubec, C.D.A. 1981. Characteristics of terrestrial ecosystems impinged by acid precipitation across Canada. Working Paper No. 19, Lands Directorate, Env. Can., Ottawa, ON. 30p.

Ryder, R.A. and J. Pesendorfer. 1988. Comparative Properties of Rivers and Lakes from an Ontario Perspective. Ontario Fisheries Tech. Rep. Ser. No. 26, Ont. Min. Nat. Res., Toronto, ON. 42p.

Sambaraju, K.R., A.L. Carroll, J. Zhu, K. Stahl, R.D. Moore and B.H. Aukema. 2011. Climate change could alter the distribution of mountain pine beetle outbreaks in western Canada. Ecography 34: 001-013.

Samuel, J., P. Coulibaly and R.A. Metcalfe. 2012. Evaluation of Future Flow Variability in Ungauged Basins: Validation of Combined Methods. McMaster University

Schiedek, D., B. Sundelin, J.W. Readman and R.W. Macdonald. 2007. Interactions between climate change and contaminants. Mar. Pollut. Bull. 54: 1845-1856.

Schindler, D.E., S.R. Carpenter, K.L. Cottingham, X. He, J.R. Hodgson, J.F. Kitchell and P.A. Soranno. 1996a. Food web structure and littoral zone coupling to pelagic trophic cascades. pp. 96-105 in G.A. Polis and K.O. Winemiller (eds.). Food Webs: Integration of patterns and Dynamics. Chapman and Hall, Toronto, ON. 472p.

Schindler, D.W. 1998. A dim future for boreal watershed landscapes. BioScience 48: 157-164.

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Can. J. Fish. Aquat. Sci. 58: 18-29.

Schindler, D.W., S.E. Bayley, B.R. Parker, K.G. Beaty, D.R. Cruikshank, E.J. Fee, E.U. Schindler and M.P Stanton. 1996b. The effects of climate warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnol. Oceanogr. 41: 1004-1017.

Schneider, K.N., R.M. Newman, V. Card, S. Weisberg and D.L. Pereira. 2010. Timing of walleye spawning as an indicator of climate change. T. Am. Fish. Soc. 139: 1198-1210.

Schlozberg, R., R. Doring and P. Spiro. 2014. Low Water Blues: An Economic Impact Assessment of Future Low Water Levels in the Great Lakes and St. Lawrence River. Council of the Great Lakes Region.

Schuster, Z.T., K.W. Potter and D.S. Liebl. 2012. Assessing the Effects of Climate Change on Precipitation and Flood Damage in Wisconsin. J. Hydrol. Eng. 17: 888-894.

Schwartz, M.D., R. Ahas and A. Aasa. 2006. Onset of spring starting earlier across Northern Hemisphere. Glob. Change Biol. 12: 343-351.

Scott, P.A. and I.T.M. Craine. 1993. The lynx cycle: a climatic perspective. Clim. Res. 2: 235-240.

Scott, D., B. Jones, C. Lemieux, G. McBoyle, B. Mills, S. Svenson and G. Wall. 2002. The vulnerability of winter recreation to climate change in Ontario's Lakelands tourism region. University of Waterloo, Department of Geography Publication Series 18. 84p.

Scott, D., H.A. Khaled and B. Jones. 2005. Climate Change: A long-term strategic issue for the NCC - implications for recreation-tourism business lines. Report prepared for the National Capital Commission. Waterloo, Ontario: University of Waterloo.

Scott, D. and B. Jones. 2007. A regional comparison of the implications of climate change for the golf industry in Canada. Can Geogr. 51: 219-232.

Seelbach, P.W, J.G. Read, K.A. Buckner, T. Eder and C. Manninen, 2014. Great Lakes Blue Accounting: Empowering Decision to Realize Regional Water Values: A report to the Council of Great Lakes Governors in response to the governors' 2013 resolution on water monitoring. March 28, 2014.

Seidou, O., A. Ramsay and I. Nistor. 2012. Climate change impacts on extreme floods I: Combining imperfect deterministic simulations and non-stationary frequency analysis. Nat. Hazards 61: 647–659.

Sharma, S., D.A. Jackson, C.K. Minns and B.J. Shuter. 2007. Will northern fish populations be in hot water because of climate change? Glob. Change Biol. 13: 2052-2064.

Shaw, S.B. and S.J. Riha. 2011. Assessing Possible Changes in Flood Frequency Due to Climate Change in Mid-sized Watersheds in New York State, USA. Hydrol. Process. 25: 3653-2550.

Sheffield, J. and E.F. Wood. 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim. Dyn. 31: 79-105.

Shuter, B., C.K. Minns and N. Lester. 2002. Climate change, freshwater fish and fisheries: case studies from Ontario and their use in assessing potential impacts. Am. Fish. Soc. Symp. 32: 77-87.

Shuter, B.J. and N.P. Lester. 2004. Climate change and sustainable lake exploitation: Predictions from a regional life history model. pp. 281-291 in J.M. Gunn, R.J. Steedman and R.A. Ryder (eds.). Boreal Shield Watersheds: Lake Trout Ecosystems in a Changing Environment. Lewis Publishers, New York, NY.

Shuter, B.J., A.G. Finstad, I.P. Helland, I. Zweimüller and F. Hölker. 2012. The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change. Aquat. Sci. 74: 637-657.

Shuter, B.J., C.K. Minns and S.R. Fung. 2013. Empirical models for forecasting changes in the phenology of ice cover for Canadian lakes. Can. J. Fish. Aquat. Sci. 70: 982-991.

Smith, R.L. 1980. Ecology and Field Biology (3rd ed.). Harper and Row, New York, NY. 835p.

Smith, A.L., N. Hewitt, N. Klenk, D.R. Bazely, N. Yan, S. Wood, I. Henriques, J.I. MacLellan and C. Lipsig-Mummé. 2012. Effects of climate change on the distribution of invasive alien species in Canada: A knowledge synthesis of range change projections in a warming world. Environ. Rev. 20: 1-16.

Sorensen, E.M. 1991. Metal Poisoning in Fish. CRC Press, Boca Raton, FL. 374p.

Sousa, M.R., D.L. Rudolph and E.O. Frind. 2014. Threats to groundwater resources in urbanizing watersheds: The Waterloo Moraine and beyond. Can. Water Resour. J. 32: 193-208.

Spielman, D., B.W. Brook and R. Frankham. 2004. Most species are not driven to extinction before genetic factors impact them. Proc. Natl. Acad. Sci. U.S.A. 101: 15261-15264.

Stankowski, P.A. and W.H. Parker. 2011. Future distribution modelling: A stitch in time is not enough. Ecol. Model. 222: 567-572.

Ste-Marie, C., E.A. Nelson, A. Dabros and M-E. Bonneau. 2011. Assisted Migration: Introduction to a Multifaceted Concept. The Forestry Chronicle. Vol. 87 No. 6. pp. 724-730.

Stefan, H.G., M. Hondzo, J.G. Eaton and J.H. McCormick. 1995. Predicted effects of global climate change on fishes in Minnesota lakes. pp. 57-72 in R.J. Beamish (ed.). Climate Change and Northern Fish Populations. Can. Spec. Publ. Fish. Aquat. Sci. 739p.

Stefan, H.G., X. Fang and J.G. Eaton. 2001. Simulated fish habitat changes in North American lakes in response to projected climate change warming. T. Am. Fish. Soc., 130: 459-477.

Steinman, A.D., M.E. Ogdahl, M. Weinert, K. Thompson, M.J. Cooper and D.G. Uzarski. 2012. Water level fluctuation and sediment-water nutrient exchange in Great Lakes coastal wetlands. J. Great Lakes Res. 38: 766-775.

Steinman, A.D., M.E. Ogdahl, M. Weinert and D.G. Uzarski. 2014. Influence of water-level fluctuation duration and magnitude on sediment-water nutrient exchange in coastal wetlands. Aquat. Ecol. 48: 143-159.

Steen, P. J., M.J. Wiley and J.S. Schaeffer. 2010. Predicting future changes in Muskegon River watershed game fish distributions under future land cover alteration and climate change scenarios. T. Am. Fish. Soc. 139: 396-412.

Stenseth, N.C., A. Mysterud, G. Ottersen, J.W. Hurrell, K-S. Chan and M. Lima. 2002. Ecological effects of climate fluctuations. Science 297: 1292-1296.

Stenseth, N.C., D. Ehrich, E.K. Rueness, O.C. Lingjærde, K.S. Chan, S. Boutin, M. O'Donoghue, D.A. Robinson, H. Viljugrein and K.S. Jakobsen. 2004. The effect of climatic forcing on population synchrony and genetic structuring of the Canadian lynx. Proc. Nat. Acad. Sci. U.S.A. 101: 6056-6061.

Stitt, B.C., G. Burness, K.A. Burgomaster, S. Currie, J.L. McDermid and C.C. Wilson. 2014. Intraspecific variation in thermal tolerance and acclimation capacity in brook trout (*Salvelinus fontinalis*): physiological implications for climate change. Physiol. Biochem. Zool. 87: 15-29.

Stocks, B.J., M.A. Fosberg, T.J. Lynham, L. Mearns, B.M. Wotton, Q. Yang, J-Z. Jin, K. Lawrence, G.R. Hartley, J.A. Mason and D.W. McKenney. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. Clim. Chang. 38: 1-13.

Stocks, B.J., M.A. Fosberg, B.M. Wotton, T.J. Lynham and K.C. Ryan. 2000. Climate change and forest fire activity in North American Boreal Forests. pp. 368-376 in Fire, Climate Change, and Carbon Cycling in the Boreal Forest. E.S. Kasishcke and B.J. Stocks (eds.). Ecological Studies 138, Springer-Verlag, New York, NY.

Stocks, B.J., J.A. Mason, J.B. Todd, E.M. Bosch, B.M. Wotton, B.D. Amiro, M.D. Flannigan, K.G. Hirsch, K.A. Logan, D.L. Martell and W.R. Skinner. 2003. Large forest fires in Canada, 1959-1997. J. Geophys. Res. 108: 8149.1-8149.12.

Street, R.B. 1989. Climate change and forest fires in Ontario. pp. 177-182 in D.C. MacIver, H. Auld and R. Whitewood (eds.). Proc. 10th Conf. Fire and Forest Meteorology, Ottawa, ON.

Sulis, M., C. Paniconi, C. Rivard, R. Harvey and D. Chaumont. 2011. Assessment of climate change impacts at the catchment scale with a detailed hydrological model of surfacesubsurface interactions and comparison with a land surface model, Water Resour. Res. 47: 1-23, doi:10.1029/2010WR009167.

Sun, Y., L. Gu, R.E. Dickinson, R.J. Norby, S.G. Pallardy and F.M. Hoffman. 2014. Impact of mesophyll diffusion on estimated global land CO_2 fertilization. Proc. Natl. Acad. Sci. 111: 15774-15779.

Swanston, C. and M. Janowiak (eds.). 2012. Forest adaptation resources: Climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-87. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 121p.

Sweeney, B.W., J.K. Jackson, J.D. Newbold and D.H. Funk. 1992. Climate change and the life histories and biogeography of aquatic insects in eastern North America. pp. 143-176 in P. Firth and S.G. Fisher (eds.). Global Climate Change and Freshwater Ecosystems. Springer-Verlag, New York, N.Y. 332p.

Taner, M.Ü., J.N. Carleton and M.C. Wellman. 2011. Integrated model projections of climate change impacts on a North American lake. Ecol. Model. 222: 3380-3393.

Taylor, K.E., R.J. Stouffer and G.A. Meehl. 2012. An Overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93:485-498.

Taylor, M.E., P.A. Gray and K. Schiefer. 2006. Helping Canadians adapt to climate change in the Great Lakes coastal zone. Great Lakes Geographer 13: 14-25.

Taylor. P.D., L. Fahrig, K. Henein and G. Merriam. 1993. Connectivity is a vital element of landscape structure. Oikos 68: 571-573.

TEEB – The Economics of Ecosystems and Biodiversity. 2011. TEEB Manual for Cities: Ecosystem Services in Urban Management. www.teebweb.org.

Terrier, A., M.P. Girardin, C. Périé, P. Legendre and Y. Bergeron. 2013. Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. Ecol. Appl. 23: 21-35.

Thompson, I.D., M.D. Flannigan, B.M. Wotton and R. Suffling. 1998. The effects of climate change on landscape diversity: an example in Ontario forests. Environ. Model Assess. 49: 213-233.

Thomson, A.M., C.L. Riddell and W.H. Parker. 2009. Boreal forest provenance tests used to predict optimal growth and response to climate change: 2. Black spruce. Can. J. For. Res. 39: 143-153.

Thomson, A.M. and W.H. Parker. 2008. Boreal forest provenance tests used to predict optimal growth and response to climate change: 1. Jack pine. Can. J. For. Res. 38: 157-170.

Thomson, A.M., K.A. Crowe and W.H. Parker. 2010. Optimal white spruce breeding zones for Ontario under current and future climates. Can. J. For. Res. 40: 1576-1587.

Travis, J.M.J. 2003. Climate change and habitat destruction: A deadly anthropogenic cocktail. P. Roy. Soc. Lond. B. Bio. 270: 467-473.

Trumpickas, J., B.J. Shuter and C.K. Minns. 2008. Potential Changes in Future Surface Water Temperatures in the Ontario Great Lakes as a Result of Climate Change. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Inf. Note. CCRN-07. 10p.

Trumpickas, J., B.J. Shuter and C.K. Minns. 2009. Forecasting impacts of climate change on Great Lakes surface water temperatures. J. Great Lakes Res. 35: 454-463.

Trumpickas, J., B.J. Shuter and C.K. Minns and H. Cyr. 2015. Characterizing patterns of nearshore water temperature variation in the North American Great Lakes and assessing sensitivities to climate change. J. Great Lakes Res. 41: 53-64.

Tylianakis J.M., R.K. Didham, J. Bascompte and D.A. Wardle. 2008. Global change and species interactions in terrestrial ecosystems. Ecol. Lett. 11: 1351-1363.

Upchurch, S.B. 1976. Chemical characteristics of the Great Lakes. 224p.

[UNEP] United Nations Environment Program. 2009. Climate information and capacity needs for Ecosystem Management under a Changing Climate. Prepared for the World Climate Conference – 3 Geneva, Switzerland [Core writing team, R. Munang, M. Rivington, G. Takle, B. Mackey, and J. Liu (eds)] Climate Change Adaptation Unit, UNEP, Nairobi, Kenya.

[US EPA] United States Environmental Protection Agency. 2006. State of the Great Lakes. Available at: http://www.epa.gov/greatlakes/solec/indicator_sheets/coastal_wetlands.pdf

Uzarski, D.G. and J. Sherman. 2012. Implementing Great Lakes Coastal Wetland Monitoring. National Wetlands Newsletter, Vol. 34, No. 4.

Vander Zanden, M.J., K.A. Wilson, J.M. Casselman and N.D. Yan. 2004. Species introductions and their impacts in North American shield lakes. pp. 239-263 in J. Gunn, R.A. Ryder and R. Steedman (eds.). Boreal Shield Watersheds: Lake Trout Ecosystems in a Changing Environment. CRC Press, Boca Raton, FL.

Varrin, R., J. Bowman and P.A. Gray. 2007. The known and potential effects of climate change on biodiversity in Ontario's terrestrial ecosystems: Case studies and recommendations for adaptation. Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON. Clim. Change Res. Rep. CCRR-09. 47p.

Vavrus, S. and J. Van Dorn. 2010. Projected future temperature and precipitation extremes in Chicago. J. Great Lakes Res. 36: 22-32.

Veloz, S., J.W. Williams, D. Lorenz, M. Notaro, S. Vavrus and D.J. Vimont. 2012. Identifying climatic analogs for Wisconsin under 21st-century climate-change scenarios. Climatic change, 112: 1037-1058.

Verhaar, P.M., P.M. Biron, R.I. Ferguson and T.B. Hoey. 2011. Implications of climate change in the twenty-first century for simulated magnitude and frequency of bed-material transport in tributaries of the Saint-Lawrence River. Hydrol. Process. 25: 1558-1573.

Vincent, W.F. 2009. Effects of climate change on lakes. pp. 55-60 in G.E. Links (ed.) Encyclopedia of Inland Waters Vol.3. Elsevier, Oxford. 859p.

Vincent, L.A., X.L. Wang, E.J. Milewska, H. Wan, F. Yang and V. Swail. 2012. A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis, J. Geophys. Res. 117, D18110, doi:10.1029/2012JD017859.

Waite, T.A. and D. Strickland. 2006. Climate change and the demographic demise of a hoarding bird living on the edge. Proc. R. Soc. B 273: 2809-2813.

Walker, K.V., M.B. Davis and S. Sugita. 2002. Climate change and shifts in potential tree species range limits in the Great Lakes region. J. Great Lakes Res. 28: 555-567.

Walpole, A.A. and J. Bowman. 2011. Patch occupancy by squirrels in fragmented deciduous forest: effects of behavior. Acta Theriol. 56: 63-72.

Walpole, A.A., J. Bowman, D. Tozer and D.S. Badzinski. 2012. Community-level response to climate change: Shifts in Anuran calling phenology. Herpetological Conservation and Biology 7: 249-257.

Walther, G-R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J-M. Fromentin, O. Hoegh-Guldberg and F. Bairlein. 2002. Ecological responses to recent climate change. Nature 416: 389-395.

Walther, G-R., A. Roques, P.E. Hulme, M.T. Sykes, P. Pyšek, I. Kühn, M. Zobel, S. Bacher, Z. Botta-Dukat, H. Bugmann, B. Czucz, J. Dauber, T. Hickler, V. Jarosik, M. Kenis, S. Klotz, D. Minchin, M. Moora, W. Nentwig, J. Ott, V.E. Panov, B. Reineking, C. Robinet, V. Semenchenko, W. Solarz, W. Thuiller, M. Vila, K. Vohland and J. Settele. 2009. Alien species in a warmer world: risks and opportunities. Trends Ecol. Evol. 24: 686-693.

Wang, J., X. Bai, H. Hu, A. Clites, M. Colton and B. Lofgren. 2012. Temporal and Spatial Variability of Great Lakes Ice Cover, 1973-2010. J. Climate 25: 1318-1329.

Wang, S. 2014e. Comparison of interpolation methods for estimating spatial distribution of precipitation in Ontario, Canada, Int. J. Climato. doi:10.1002/joc.3941.

Wang, T., E.M. Campbell, G.A. O'Neill and S.A. Aitken. 2012b. Projecting future Potential Changes in Future Surface Water Temperatures in the Ontario Great Lakes as a Result of Climate Change distributions of ecosystem climate niches: Uncertainties and management applications. Forest Ecol. Manag. 279: 128-140.

Wang, X. and G. Huang. 2013. Ontario Climate Change Data Portal. Available online http://www.ontarioccdp.ca

Wang, X., G. Huang, Q. Lin, X. Nie, G. Cheng, Y. Fan, Z. Li, Y. Yao and M. Suo. 2013. A stepwise cluster analysis approach for downscaled climate projection - A Canadian case study. Environ. Modell. Softw. 49: 141-151.

Wang, X., G. Huang, Q. Lin and J. Liu. 2014a. High-Resolution Probabilistic Projections of Temperature Changes over Ontario, Canada. J. Climate 27: 5259–5284

Wang, X., G. Huang, Q. Lin, X. Nie and J. Liu. 2014b. High-resolution temperature and precipitation projections over Ontario, Canada: a coupled dynamical-statistical approach. Q. J. Roy. Meteor. Soc., doi: 10.1002/qj.2421.

Wang, X., G. Huang and J. Liu. 2014c: Projected increases in near-surface air temperature over Ontario, Canada: a regional climate modeling approach. Clim. Dyn.: 1-13.

Wang, X., G. Huang and J. Liu. 2014d: Projected increases in intensity and frequency of rainfall extremes through a regional climate modeling approach. J. Geophys. Res.: Atm. 119: 13-271.

Ward, J.V. 1985. Thermal characteristics of running waters. Hydrobiol. 125: 31-46.

Ward, P.C., A.G. Tithecott and B.M. Wotton. 2001. Reply: A re-examination of the effects of fire suppression in the boreal forest. Can. J. Forest Res. 31: 1467-1480.

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

Warren, R.J., J. VanDerWal, J.A. Price, J.A.. Welbergen, I. Atkinson, J. Ramirez-Villegas, T.J. Osborn, A. Jarvis, L.P. Shoo, S.E. Williams and J. Lowe. 2013. Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. Nature Climate Change 3: 678-682.

Weaver, J.E. 2012. Invasive species distribution models: an analysis of scale, sample selection bias, transferability and prediction (Doctoral dissertation). University of Toronto. 126p.

Weber, M.G. and M.D. Flannigan. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environ. Rev. 5: 145-166.

Wellenius, G.A., D.N. Fisman, J.E. Soverow and M.A. Mittleman. 2009. Infectious Disease in a Warming World: How Weather Influenced West Nile Virus in the United States (2001-2005). Environ Health Persp. 117: 1049-1052.

Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet and J.E. Williams. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. PNAS 108: 4204-4211.

Westmacott, J.R. and D.H. Burn. 1997. Climate change effects on the hydrologic regime within the Churchill-Nelson River basin. J. Hydrol. 202: 263-279.

Wetzel, R.G. 1975. Limnology. W.B. Saunders Co., Philadelphia, P.A. 743p.

Whillans, T.H. 1990. Assessing threats to fishery values of Great Lakes wetlands. pp. 156-164 in Proceed. Int. Wetland Symp. On Wetlands of the Great Lakes. Niagara Falls, NY.

White, M.A. and G.E. Host. 2008. Forest disturbance frequency and patch structure from pre-European settlement to present in the mixed forest province of Minnesota, USA. Can. J. Forest Resear. 38: 2212-2226.

Whitfield, P.H. and A.J. Cannon. 2000. Recent variations in climate and hydrology in Canada. Can. Water Resour. J. 25: 19-65.

Wilby, R.L., C.W. Dawson, C. Murphy, P. O'Connor and E. Hawkins. 2014. The Statistical DownScaling Model-Decision Centric (SDSM-DC): conceptual basis and applications. Climate Res. 61: 259-276.

Wilby, R.L., S.P. Charles, E. Zorita, B. Timbal, P. Whetton and L.O. Mearns. 2004. Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods *(*IPCC*)*. *A*vailable online: www.ipcc-data.org/guidelines/dgm_no2_v1_09_2004.pdf.

Wilcox, D. and J. Meeker. 1995. Wetlands in Regulated Great Lakes. pp. 247-249 in Our Living Resources: A Report to the Nation on the Distribution, Abundance and Health of U.S. Plants, Animals and Ecosystems. US Dept. of the Inter., Nation. Biol. Serv., Washington. DC. 552p.

Wilcox, D.A., T.A. Thompson, R.K. Booth and J.R. Nicholas. 2007. Lake-level variability and water availability in the Great Lakes: U.S. Geological Survey Circular 1311. Available at: http://pubs.usgs.gov/circ/2007/1311/pdf/circ1311_web.pdf

Wiley M.J., D.W. Hyndman, B.C. Pijanowski, A.D. Kendall, C. Riseng, E.S. Rutherford, S.T. Cheng, M.L. Carlson, J.A. Tyler, R.J. Stevenson, P.J. Steen, P.L. Richards, P.W. Seelbach, J.M. Koches and R.R. Rediske. 2010. A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes river basin. Hydrobiologia 657: 243–262.

Williams, B.K. 2011.Passive and active adaptive management: approaches and an example. J. Environ. Manage. 92: 1371-1378.

Wilson, C.O. and Q. Weng. 2011. Simulating the impacts of future land use and climate changes on surface water quality in the Des Plaines River watershed, Chicago Metropolitan Statistical Area, Illinois. Science of the Total Environment 409: 4387-4405.

World Business Chicago. 2013. Great Lakes St. Lawrence Economic Region: 2013 Economy Profile Update. Available online:

http://www.worldbusinesschicago.com/files/data/GLSL_Economy_2013%20%282011%20data%29.pdf.

World Meteorological Organization [WMO]. 1995. INFOHYDRO manual. WMO-No. 683. Table 4.4.07.

Woodbury, J. and C.A. Shoemaker. 2013. Stochastic Assessment of Long-Term Impacts of Phosphorus Management Options on Sustainability with and without Climate Change. J. Water Resour. Plann. Manage. 139: 512-519.

Woodward, F.I. 1992. Global climate change: The ecological consequences. Academic Press. 337p.

Wotton, B.M., C.A. Nock and M.D. Flannigan. 2010. Forest fire occurrence and climate change in Canada. International Journal of Wildland Fire 19: 253-271.

Wrona, F.J., T.D. Prowse, J.D. Reist, J.E. Hobbie, L.M.J. Lévesque, R.W. Macdonald and W.F. Vincent. 2006. Effects of ultraviolet radiation and contaminant-related stressors on arctic freshwater ecosystems. Ambio 35: 388-401.

Wuebbles, D.J., K. Hayhoe and J. Parzen. 2010. Introduction: Assessing the effects of climate change on Chicago and the Great Lakes. Journal of Great Lakes Research no. 36, Supplement 2 (0):1-6.

Yan, N.D., W. Keller, N.M. Scully, D.R.S. Lean and P.J. Dillon. 1996. Increased UV-B penetration in a lake owing to drought-induced acidification. Nature 381: 141-143.

Yao, Y., G.H. Huang and Q. Lin. 2012. Climate change impacts on Ontario wind power resource. Envir. Sys. Resear. 1: 2.

Yediler, A. and J. Jacobs. 1995. Synergistic effects of temperature-oxygen and water-flow on the accumulation and tissue distribution of mercury in carp (*Cyprinus carpio* L.) Chemosphere 31: 4437-4453.

Zananski, T.J., T.M. Holsen, P.K. Hopke and B.S. Crimmins. 2011. Mercury temporal trends in top predator fish of the Laurentian Great Lakes. Ecotoxicology 20: 1568-1576.

Zhang, X., L.A. Vincent, W.D. Hogg and A. Niitsoo. 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere Ocean 38: 395-429.

Zhang, X., R. Brown, L. Vincent, W. Skinner, Y. Feng and E. Mekis. 2011. Canadian climate trends, 1950-2007. Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 5. Canadian Councils of Resource Ministers. Ottawa, ON. iv + 21p. http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-0.

Zuckerberg, B., A.M. Woods and W.F. Porter. 2009. Poleward shifts in breeding bird distributions in New York State. Glob. Change Biol. 15: 1866-1883.

Zwick, P. 1981. Das Mittelmeergebiet als galziales Refugium für Plecoptera. Acta Entomological Jugoslavica 17: 107-111.

APPENDIX 1: DATABASE FIELDS FOR THE ASSESSMENT OF CLIMATE INFORMATION

To Download Accompanying Database please visit:
http://ontarioclimate.org/our-work/the-state-of-climate-change-science-in-the-great-lakes/

Descriptive Information

Field	Description / Definition	Example
Study name	Published title of the study	Lake Superior Climate Change Impacts and Adaptation
Author name	List of author names	Huff, A. and Thomas, A.
Organization	Publishing or responsible organization	The Superior Work Group of the Lake Superior Lakewide Action and Management Plan
Date	Year and month of publication	January, 2014
Full citation	CMS-style citation	Huff, A. and A. Thomas. 2014. Lake Superior Climate Change Impacts and Adaptation. Prepared for the Lake Superior Lakewide Action and Management Plan – Superior Work Group. Available at http://www.epa.gov/glnpo/lakesuperior/index.html.
URL	Web address for pointing or permalink	http://www.epa.gov/glnpo/lakesuperior/index.html
Format of item	Type of information: original research, meta-analysis, policy report, risk assessment etc.	Original academic research
Research theme(s)	List of the relevant research themes	Theme 1-9
Type of review	Whether the article/report has been peer reviewed or not. Note that peer review can be a scientific committee on a project, not just an academic journal	Anonymous peer review

Study or Report Overview

Field	Description / Definition	Example
Study objective or research question	A brief statement of the objectives the study set out to achieve	Prediction of how concentrations of pollutants will change under climate change, driven by changes in hydrology
Method summary	A brief statement of the research approach specifically pertaining to the use of climate scenarios	Hydrologic modelling to predict flows and concentrations based on land uses (used SWAT model)
Key result	The main findings of the study	Climate change is less of a problem on nutrient loading than land-use changes, Nutrients are more sensitive to climate than chemical contaminants.
Study limitations	Notes from the researcher or the	Addition GCMs should be run

and gaps	authors on any key gaps in the study	Indicators need to be validated (do they express what we want them to?)

Model and Scenario Information

Field	Description / Definition	Example	
Integration into other models	Type of model	SWAT Model	
Resolution of process model	Scale at which projections were applied (i.e., the process model spatial scale)	5 km scale	
Baseline period	Baseline period(s) used for analysis of historical trends	1970-2000	
Future period	Future time horizon(s) used for projections	e.g. 2060-2090	
Geographic location	The name of the location referenced	Lake Superior Primary Watershed	
Global circulation model	List of the GCM(s) used in the study, including those used to drive downscaling	CanESM, Hadley CM2, NCAR-CCCSM	
Future emission scenario	The name and characteristic of the emission scenario used	RCP4.5, RCP8.5 (CMIP5)	
Climate variables used	A list of the variables that were included in the climate models	100-year rainstorm intensity, mean monthly temperature, total monthly precipitation	
Temporal scale	The time interval of climate modelling used in impact models or studies and the input to the process model	Monthly	
Name of RCM and downscaling technique(s)	A list of the downscaling methods from GCM all the way to end-use	RCM (CanRCM4) bias-corrected using quantile mapping and spatially disaggregated using historical gridded data	
Treatment of uncertainty	A description of how uncertainty was analyzed and reported	Error bars established though variance on ensemble	
Climate change trends for final research results	For each of the variables used, use numbers and present symbols to communicate the trend and magnitude of change	Trend: +	Magnitude: 15-23%
		Trend: +	Magnitude: 2-4°C
		Trend: -/+	Magnitude: -3 to 6 %

APPENDIX 2: CLIMATE DATASETS WITH FUTURE DATA AVAILABLE FOR THE GREAT LAKES BASIN

Name	Time Horizon	Downscaling Method	GCM	Downscaling Type	Emission Scenario	Spatial Resolution	Variables	Interval	Reference
CCAFS GCM Downscaled	2020s-2080s	Spline Interpolation algorithm based on WorldClim database, downscaled using delta method or using PRECIS RCM (option available in data portal)	Multiple available	Dynamical / Statistical	B2, A1B, A2 RCP26, RCP45, RCP6, RCP85	4 scales available: 30 seconds (0.93 x 0.93 = 0.86 km2 at the equator), 2.5, 5 and 10 minutes (18.6 x 18.6 = 344 km2 at the equator)	Tav, Tmax, Tmin, Precip	Daily	Research Program on Climate Change, Agriculture and Food Security (CCAFS), (2014). GCM Downscaled Data Portal. Downloaded from http://www.ccafs-climate.org/data/ on 26/06/14
CCCMA	2020s-2080s	Two methods can be used for interpolation: Delta Method or Disaggregation. Downscaling with CRCM RCM model	All Canadian models	Dynamical	All CMIP3 and CMIP5	2 scales available: 30 seconds (0.93 x 0.93 = 0.86 km2 at the equator), and 2.5 minutes (18.6 x 18.6 = 344 km2 at the equator)	Tav, Tmax, Tmin, Precip	Daily	Research Program on Climate Change, Agriculture and Food Security (CCAFS), (2014). GCM Downscaled Data Portal. Downloaded from http://www.ccafs-climate.org/data/ on 26/06/14
Climate Wizard	2000-2099	Linear regression-style trend analysis to calculate the rate of climate change within every grid cell, Raw re-gridded or BCSD GCM projections both available	16 GCMs	Statistical	B1, A1B, A2	Downscaled to 1 deg and 1/8 deg	Tav (monthly only), Tmax, Tmin, Precip	Monthly	Girvetz, E., Zganjar, C., Raber, G., Maurer, E., Kareiva, P., Lawler, J. (2009). Applied Climate-Change Analysis: The Climate Wizard Tool. PLoS ONE: 4(12).

Name	Time Horizon	Downscaling Method	GCM	Downscaling Type	Emission Scenario	Spatial Resolution	Variables	Interval	Reference
Daily Statistically Downscaled Climate Projections for the U.S. and southern Canada east of the Rocky Mountains	Three distinct projected periods: 1961-2000 2046-2065 2081-2100	Interpolate to a grid using PRISM and Canadian normals data (Spatially and temporally varying Probability Density Function)	Multiple available	Statistical	B1, A1B, A2	0.1 degree resolution	Tmax, Tmin, Precip	Monthly, Daily	Lorenz, D. (2012). Daily Statistically Downscaled Climate Projections for the U.S. and southern Canada east of the Rocky Mountains. U.S. Geological Survey (USGS). Retrieved from: http://cida.usgs.gov/gdp/ on 27/06/14
Eighth degree-CONUS Daily Downscaled Climate Projections by Katherine Hayhoe	1960-2099	Statistical downscaling method that combines high-resolution observations with outputs from 16 different global climate models	Multiple available	Statistical	B1, A1B, A2	1/8 degree resolution	Tmax, Tmin, Precip	Daily	Hayhoe, D. (2010). Eighth degree-CONUS Daily Downscaled Climate Projections by Katharine Hayhoe. U.S. Geological Survey (USGS). Retrieved from: http://cida.usgs.gov/gdp/ on 27/06/14
ENSEMBLES Scenario Data	2001-2100 (split up into 10 decades)	User selects method: Linear regression, Generalized linear model (for precip only), Neural Network (ELM)	Limited Number (BCM2, CNCM3, HADGEM2, MPEH5)	Statistical	B1, A1B, A2	2.5 x 2.5 degree grids	Tav, Precip, RH	Monthly, Daily	Cofiño, A.S., San-Martín, and Gutiérrez, J.M. (2007) A web portal for regional projection of weather forecast using GRID middleware. Lecture Notes in Computer Science, 4489, 82-89 [download pdf]
Maurer et al. Future Projections	2000-2099	Two techniques used for downscaling: monthly bias-correction and spatial disaggregation (BCSD) and daily bias-correction and constructed analogs (BCCA)	All	Statistical	All CMIP3 and CMIP5	Downscaled to 1 deg and 1/8 deg	Tav (monthly only), Tmin, Tmax, Precip	Monthly, Daily	Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy (2007), 'Fine-resolution climate projections enhance regional climate change impact studies', Eos Trans. AGU, 88(47), 504. Reclamation, 2013. 'Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information,

Name	Time Horizon	Downscaling Method	GCM	Downscaling Type	Emission Scenario	Spatial Resolution	Variables	Interval	Reference
									and Summary of User Needs', prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado. 47pp.
McKenney et al. (2011) – Canadian Forest Service Gridded	2011-2100	Change fields and ANUSPLINE interpolation	Multiple available	Statistical	B2, A1B, A2, RCP4.5, RCP8.5	10 x 10km 5 x 5 km	Tmax, Tmin, Precip, Bioclimatic parameters	Monthly	McKenney, D. W., Hutchinson, M.F., Papadopol, P., Lawrence, K., Pedlar, J., Campbell, K., Milewska, E., Hopkinson, R., Price, D., Owen, T. (2011). "Customized spatial climate models for North America." Bulletin of American Meteorological Society-BAMS December: 1612-1622. Available Online: https://cfs.nrcan.gc.ca/projects/3/5
Wang and Huang (2013) – Ontario Climate Data Portal	1960 - 2095 (four, 31-yr periods available: 1960-1990, 2015-2045, 2035-2065,2065-2095)	PRECIS RCM – Results presented as percentiles from 5-member ensemble	HadleyCM3 (5 runs)	Dynamical	A1B (RCPs underway)	25x25 km	Tav, Tmax, Tmin, Precip, RH, SolRad, Wndspd, Wnddir, IDF curves	Monthly, Daily, Hourly	Wang, Xiuquan and Gordon Huang (2013). "Ontario Climate Change Data Portal". Available Online: http://www.ontarioccdp.ca
PCIC Statistically Downscaled GCM Scenarios	1950-2014	Change fields and ANUSPLINE interpolation. Bias-Correction Spatial Disaggregation (BCSD) used in downscaling	Multiple available	Statistical	RCP26, RCP45, RCP85	10 x 10km	Tmax, Tmin, Precip	Daily, Monthly	Pacific Climate Impacts Consortium, University of Victoria, (Jan. 2014). Statistically Downscaled Climate Scenarios. Downloaded from http://tools.pacificclimate.org/dataportal/downscaled_gcms/map/ on 26/06/14

Name	Time Horizon	Downscaling Method	GCM	Downscaling Type	Emission Scenario	Spatial Resolution	Variables	Interval	Reference
PCIC Statistically Downscaled GCM Scenarios	1950-2014	Change fields and ANUSPLINE interpolation. Bias-Correction CAQ (BCCAQ) used in downscaling	Multiple available	Statistical	RCP26, RCP45, RCP85	10 x 10km	Tmax, Tmin, Precip	Daily, Monthly	Pacific Climate Impacts Consortium, University of Victoria, (Jan. 2014). Statistically Downscaled Climate Scenarios. Downloaded from http://tools.pacificclimate.org/dataportal/downscaled_gcms/map/ on 26/06/14
Gula and Peltier (2012)	1979-1994 2045-2060	Nested WRF and Flake	NCAR CCSM	Dynamical	A1B, A2 (RCPs underway)	1.5 x 1.5 degree grids (10x10km)	Tav, Precip	6-hour intervals	Gula, J. and W.R. Peltier, W. R. 2012. Dynamical Downscaling over the Great Lakes Basin of North America using the WRF Regional Climate Model: The impact of the Great Lakes system on regional greenhouse warming. J Climate 25(21): 7723-7742.
Probabilistic Climate Projections over Ontario from Multiple Global and Regional Climate Models	2005-2100 (various 30-yr periods available for analysis)	PRECIS RCM	All GCMs and NARCCAP RCMs	Dynamical	All	45 x 45km	Tav, Hot DegDay, Cool DegDay, Wet DayPrecip, Cool Days, Cool Nights, Hot Days, Warm Nights, Heat Wave Days, Wet days, P > 10mm, P > 20mm, 95th perc P, 99th perc P, max humidex	Unsure	Laboratory of Mathematic Parallel Systems (LAMPS), (2014). Developing High-Resolution (45km x 45km) Probabilistic Climate Projections over Ontario from Multiple Global and Regional Climate Models. Downloaded from http://haze.hprn.yorku.ca/moe/ on 26/06/14; Research poster: http://climateontario.org/wp/wp-content/uploads/2014/05/Deng_Ziwang.pdf
SENES (2011)	2040-2049	Nesting technique using: PRECIs (RCM) & FReSH Weather Model	HadleyCM3	Dynamical	A1B	~1x1km horizontally, 30km vertically	Tav, Tmax, Tmin, Precip, Rainfall, Snowfall, Wndspd, MaxWndspd, MaxGustWndSpd, DegDays, RainReturnPeriod	Daily, Hourly	SENES Consultants Limited. (2011). "Toronto's Future Weather and Climate Driver Study: Volume 1 – Overview." Toronto, Canada.

Name	Time Horizon	Downscaling Method	GCM	Downscaling Type	Emission Scenario	Spatial Resolution	Variables	Interval	Reference
Taylor et al. (2012)	<1950-2300	Raw GCM data from CMIP5	All	Dynamical	All CMIP5	~200 x 200 km	All	Month, Daily, 6-hourly, 3-hourly	Taylor, K.E., R.J. Stouffer, G.A. Meehl: An Overview of CMIP5 and the experiment design.” Bull. Amer. Meteor. Soc., 93, 485-498, doi:10.1175/BAMS-D-11-00094.1, 2012.
USGS Dynamical Downscaled Regional Climate	1960-2099	RegCM3 RCM	Limited Number (USGS GENMOM, MPI ECHAM5, GFDL CM2.0, NOAA NCEP)	Dynamical	A2	15km grids	All	Monthly, Daily	Hostetler, S.W., Alder, J.R., and Allan, A.M. (2011). Dynamically downscaled climate simulations over North America: Methods, evaluation, and supporting documentation for users: U.S. Geological Survey Report 2011-1238, p. 64.
Waterbudget Future Climate Datasets	2011-2100 (three, 30-yr periods available: 2011-2040, 2041-2070, 2071-2100)	LARS-WG and Canadian Regional Climate Model, Interpolation using change fields method	All	Dynamical	B2, A1B, A2	for Ontario weather stations only	Tmax, Tmin, Precip, Snow, Rain	Daily, Hourly	AquaResources Inc., EBNFLO Environmental. (2011). Future Climate Datasets Guide. Prepared for the Ontario Ministry of Natural Resources
World Climate Research Programme's (WCRP's) CMIP3 multi-model dataset	2041–2060 ("2050") & 2081–2100 ("2090")	Statistically downscaled using the CRU CL 2.0 20th century climate dataset	All	Statistical	B1, A1B, A2	Downscaled to 2.8 deg (18.5x18.5 km)	Temp, Precip	Monthly	Tabor, K. and J.W. Williams (2010). Globally downscaled climate projections for assessing the conservation impacts of climate change. Ecological Applications 20(2):554-565.
World Climate Research Programme's (WCRP's) CMIP5 multi-model dataset	2041–2060 ("2050") & 2081–2100 ("2090")	Statistically downscaled using the CRU CL 2.0 20th century climate dataset	All	Statistical	All CMIP5	Downscaled to 2.8 deg (18.5x18.5 km)	Tmax, Tmin, Precip	Monthly	Tabor, K. and J.W. Williams (2010). Globally downscaled climate projections for assessing the conservation impacts of climate change. Ecological Applications 20(2):554-565.

Name	Time Horizon	Downscaling Method	GCM	Downscaling Type	Emission Scenario	Spatial Resolution	Variables	Interval	Reference
NARCCAP	1950-2100	Dynamically downscaled ensemble of GCMs using a variety of RCMs	NCEP, CCSM, CGCM3, GFDL, HadCM3	Dynamical	A2	50 km	All	Month, Daily, 6-hourly, 3-hourly	Mearns, L.O., et al., 2007, updated 2014. The North American Regional Climate Change Assessment Program dataset, National Center for Atmospheric Research Earth System Grid data portal, Boulder, CO. Data downloaded 2014-07-02. [doi:10.5065/D6RN35ST]

APPENDIX 3: GRIDDED AND IN-FILLED CLIMATE DATASETS AVAILABLE FOR THE GREAT LAKES BASIN

Name	Time Horizon	Interpolation / Analysis Method	Spatial Resolution	Variables	Interval	Reference
CRU CL 1.0 – New et al. (1999)	1961-1990	Thin-plate smoothing spline method	0.5 degree grids	Tav, DTR, Frost Days, Wndspd, WetDays, VapPress, CloudCover, SunCover	Monthly	New, M., Hulme, M. and Jones, P.D., 1999: Representing twentieth century space-time climate variability. Part 1: development of a 1961-90 mean monthly terrestrial climatology. Journal of Climate 12, 829-856 doi:10.1175/1520-0442(1999)012<0829:RTCSTC>2.0.CO;2 (click doi to access paper)
CRU CL 2.0 – New et al. (2002)	1961-1990	Thin-plate smoothing spline method	10 minutes (18.6 x 18.6 = 344 km2 at the equator)	Tav, Tmax, Tmin, DTR, RH, SunCover, Frost Days, WetDays	Monthly	New, M., Hulme, M. and Jones, P.D., 2000: Representing twentieth century space-time climate variability. Part 2: development of 1901-96 monthly grids of terrestrial surface climate. Journal of Climate 13, 2217-2238 doi:10.1175/1520-0442(2000)013<2217:RTCSTC>2.0.CO;2 (click doi to access paper)
CRU TS 3.21 – Harris et al. (2013)	1901-1996	Fields of monthly climate anomalies, relative to the 1961–90 mean, were interpolated from surface climate data. The anomaly grids were then combined with a 1961–90 mean monthly climatology to arrive at grids of monthly climate over the 96-yr period	0.5 degree grids	Tav, CloudCover, DTR, Frost Days, Precip, Tmax, VapPress, WetDays	Monthly	Harris, I., Jones, P.D., Osborn, T.J. and Lister, D.H., 2013: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 dataset. International Journal of Climatology online. doi:10.1002/joc.3711.
ECMWF Reanalysis (ERA 40)	1957-2002	Meteorological observations interpolated using forecast fields and a Gaussian grid symmetric about the equator	2.5 x 2.5 degree grids	All	6-hour intervals, Daily, Monthly	Kallberg et al. (2007). ERA-40 Project Report Series 17. The ERA-40 Archive. European Centre for Medium-Range Weather Forecasts. Shinfield Park, Reading, England. Additional information available here: http://old.ecmwf.int/research/ifsdocs/CY25r1/Technical/Technical-3-01.html
ECMWF Reanalysis (ERA-Interim)	1979-2014	Meteorological observations interpolated using forecast fields and a Gaussian grid symmetric about the equator (considered an improvement on the "data-rich" period of the	1 degree grids	All	6-hour intervals, Daily, Monthly	Berrisford, P. et al. (2011). ERA-40 Project Report Series: The ERA-Interim Archive Version 2.0. European Centre for Medium-Range Weather Forecasts. Shinfield Park, Reading, England.

Name	Time Horizon	Interpolation / Analysis Method	Spatial Resolution	Variables	Interval	Reference
		ERA 40 dataset				
Environment Canada – Waterbudget Climate Datasets	1961-2000 (two baselines available: 1961-1990 and 1971-2000)	Change fields method, used historical climate station data from EC	For Ontario weather stations only	Tmax, Tmin, Precip, Snow, Rain	Daily, Hourly	AquaResources Inc., EBNFLO Environmental. (2011). Future Climate Datasets Guide. Prepared for the Ontario Ministry of Natural Resources
Girvetz et al. (2009)	1950-1999	Based on CRU TS2.1 (a global, previous version of CRU TS3.1 identified above) dataset and in-filled with 1961-1990 averages for grid cells missing data	0.5 degree grids	Tav, Tmax, Tmin, Precip	Monthly	Girvetz, E., Zganjar, C., Raber, G., Maurer, E., Kareiva, P., Lawler, J. (2009). Applied Climate-Change Analysis: The Climate Wizard Tool. PLoS ONE: 4(12).
Global Historical Climatology Normal Data (GHCN) 3.12	1763-2014	Raw, observed meteorological conditions from the World Meteorological Organization (WMO) compiled by NOAA	For weather stations globally	Tmax, Tmin, Precip, Snow, Snowdepth	Monthly, Daily	National Oceanic and Atmospheric Administration (NOAA) – National Climatic Data Center (NCDC). Available online at: http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/index.php?name=data
International Comprehensive Ocean-Atmosphere Data Set (ICOADS)	1662-2007	Surface marine data spanning the past three centuries, and simple gridded monthly summary products (including information for Great Lakes area of N. America)	2 x 2 degree grids back to 1800, and 1 x 1 degree grids since 1960	Sea Surface Temperature, Sea level pressure	Monthly	Related publications and documentation available online: http://icoads.noaa.gov/publications.html
Maurer et al. Gridded Observations	1950-1999	Re-gridded meteorological observations by spatially interpolating to 2-degree grid over the contiguous U.S.	2 degree grids	Tav (monthly only), Tmin, Tmax, Precip	Monthly, Daily	Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, 2002, A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States, J. Climate 15, 3237-3251.
McKenney et al. (2011) – Canadian Forest Service Gridded	1971-2000	Change fields and ANUSPLINE interpolation	10 x 10km	Tmax, Tmin, Precip	Daily	McKenney, D. W., Hutchinson, M.F., Papadopol, P., Lawrence, K., Pedlar, J., Campbell, K., Milewska, E., Hopkinson, R., Price, D., Owen, T. (2011). "Customized spatial climate models for North America." Bulletin of American Meteorological Society-BAMS December: 1612-1622. Documentation available online: https://cfs.nrcan.gc.ca/projects/3/1

Name	Time Horizon	Interpolation / Analysis Method	Spatial Resolution	Variables	Interval	Reference
NCEP Reanalysis	1948-2013	Linear regression model (based on 6-hourly data for 1948-1999)	2.5 x 2.5 degree grids	All	6-hour intervals, Daily, Monthly	National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 1994, updated monthly. NCEP/NCAR Global Reanalysis Products, 1948-continuing. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. http://rda.ucar.edu/datasets/ds090.0/.
Oregon State University – PRISM Climate Group	1895-2011	Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate mapping system	30 seconds (0.93 x 0.93 = 0.86 km2 at the equator)	Tmax, Tmin, Precip	Yearly, Monthly	PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu
University of Delaware (UDEL) Air Temperature and Precipitation	1901-2010	Station data taken from GHCN2 (Global Historical Climate Network) and from the archive of Legates & Willmott. Result: time-series climatology of monthly precip and temp complementing ICOADS (International Comprehensive Ocean-Atmosphere Data Set)	0.5 x 0.5 degree grids	Tav, Precip	Monthly	Center for Climatic Research Department of Geography University of Delaware Newark, DE 19716 The University of Delaware website offers extensive documentation of this data set. Please address questions on the analysis method to Kenji Matsuura (kenjisan@udel.edu) University of Delaware.