CLIMATE CHANGE IN THE GREAT LAKES BASIN:

SUMMARY OF TRENDS AND IMPACTS

Acknowledgements

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Sunset canoeing on Lake Michigan

Table of Contents


Ontario - Canada, Georgian Bay Lake Huron

Executive Summary

Under the 2012 Canada-United States Great Lakes Water Quality Agreement (GLWQA), the Climate Change Impacts Annex Subcommittee coordinates efforts to identify, quantify, understand, and predict climate change impacts on the waters of the Great Lakes, and shares information that Great Lakes resource managers need to proactively address these impacts. The purpose of this report is to characterize historical and future climate trends within the Great Lakes basin, and to summarize the impacts that are already being felt by communities across the basin. This report was created for the Climate Change Impacts Annex Subcommittee and is intended to further the understanding of climate change impacts in the Great Lakes basin.

This report translates technical climate and hydrological data into practical information for decision-makers based on climate and water level projections, developed by Environment and Climate Change Canada (ECCC) and ice cover projections developed by the Nelson Institute Center for Climatic Research (CCR), respectively. Observed historical data was retrieved from the National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory (GLERL). This report also seeks to enhance understanding of climate change impacts based on a review of peer-reviewed and grey literature to help inform adaptation and resilience-building efforts across the region.

By the end of the century, significant changes in over-land air temperature, over-lake precipitation, water levels, and ice cover are anticipated across the Great Lakes under a moderate (RCP 4.5) and high-emissions (RCP 8.5) scenarios. Similar climate and hydrological trends were found for all lakes, though each lake may experience these changes differently.

Over-land air temperatures are expected to increase significantly across the basin compared to 1961-2000. The greatest temperature increases are projected for the fall and winter seasons. Changes in average over-land air temperatures are expected to bring warmer winters, more extreme heat, a longer growing season, heavier precipitation, and less ice cover. The greatest increases in over-land air temperatures are expected for lakes Superior and Michigan-Huron.

Over-lake precipitation is anticipated to increase in all seasons and over the year under both climate scenarios for all lakes, although the increase is generally less in the summer season. Changes in seasonal over-lake precipitation is anticipated to vary by lake and climate scenario. With warmer winters, snowfall is expected to decrease on average, with more precipitation falling as rain instead of snow. The greatest increases in over-lake precipitation are expected for lakes Superior and Ontario.

Lake levels are anticipated to increase in variability as the climate changes, with more extreme high and extreme low values becoming possible with greater changes in global average temperatures. Lake level projections indicate significant deviations from lake-specific, long-term averages (1918-2019) across the basin with a slight upward trend on all lakes apparent in the latter half of the century. Lake Michigan-Huron is expected to experience the greatest variation in lake levels and has historically been the most variable among the Great Lakes (Wuebbles et al. 2019). Lakes Erie, St. Clair, and Ontario are also expected to see significant variations in lake levels.

Ice cover is expected to decline across all lakes, especially in the months of February and March under the high-emissions scenario. In the future, there may be more years with little to no ice cover and shorter ice seasons during winter and spring. Average ice cover over lakes Superior and Erie show the greatest projected declines, followed by lake Huron. Ice growth may also peak earlier for deeper lakes such as lakes Superior and Huron.

Changes to the climate over the Great Lakes and its water levels and ice cover can cause wide-ranging environmental, social, and economic impacts on local communities. These impacts are cumulative, compounding, and interactive, which in turn can lead to even more severe consequences. The following are key climate change risks identified for the Great Lakes basin based on a review of the literature:

- More frequent extreme high and low water levels
- Increase in flooding and erosion
- More variable and intense precipitation
- Increase in storm-induced runoff carrying nutrients and contaminants into the lakes
- Increase in combined sewer overflows
- Increase in extreme weather events
- More toxic and non-toxic algal blooms, low-oxygen conditions, and dead zones
- Increased stress on drinking water infrastructure
- Increase in unsafe ice conditions for travel and recreation
- Increase in the resuspension of contaminated sediments that can accumulate up the aquatic food chain
- Increase in invasive species, pests, and diseases
- Potential for reduced or interruptions to shipping and hydropower generation
- Loss of cold/coolwater fish species habitat
- Loss of wildlife habitat (e.g. breeding, spawning, and nursery), including essential habitats such as coastal wetlands
- Loss of Indigenous traditional ways of life
- Loss of sense of place and identity
- Loss of livelihoods and local economic drivers

This list is not intended to be exhaustive, but rather to highlight important risks that could serve as a starting point to make informed decisions on adaptation planning.

Point Pelee National Park, Lake Erie

1.0 Introduction

Climate change is threatening the health of the Great Lakes and the many ecosystem services they provide.

The Great Lakes contain one-fifth of the world's fresh surface water (Great Lakes Commission, 2021). Spanning two nations and many Indigenous communities, the Great Lakes provide drinking water to 40 million people (see Figure 1). Its large network of streams, lakes, wetlands, grasslands, and forests are home to more than 3,500 species of plants and animals (Wuebbles et al. 2019). The Great Lakes also support many industries, including shipping, hydropower, agriculture, fishing, tourism and recreation, and provide important cultural and spiritual connections for people. If the Great Lakes region were a country, it would have the third largest economy in the world (Desjardins, 2017). However, climate change is threatening the health of the Great Lakes and the many ecosystem services they provide, affecting the people, plants, and animals across the basin who rely on the Great Lakes.

Figure 1: Map of the Great Lakes Basin

Through the 2012 Canada-United States Great Lakes Water Quality Agreement (GLWQA), Canada and the United States recognized the need to strengthen efforts to address new and continuing threats to the quality of the waters of the Great Lakes, including climate change impacts. The 2012 GLWQA incorporated a new Climate Change Impacts Annex (Annex 9) to facilitate the coordination of efforts to address climate change impacts within the Great Lakes basin. This Annex aims to identify, quantify, understand, and predict the climate change impacts on the quality of the waters of the Great Lakes, and share information that resource managers need to proactively address these impacts. In order to implement the commitments under the Annex, Canada and the United States established a Climate Change Impacts Annex Subcommittee, co-led by Environment and Climate Change Canada (ECCC) and the National Oceanic and Atmospheric Administration (NOAA), with members from U.S. and Canadian federal government departments, state, provincial, and local governments, tribal and Indigenous organizations, watershed management agencies, non-governmental organizations, and academic institutions and organizations.

This summary report was prepared by the Ontario Climate Consortium for the Climate Change Impacts Annex Subcommittee to characterize historical and future climate trends within the Great Lakes basin and summarize the impacts that are already being felt by communities across the basin. This report seeks to translate technical climate and hydrological data into practical information for decision-makers and increase understanding of climate change impacts to help inform adaptation and resilience-building efforts across the region.

The information presented in this report is based on a review of published literature (including peer-reviewed articles, reports, and news articles from both Canada and the United States); ice cover projections developed by the Nelson Institute Center for Climatic Research (CCR); and climate and water level projections developed by ECCC as part of a study called, "Assessing and Enhancing the Resilience of Great Lakes Coastal Wetlands" supported by the Great Lakes Protection Initiative (GLPI; 2017-2022).

Projections were developed to the end of the century on either a daily or monthly basis (see Box 1 for more information). This report summarizes several key hydroclimate parameters, including over-land air temperature, over-lake precipitation, lake levels, and ice cover:

- Over-land air temperature refers to air temperature over the lands surrounding the Great Lakes
- Over-lake precipitation refers to precipitation that falls on the lakes' surfaces
- Lake levels refer to the surface water level of the Great Lakes
- Ice cover refers to the amount of ice that forms on the surface of the Great Lakes

Section 2.0, Historical and Future Climate Trends, examines how over-land air temperature, over-lake precipitation, lake levels, and ice cover have changed within the Great Lakes basin and how these are expected to continue to change until the end of the century under two climate change scenarios. Climate trends are summarized by lake where information is available.

Section 3.0, Climate Change Impacts, discusses what these projected climate and hydrological changes mean for communities within the Great Lakes basin and highlights some of the major impacts that are already being felt by communities.

Section 4.0, Looking Ahead, presents a summary of the key climate change risks identified for the Great Lakes basin that need to be proactively addressed in order to reduce negative impacts and build resilience.

BOX 1: ABOUT THE METHODOLOGY USED TO DEVELOP THE HYDROCLIMATE PROJECTIONS FOR THE GREAT LAKES BASIN

The projections used in this report have been developed by Environment and Climate Change (ECCC) and the Nelson Institute Center for Climatic Research (CCR) at the University of Wisconsin-Madison. Observed historical data was retrieved from the NOAA-Great Lakes Environmental Research Laboratory (GLERL).

What are Climate Projections?

Climate projections are simulations of what Earth's climate may look like in the future using climate models to simulate different atmospheric, oceanic, and land processes that influence climate. These simulations are based on plausible future scenarios of emissions patterns from human activities and concentrations of greenhouse gases and aerosols in the atmosphere (typically until 2100), known as Representative Concentration Pathways (RCPs). There are four main RCPs, representing scenarios of high emissions (RCP 8.5), moderate emissions (RCPs 4.5 and 6.0), and low emissions (RCP 2.6). These scenarios are based on different assumptions of future socioeconomic and technological developments, such as changes in population growth, technology, energy, and land use.

How Did ECCC Develop the Climate and Water Level Projections Used in this Report?

Not all climate models are able to capture the Great Lakes and their dynamics. In order to obtain simulated responses of future climate within the Great Lakes basin, ECCC used data from select climate models that do capture the Great Lakes at sufficiently high resolution, as well as simulating lake processes, including lake evaporation. Modelled data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) were available from NA-CORDEX, the North American component of the International Coordinated Regional Downscaling Experiment program sponsored by the World Climate Research Program (WCRP).

Two climate change scenarios were used, including RCPs 4.5 and 8.5, which represent the most commonly modelled scenarios. Under RCP 4.5, an intermediate climate change scenario, global average temperatures could increase by 1.7 to 3.2°C (or 3.1 to 5.8°F) compared to 1986-2005 by the 2090s (Government of Canada, 2018). Under RCP 8.5, the high-emissions scenario, global average temperatures could increase by 3.2 to 5.4°C (or 5.8 to 9.7°F) compared to 1986-2005 by the 2090s.

RCP 8.5 was simulated by seven model runs, while RCP 4.5 was simulated by six model runs. The modelled data have resolutions that range from approximately 25 km by 25 km to approximately 45 km by 45 km.

Lake level projections have been determined based on over-lake precipitation, runoff into the lake, over-lake evaporation, water flow, and the regulation plans that control outflows from Lake Superior and Lake Ontario. Both the over-lake precipitation and over-lake evaporation were taken directly from the modelled data available from NA-CORDEX. A hydrological model called, WATFLOOD, was used to calculate surface runoff and the flow from rivers into each of the lakes.

Projections were developed to the end of the century on a monthly basis for various key climate parameters and water levels to inform the coastal wetland climate change vulnerability assessment as part of the "Assessing and Enhancing the Resilience of Great Lakes Coastal Wetlands" project. This report summarizes several of these key hydroclimate parameters.

How Did CCR Develop the Ice Cover Projections Used in this Report?

Unlike climate and water level projections, ice cover projections are only available for RCP 8.5. Ice cover projections were simulated by six model runs and have resolutions of approximately 25 km by 25 km. These simulations also include representation of the Great Lakes and their thermodynamics. Projections were developed to the end of the century on a daily basis.

For more detailed information about the methodology used by ECCC to develop the climate and water level projections and adjust for biases, please see Appendix A. For information about the methodology used by CCR to develop the ice cover projections and adjust for biases, please see Appendix B.

Bald eagle lands on the breakwater in Lake Michigan.

2.0 Historical and Future Climate Trends

"It is unequivocal that human influence has warmed the atmosphere, ocean and land"– The Intergovernmental Panel on Climate Change, Sixth Assessment Report (2021)

In the last seven years (2014-2020), global average surface temperatures have been the warmest on record, with 2020 tied with 2016 as the warmest year (The Earth Observatory, 2021). As human activities continue to impact the climate, we will likely continue to see more record-breaking temperatures in the future. Human activities are estimated to have caused global average temperatures to increase by approximately 1˚C (or 1.8˚F) above pre-industrial levels (IPCC, 2018). In the contiguous United States, the regions bordering the Great Lakes are warming faster than the rest of the country (Hayhoe et al. 2018; Wuebbles et al. 2019). Meanwhile in Canada, average surface temperatures are warming twice as fast as the rest of the world as a whole, with northern Canada warming even faster (Government of Canada, 2019a).

As global climate change and the rate of warming over the Great Lakes continue, we can expect to see more changes to the climate across the basin in the coming decades. The following subsections provide a summary of how over-land air temperature, over-lake precipitation, lake levels, and ice cover have changed within the basin and how these are expected to continue to change until the end of the century. In order to prepare for the impacts of climate change on communities and ecosystems across the basin, it is important to understand what the future climate might look like.

The historical climate and hydrological data used in this report were retrieved from the NOAA-Great Lakes Environmental Research Laboratory (GLERL).

For the climate and water level projections, observed historical and modelled future data are compared across 30 consecutive years (i.e. 1961-2000, 2006-2035, 2036-2065, and 2066-2095). Meanwhile, for the ice cover projections, data is only available for 20 consecutive years (i.e. 1980-1999, 2040-2059, and 2080-2099). Using data from multiple decades is important to ensure that climate trends are not driven by occasional extremes.

In some cases, the graphs display observed historical data up to the most recent year with data available in order to capture the breadth of historical variation and/or avoid a break in the timeline when data is displayed as a continuous time series. Historical climate data is currently available up to 2019 for over-lake precipitation, lake levels, and ice cover, while historical climate data for over-land air temperature is available up to 2014.

Projections are presented for individual lakes where possible (see Table 1). For most parameters (except ice cover), lakes Michigan and Huron are presented as a single unit as they are hydrologically one body of water. Georgian Bay is part of Lake Huron and stakeholders interested in projections for this area should use the projections available for Lake Michigan-Huron. Projections for Lake St. Clair are only available for lake levels. For those interested in over-land air temperature and over-lake precipitation projections for Lake St. Clair, we suggest considering the projections available for Lake Erie.

Table 1: Overview of climate and hydrological projections available by lake in this study.

LAKE	OVER-LAND AIR TEMPERATURE	OVER-LAKE PRECIPITATION	LAKE LEVELS	ICE COVER
Superior	✓	✓	✓	✓
Michigan -Huron	✓	✓	✓	(presented as two lakes)
Erie	✓	✓	✓	✓
St. Clair			✓	
Ontario	✓	✓	✓	✓

2.1 Over-Land Air Temperature (ECCC Projections)

KEY FINDINGS:

- Climate projections indicate significant increases in annual average over-land air temperatures across the basin compared to the historical period (1961-2000).
- The greatest temperature increases are projected for the fall and winter seasons.
- Changes in average over-land air temperatures are expected to bring warmer winters, more extreme heat, a longer growing season, heavier precipitation, and reduced ice cover.
- Average over-land air temperatures over the Lake Superior basin show the greatest future warming, followed by Lake Michigan-Huron.

Over-land air temperature refers to air temperature over the lands surrounding the Great Lakes. In the Great Lakes basin, residents have benefited from the influence of the lakes on regional weather. Throughout the year, the Great Lakes help to moderate temperatures, cooling nearby lands in the summer and warming them in the winter, which support agriculture and other industries (Wuebbles et al. 2019). Under both climate scenarios, average over-land air temperatures are anticipated to increase in all seasons and over the year.

Figure 2 presents a series of graphs showing historical and projected over-land air temperatures for each lake basin under both climate scenarios averaged by month and time period. These graphs illustrate the anticipated changes in over-land air temperatures over the short (2030s), medium (2050s), and long-term (2080s) future compared to historical measured data (1961-2014) across the two climate scenarios (RCPs 4.5 and 8.5). The 5th and 95th percentile values across the model runs are presented to highlight the range of possible over-land air temperatures over the lake basins for each month (see Box 2 for information on percentiles). Tables 2 and 3 present temperature values in degrees Celsius for RCP 4.5 and RCP 8.5, respectively.

BOX 2: WHAT ARE 5TH AND 95TH PERCENTILES AND WHY ARE THEY BEING USED?

The 5th percentile represents the value below which 5 percent of the data falls. The 95th percentile represents the value below which 95 percent of the data falls, and 5 percent are above that value. Together, they make up 90 percent of where all the data points fall. This range is helpful to understand where most projected climate, water level, and ice cover data fall within and removes extreme values that occur 5 percent of the time on either end of the distribution, which may skew comparisons.

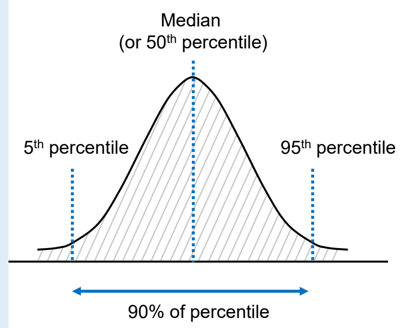


Figure 2: Historical and projected average over-land air temperature under RCPs 4.5 and 8.5 by month and time period for:

a) Lake Superior, b) Lake Michigan-Huron, c) Lake Erie, and d) Lake Ontario. Projected land air temperatures under both climate change scenarios are presented side by side with RCP 4.5 on the left and RCP 8.5 on the right. The dotted grey area shows historical land air temperatures averaged by month between 1961 and 2014 that fall within the 5th and 95th percentiles. Future air temperatures are projected for three time periods: 2030s, 2050s, and 2080s, with each represented by a different colour and pattern. The top lines represent the 95th percentile of the projected values under six RCP 4.5 model runs and seven RCP 8.5 model runs, respectively, and the bottom lines represent the 5th percentile.

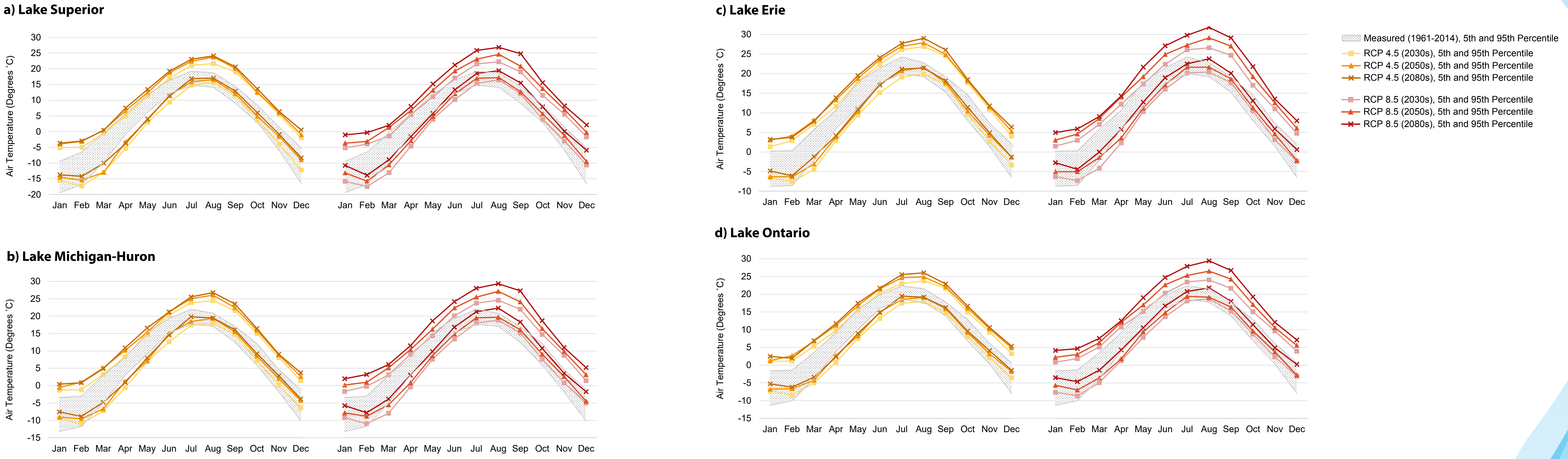


Table 2. Historical and projected annual and seasonal average over-land air temperatures under RCP 4.5 by time period.

LAKE AND TIME PERIOD	Historical and Projected Values Under RCP 4.5 (°C)					Difference from Corresponding 1961-2000 Values (°C)				
	Annual	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)	Annual	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)
LAKE SUPERIOR										
Historical (1961-2000)	2.4	1.8	15.8	4.7	-12.7	-	-	-	-	-
2030s (2006-2035)	3.9	0.5	16.6	7.9	-9.2	1.5	-1.3	0.8	3.2	3.5
2050s (2036-2065)	5.2	1.6	17.9	8.8	-7.3	2.8	-0.2	2.0	4.1	5.4
2080s (2066-2095)	5.9	2.3	18.5	9.5	-6.6	3.5	0.6	2.7	4..8	6.1
LAKE MICHIGAN-HURON										
Historical (1961-2000)	6.2	5.3	18.7	8.2	-7.2	-	-	-	-	-
2030s (2006-2035)	7.6	4.6	19.5	11.0	-4.5	1.4	-0.8	0.8	2.9	2.7
2050s (2036-2065)	8.9	5.6	20.7	12.0	-2.8	2.6	0.3	2.0	3.9	4.4
2080s (2066-2095)	9.5	6.3	21.2	12.7	-2.3	3.2	1.0	2.6	4.5	4.9
LAKE ERIE										
Historical (1961-2000)	9.1	8.2	20.8	10.8	-3.4	-	-	-	-	-
2030s (2006-2035)	10.4	7.8	21.6	13.4	-1.3	1.3	-0.4	0.9	2.7	2.1
2050s (2036-2065)	11.6	8.8	22.8	14.4	0.1	2.5	0.6	2.1	3.7	3.5
2080s (2066-2095)	21.1	9.4	23.3	15.1	0.5	3.0	1.2	2.6	4.3	3.9
LAKE ONTARIO										
Historical (1961-2000)	7.3	6.2	19.3	9.2	-5.5	-	-	-	-	-
2030s (2006-2035)	8.6	6.0	19.4	11.5	-2.3	1.3	-0.2	0.1	2.3	3.2
2050s (2036-2065)	9.8	7.0	20.5	12.6	-0.9	2.5	0.8	1.2	3.3	4.6
2080s (2066-2095)	10.3	7.6	21.0	13.2	-0.5	3.0	1.4	1.7	4.0	5.0

Table 3. Historical and projected annual and seasonal average land air temperatures under RCP 8.5 by time period

LAKE AND TIME PERIOD	Historical and Projected Values Under RCP 8.5 (°C)					Difference from Corresponding 1961-2000 Values (°C)				
	Annual	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)	Annual	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)
LAKE SUPERIOR										
Historical (1961-2000)	2.4	1.8	15.8	4.7	-12.7	-	-	-	-	-
2030s (2006-2035)	4.2	0.5	16.9	8.1	-8.9	1.8	-1.3	1.1	3.4	3.8
2050s (2036-2065)	5.9	2.2	18.7	9.6	-6.8	3.5	0.4	2.9	4.9	5.9
2080s (2066-2095)	8.0	4.0	20.7	11.7	-4.2	5.6	2.2	4.9	7.0	8.5
LAKE MICHIGAN-HURON										
Historical (1961-2000)	6.2	5.3	18.7	8.2	-7.2	-	-	-	-	-
2030s (2006-2035)	7.9	4.6	19.7	11.3	-4.1	1.7	-0.7	1.1	3.2	3.1
2050s (2036-2065)	9.5	6.2	21.6	12.8	-2.5	3.3	0.9	2.9	4.6	4.7
2080s (2066-2095)	11.4	7.8	23.4	14.8	-0.4	5.2	2.5	4.8	6.6	6.8
LAKE ERIE										
Historical (1961-2000)	9.1	8.2	20.8	10.8	-3.4	-	-	-	-	-
2030s (2006-2035)	10.7	7.9	21.9	13.7	-1.0	1.6	-0.3	1.2	3.0	2.5
2050s (2036-2065)	12.2	9.3	23.7	15.2	0.5	3.1	1.1	2.9	4.4	3.9
2080s (2066-2095)	13.9	10.6	25.5	17.1	2.3	4.8	2.5	4.7	6.3	5.7
LAKE ONTARIO										
Historical (1961-2000)	7.3	6.2	19.3	9.2	-5.5	-	-	-	-	-
2030s (2006-2035)	8.9	6.0	19.6	11.9	-2.0	1.6	-0.2	0.3	2.6	3.5
2050s (2036-2065)	10.4	7.4	21.4	13.3	-0.6	3.1	1.2	2.1	4.0	5.0
2080s (2066-2095)	12.2	8.9	23.3	15.2	1.3	4.9	2.7	3.9	6.0	6.9

Ice huts on Lake Superior

As Figure 2 illustrates, over-land air temperatures are projected to increase throughout the year across all lakes, especially in the months of January and February, and between July and December under both climate scenarios. These changes in average over-land air temperatures are expected to bring warmer winters, more extreme heat, and a longer growing season (see Section 3.0 for the impacts of these changes).

Average over-land air temperatures over the Lake Superior basin show the greatest warming compared to other lake basins under both climate scenarios, followed by the Lake Michigan-Huron basin. Annual average over-land air temperatures have historically (1961-2000) ranged from 2.4˚C (or 36.3˚F) over the Lake Superior basin, the northern-most lake, to 9˚C (or 48.2˚F) over the Lake Erie basin, the southern-most lake. Under RCP 4.5, annual average over-land air temperatures could increase by approximately 3.5˚C (or 6.3˚F) over the Lake Superior basin and 3˚C (or 5.4˚F) over the Lake Erie basin by the end of the century. While under RCP 8.5, annual average over-land air temperatures are expected to increase even further by 5.6˚C (or 10˚F) over the Lake Superior basin and 4.8˚C (or 8.6˚F) over the Lake Erie basin by the end of the century. These projections indicate significant increases in annual average over-land air temperatures across the Great Lakes basin.

The greatest temperature increases are projected for the fall and winter seasons compared to average seasonal values between 1961-2000, which aligns with trends already being observed. Under RCP 4.5, winter average over-land air temperatures could increase by 3.4 to 5˚C (or 6.1 to 9˚F) by the end of the century across lands within the basin. While under RCP 8.5, winter average over-land air temperatures could increase even further by 5 to 7.2˚C (or 9 to 13˚F) by the end of the century. With warmer winters, less ice cover can be expected on average over the Great Lakes, which has already been found to be declining (see Section 2.4 for historical and projected ice cover trends). Additionally, as warmer air can retain more moisture, heavier precipitation events that are already increasing can be expected to increase further in the region as more moisture is available to produce heavier storms.

2.2 Over-Lake Precipitation (ECCC Projections)

KEY FINDINGS:

- Average total over-lake precipitation is anticipated to increase in all seasons and over the year under both climate scenarios for all lakes.
- Changes in seasonal over-lake precipitation is anticipated to vary by lake and climate scenario.
- With warmer winters, snowfall is expected to decrease on average, with more precipitation falling as rain instead of snow.
- Lake Superior is expected to experience the greatest increase in over-lake precipitation, followed by Lake Ontario.

Over-lake precipitation refers to precipitation that falls on the lake's surface, which may vary from year to year. This is generally similar to precipitation that falls over the lands surrounding the Great Lakes, but differences can be observed based on wind patterns and local topography (Seglenieks and Temgoua, 2021). The impact of the Great Lakes on atmospheric stability can also result in more over-land precipitation in the summer and more over-lake precipitation in the winter (M. Notaro, personal communication, October 16, 2021).

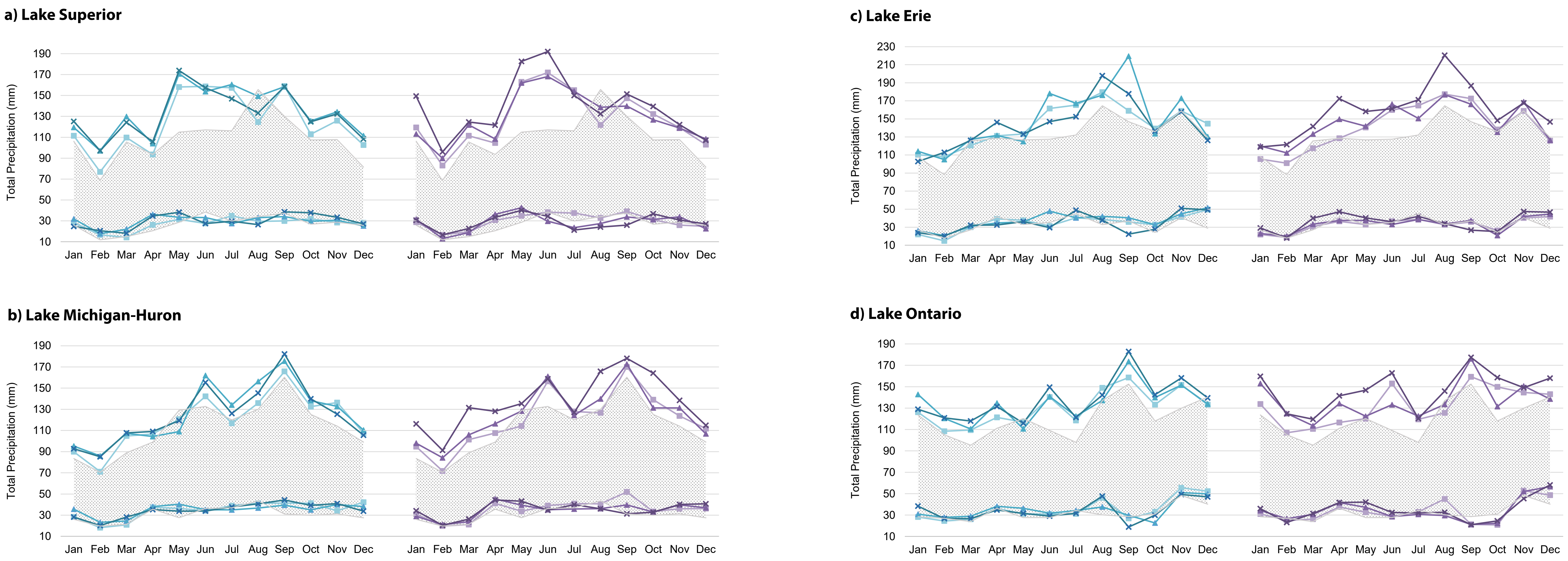
Figure 3 presents a set of graphs showing historical and projected over-lake precipitation for each lake under both climate scenarios averaged by month and time period. These graphs illustrate the anticipated changes in total over-lake precipitation averaged over the short (2030s), medium (2050s), and long-term (2080s) future compared to historical measured data (1961-2019) across the two climate scenarios (RCPs 4.5 and 8.5). The 5th and 95th percentile values across the model runs are presented to highlight the range of possible total over-lake precipitation falling over the lakes for each month (see Box 2 for information on percentiles). Tables 4 and 5 present average total over-lake precipitation values in millimetres and percentage differences compared to historical values for RCP 4.5 and RCP 8.5, respectively.

Figure 3: Historical and projected total over-lake precipitation under RCP 4.5 and 8.5 by month and time period for:

a) Lake Superior, b) Lake Michigan-Huron, c) Lake Erie, and d) Lake Ontario. Projected over-lake under both climate change scenarios are presented side by side with RCP 4.5 on the left and RCP 8.5 on the right. The dotted grey area shows historical over-lake precipitation averaged by month between 1961 and 2019 that fall within the 5th and 95th percentiles. Future over-lake precipitation is projected for three time periods: 2030s, 2050s, and 2080s, with each represented by a different colour and pattern. The top lines represent the 95th percentile of the projected values under six RCP 4.5 model runs and seven RCP 8.5 model runs, respectively, and the bottom lines represent the 5th percentile.

Measured (1961-2019), 5th and 95th Percentile
RCP 4.5 (2030s), 5th and 95th Percentile
RCP 4.5 (2050s), 5th and 95th Percentile
RCP 4.5 (2080s), 5th and 95th Percentile

RCP 8.5 (2030s), 5th and 95th Percentile
RCP 8.5 (2050s), 5th and 95th Percentile
RCP 8.5 (2080s), 5th and 95th Percentile



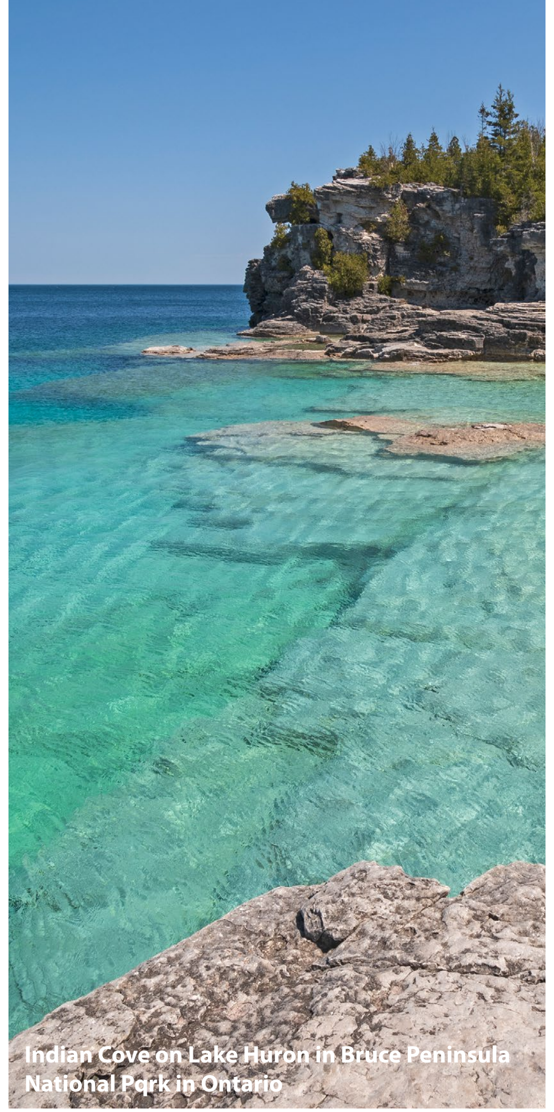

Indian Cove on Lake Huron in Bruce Peninsula National Park in Ontario

Table 4. Historical and projected annual and seasonal average total over-lake precipitation under RCP 4.5 by time period

LAKE AND TIME PERIOD	Historical and Projected Values Under RCP 4.5 (mm)					Percentage Difference from Corresponding 1961-2000 Values (%)				
	Annual	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)	Annual	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)
LAKE SUPERIOR										
Historical (1961-2000)	755.1	163.5	231.3	213.8	146.5	-	-	-	-	-
2030s (2006-2035)	857.4	203.8	250.1	230.8	172.6	14%	25%	8%	8%	18%
2050s (2036-2065)	898.3	219.9	255.3	242.3	180.8	19%	34%	10%	13%	23%
2080s (2066-2095)	908.7	233.3	246.6	245.5	183.3	20%	43%	7%	15%	25%
LAKE MICHIGAN-HURON										
Historical (1961-2000)	808.3	188.5	228.2	229.5	162.2	-	-	-	-	-
2030s (2006-2035)	873.0	193.0	245.0	257.2	177.8	8%	2%	7%	12%	10%
2050s (2036-2065)	915.3	201.8	255.7	265.9	191.9	13%	7%	12%	16%	18%
2080s (2066-2095)	910.5	207.0	247.2	266.4	189.9	13%	10%	8%	16%	17%
LAKE ERIE										
Historical (1961-2000)	909.6	228.8	252.0	239.8	189.0	-	-	-	-	-
2030s (2006-2035)	960.6	221.3	275.4	267.4	196.4	6%	-3%	9%	12%	4%
2050s (2036-2065)	1002.2	228.3	283.5	283.0	207.4	10%	0%	13%	18%	10%
2080s (2066-2095)	991.8	230.2	279.0	276.8	205.8	9%	1%	11%	15%	9%
LAKE ONTARIO										
Historical (1961-2000)	846.6	203.2	213.5	235.1	194.9	-	-	-	-	-
2030s (2006-2035)	938.8	210.7	240.5	276.1	211.6	11%	4%	13%	17%	9%
2050s (2036-2065)	970.9	220.5	247.8	278.3	224.3	15%	9%	16%	18%	15%
2080s (2066-2095)	970.5	218.5	245.4	280.7	225.9	15%	8%	15%	19%	16%

Table 5. Historical and projected annual and seasonal average total over-lake precipitation under RCP 8.5 by time period

LAKE AND TIME PERIOD	Historical and Projected Values Under RCP 8.5 (mm)					Percentage Difference from Corresponding 1961-2000 Values (%)				
	Annual	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)	Annual	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)
LAKE SUPERIOR										
Historical (1961-2000)	755.1	163.5	231.3	213.8	146.5	-	-	-	-	-
2030s (2006-2035)	861.7	210.9	248.2	227.8	174.8	14%	29%	7%	7%	19%
2050s (2036-2065)	892.5	223.5	250.6	236.4	182.0	18%	37%	8%	11%	24%
2080s (2066-2095)	936.9	250.2	249.1	243.7	193.8	24%	53%	8%	14%	32%
LAKE MICHIGAN-HURON										
Historical (1961-2000)	808.3	188.5	228.2	229.5	162.2	-	-	-	-	-
2030s (2006-2035)	879.2	199.9	244.5	254.5	180.3	9%	6%	7%	11%	11%
2050s (2036-2065)	907.5	208.4	248.3	259.7	191.1	12%	11%	9%	13%	18%
2080s (2066-2095)	965.3	235.5	258.1	267.0	204.7	19%	25%	13%	16%	26%
LAKE ERIE										
Historical (1961-2000)	909.6	228.8	252.0	239.8	189.0	-	-	-	-	-
2030s (2006-2035)	955.1	227.5	273.2	260.9	193.6	5%	-1%	8%	9%	2%
2050s (2036-2065)	1001.4	240.1	279.0	273.5	208.8	10%	5%	11%	14%	10%
2080s (2066-2095)	1076.5	273.8	295.6	284.6	222.5	18%	20%	17%	19%	18%
LAKE ONTARIO										
Historical (1961-2000)	846.6	203.2	213.5	235.1	194.9	-	-	-	-	-
2030s (2006-2035)	923.4	213.0	236.0	263.1	211.3	9%	5%	11%	12%	8%
2050s (2036-2065)	969.8	227.6	241.1	270.0	231.0	15%	12%	13%	15%	19%
2080s (2066-2095)	1033.1	257.2	254.4	276.7	244.7	22%	27%	19%	18%	26%

Under both climate scenarios, average total over-lake precipitation is anticipated to increase in all seasons and annually over the next century though the amount may vary from year to year. As Figure 3 illustrates, the greatest changes in total over-lake precipitation are anticipated among projected values that fall within the 95th percentile across all lakes. Meanwhile, projected values that fall within the 5th percentile are expected to remain relatively similar to measured historical data (1961- 2019), with some months showing an increase.

Overall, changes in 95th percentile monthly total over-lake precipitation are not uniform across the lakes. For some lakes, the projections indicate precipitation patterns that vary greatly from measured historical data. For Lake Superior, the greatest changes in the 95th percentile of total over-lake precipitation are expected for the months of May, June, July, and September under both climate scenarios. For Lake Michigan-Huron, the greatest changes are anticipated for the months of March and June under both climate scenarios. For Lake Erie, the greatest changes are anticipated for the months of April, June, August, and September. Meanwhile for Lake Ontario, increases in total over-lake precipitation are anticipated for most months of the year. When coupled with the projected increases in over-land air temperatures (as discussed in Section 2.1), more extreme precipitation can be expected over the Great Lakes as warmer air can hold more moisture to produce heavier storms.

The greatest increase in total over-lake precipitation is expected for Lake Superior under both climate scenarios, followed by Lake Ontario. Annual total over-lake precipitation has historically (1961-2000) ranged from 755 mm (or 29.7 inches) over Lake Superior to 909 mm (or 35.8 inches) over Lake Erie. Under RCP 4.5, annual total over-lake precipitation could increase by 20 percent over Lake Superior and 9 percent over Lake Erie by the end of the century. While under RCP 8.5, annual total over-lake precipitation is expected to increase even further by 24 percent over Lake Superior and 18 percent over Lake Erie by the end of the century. These projections indicate significant increases in annual total over-lake precipitation across the basin.

Changes in seasonal average total over-lake precipitation is anticipated to vary by lake. Under RCP 4.5, the greatest increases in precipitation by the end of the century are generally anticipated for fall and winter, with the exceptions of Lake Superior where spring shows the largest increase (43 percent increase compared to average spring totals between 1961-2000), and Lake Ontario where summer shows similar increases as winter (15 percent increase compared to average summer totals between 1961-2000). Meanwhile under RCP 8.5, the greatest increases are generally anticipated for spring and winter, with the exception of Lake Erie where fall shows similar increases as spring by the end of the century (19 and 20 percent increase, respectively, compared to average seasonal totals between 1961-2000). With warmer winters, snowfall is expected to decrease on average, with more precipitation falling as rain instead of snow.

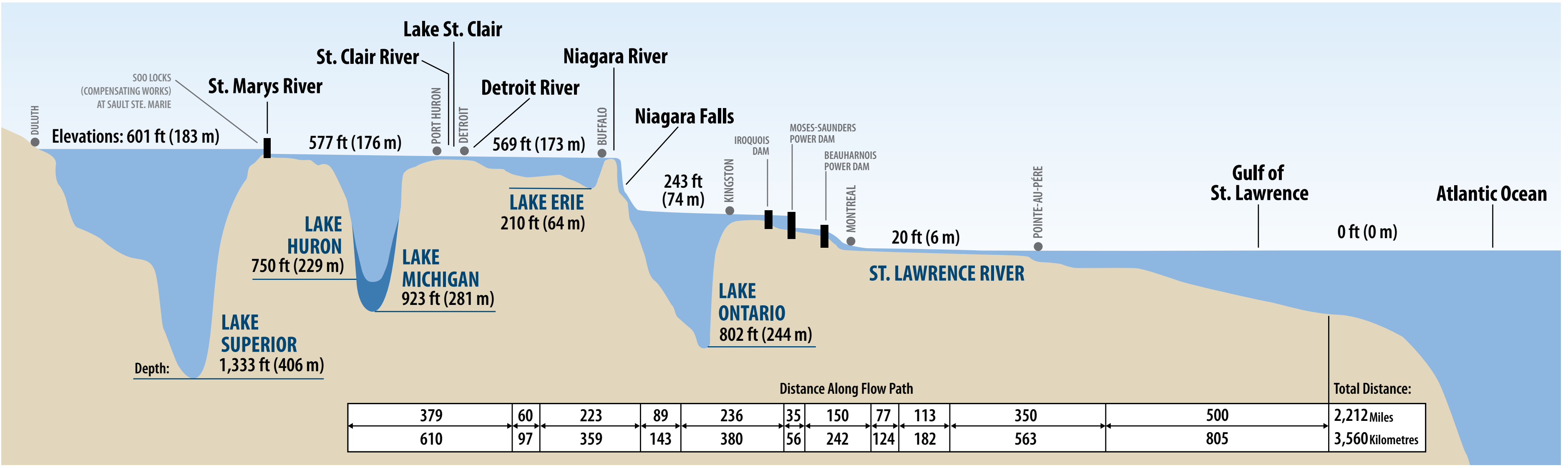
2.3 Lake Levels (ECCC Projections)

KEY FINDINGS:

- Lake level projections indicate significant deviations from lake-specific, long-term averages (1918-2019) across the basin with a slight upward trend apparent on all lakes in the latter half of the coming century.
- Projections indicate the potential for more frequent and severe extreme high and extreme low water levels.
- The greatest variation in lake levels is anticipated for lakes Michigan-Huron, Erie, St. Clair, and Ontario.

Lake levels refer to the surface water level of the Great Lakes (see Figure 4). Currently, lake levels are referenced to the International Great Lakes Datum 1985 (IGLD85; see Box 3 for more information).

Figure 4: Illustration of Great Lakes surface water level elevations and depths (adapted based on the Michigan Sea Grant illustration)



BOX 3: WHAT IS IGLD85?

IGLD85, or International Great Lakes Datum of 1985, is a common height reference system that is used to measure Great Lakes water levels (Vertical Control – Water Levels Subcommittee, 2017). This datum consists of elevations that were measured through geodetic leveling (a form of surveying), which was performed from the Atlantic Ocean (sea level), inland up the St. Lawrence River, and then to each lake along the connecting channels (Niagara, Detroit, St. Clair, and St. Marys River) (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1992). A new reference system needs to be established approximately every 25 to 30 years to account for differential movement of the earth's crust in the Great Lakes region (Government of Canada, 2019c). IGLD85 was implemented in January 1992, replacing the previous system, IGLD55. Currently, the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data is preparing the next update to the IGLD (Vertical Control – Water Levels Subcommittee, 2017).

Through a binational partnership, water levels on the Great Lakes are continuously monitored by U.S. and Canadian federal agencies using a network of water level monitoring stations in the region (NOAA, 2021a). This dataset represents one of the longest sets of direct hydrometeorological measurements for any aquatic system in the world, spanning more than 150 years (Lofgren et al. 2002; Allan et al. 2013; Gronewold et al. 2018). Over this time period, lake levels have ranged within a 2-metre (or 6.6-ft) difference between the recorded maximum monthly average and minimum monthly average. However, in the past three decades, a greater degree of fluctuation has been observed relative to the 2-metre range.

Great Lakes water levels are influenced by a number of factors, including over-lake precipitation, runoff from the drainage basin, evaporation from the lake surface, inflows from upstream lakes, outflows to downstream lakes, lake water diversions, water use, and regulation plans that control outflows from Lake Superior and Lake Ontario (Government of Canada, 2019b). Lake water flows from Lake Superior to Lake Michigan-Huron, then travels south through connecting channels including Lake St. Clair to Lake Erie, and then out through the Niagara River over Niagara Falls into Lake Ontario, before moving through the St. Lawrence River and into the Atlantic Ocean (see Figure 4). As noted previously, lakes Michigan and Huron are measured as one body of water because they share the same surface elevation above sea level and are connected at the Straits of Mackinac (NOAA, 2021c). Outflows from Lake Superior and Lake Ontario are overseen by binational regulatory boards and regulated through dams and control structures that can influence, but not control, water levels in the lakes (International Joint Commission [IJC], 2020). While outflows from Lakes Michigan-Huron, Erie, and St. Clair have no controls (US Army Corps of Engineers, 2021). It is important to note that ability to alter lake levels through the regulation plan is limited and dominated by changes in water supplies, which are driven by weather (Government of Canada, 2019b).

The lake level projections included in this report have been determined based on most, but not all, of the aforementioned factors that can alter water levels, including over-lake precipitation, runoff into the lake, evaporation, water flow, and the regulation of lakes Superior and Ontario outflows. It is important to note that these projections are not predicting exactly what future water levels will be for a certain year. Instead, they represent an envelope of possible values that the actual values will likely come from in the future.

Some projections for Lake Ontario under two RCP 8.5 models resulted in extremely high values due to the potential over-exaggeration of water accumulation from all Great Lakes flowing into Lake Ontario in the future and therefore have been excluded from our analysis. These extreme values have been excluded because it is impossible to anticipate what changes to the regulation plan might be made that would alter flows out of the system if extremely high inflows were to occur in Lake Ontario in the future. It is important to remember that projections of climate parameters and lake levels are based on current understanding of the climate system and assumptions made about the future behaviour of society, which will result in the amount of greenhouse gases that will be put into the atmosphere. There are many uncertainties and assumptions that are inherent in these projections and thus the projections are most useful in showing general trends of what could happen in the future.

Figure 5 presents a series of graphs showing historical and projected lake levels averaged by decade for each lake under both climate scenarios. Note that some periods are averaged over less than 10 years (i.e. 2011-2019, 2025-2030, and 2091-2095). Historical lake levels are displayed from 1961-2019, while projections under both climate scenarios are displayed from 2025 to 2095. Lake-wide, long-term averages (1918-2019) are presented for each lake, which are benchmarks used in forecasting models and monitoring of the Great Lakes' water budget (NOAA, 2021a). These graphs are intended to show the long-term variation in water levels, using box and whisker plots to show the minimum, maximum, average, and different quartiles for each period (see Box 4 for information on how to interpret box and whisker plots).

BOX 4: HOW TO READ BOX AND WHISKER PLOTS

Box and whisker plots are a form of graph that present a breakdown of the data by quartiles (or 25 percent increments). The bottom whisker starts with the minimum value and represents the range of the first quartile. The middle line in the box represents the median (or second quartile). From the median to the top of the box is the third quartile. The top whisker shows the range of the fourth quartile, ending with the maximum value. The average can also be displayed, which is represented by an 'x' symbol in this report.

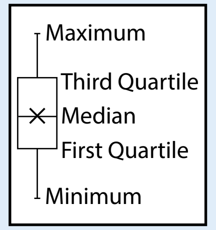
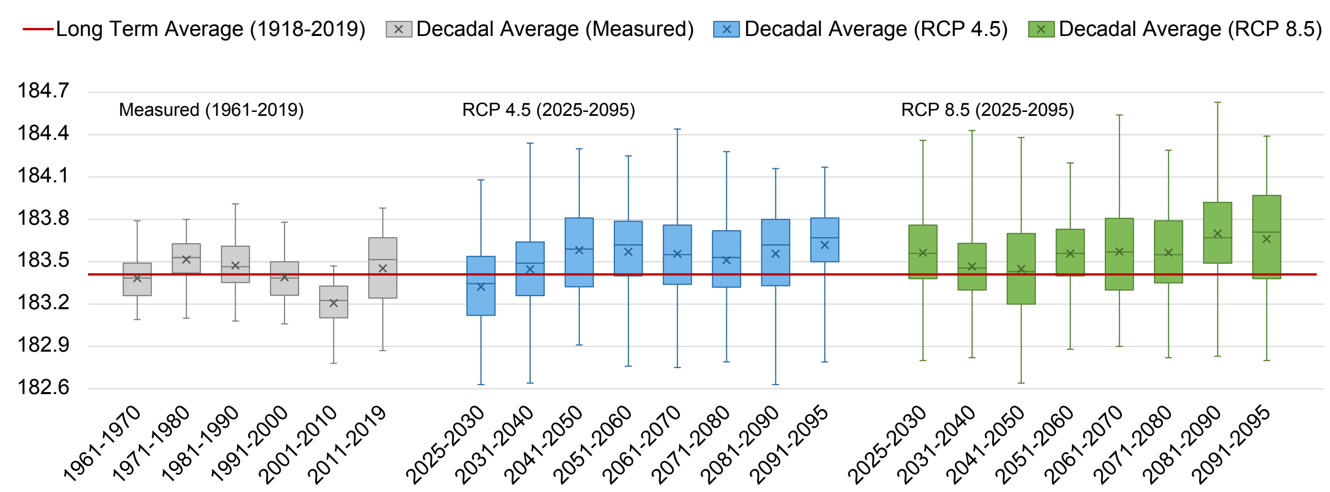


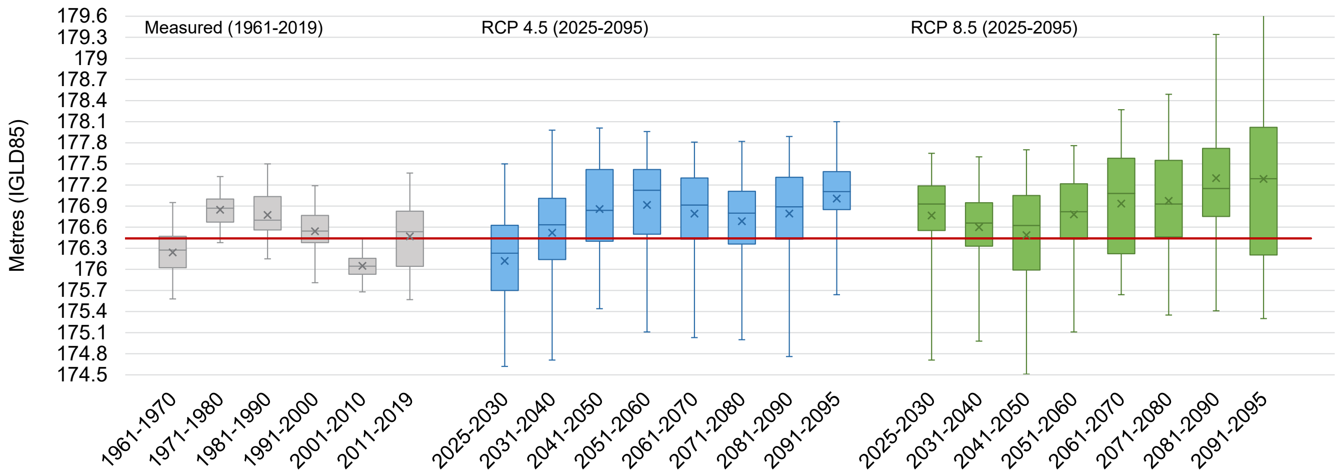
Figure 5: Historical and projected decadal average lake levels under RCP 4.5 and 8.5 for:

a) Lake Superior, b) Lake Michigan-Huron, c) Lake Erie, d) Lake St. Clair, and e) Lake Ontario. Each decade is represented by a box and whisker plot. Projected lake levels under both climate change scenarios are presented side by side with RCP 4.5 in blue and RCP 4.5 in blue and RCP 8.5 in green. Historical lake levels are presented in grey between 1961 and 2019. The red line shows the long-term average reported for each lake between 1918 and 2019 as a point of reference. Future lake levels are projected for the period between 2025 and 2095. Projections under six RCP 4.5 model runs are presented in blue and projections under seven RCP 8.5 model runs are presented in green. Note that some projections for Lake Ontario under two RCP 8.5 models resulted in extreme values and therefore have been excluded.

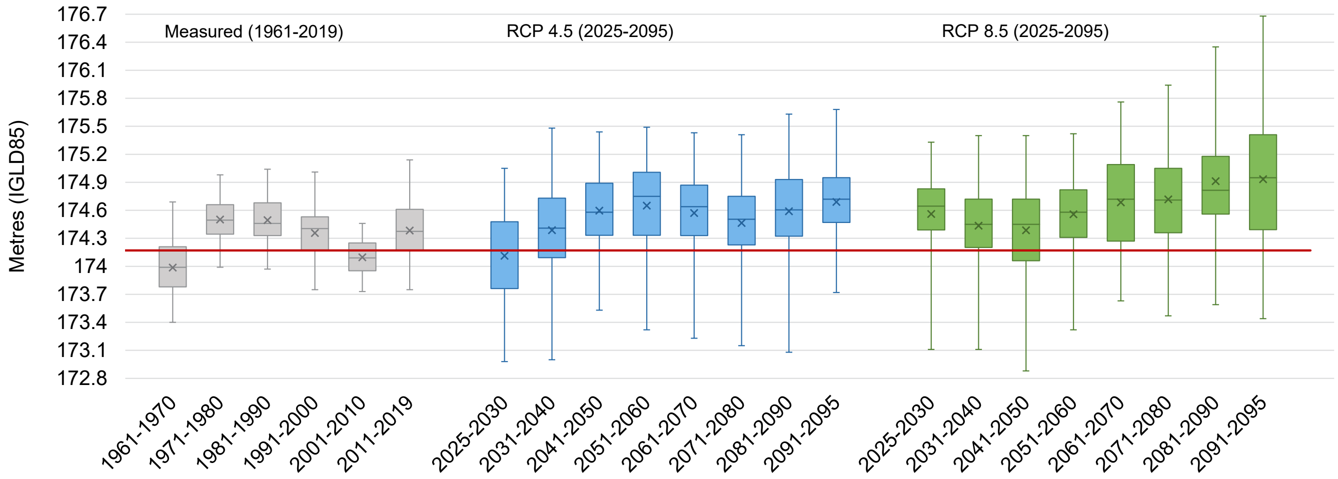
a) Lake Superior



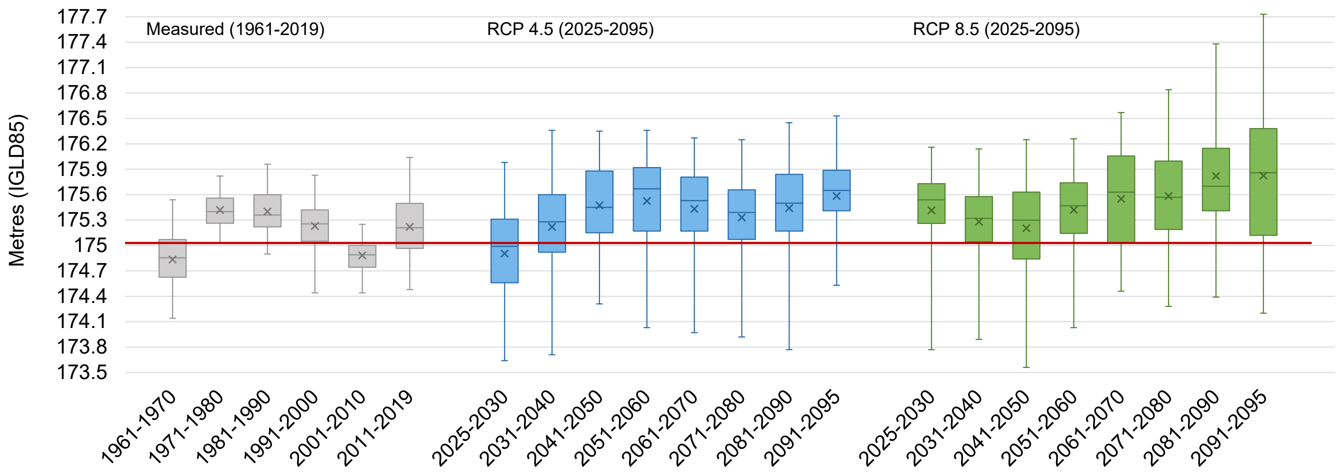
b) Lake Michigan-Huron



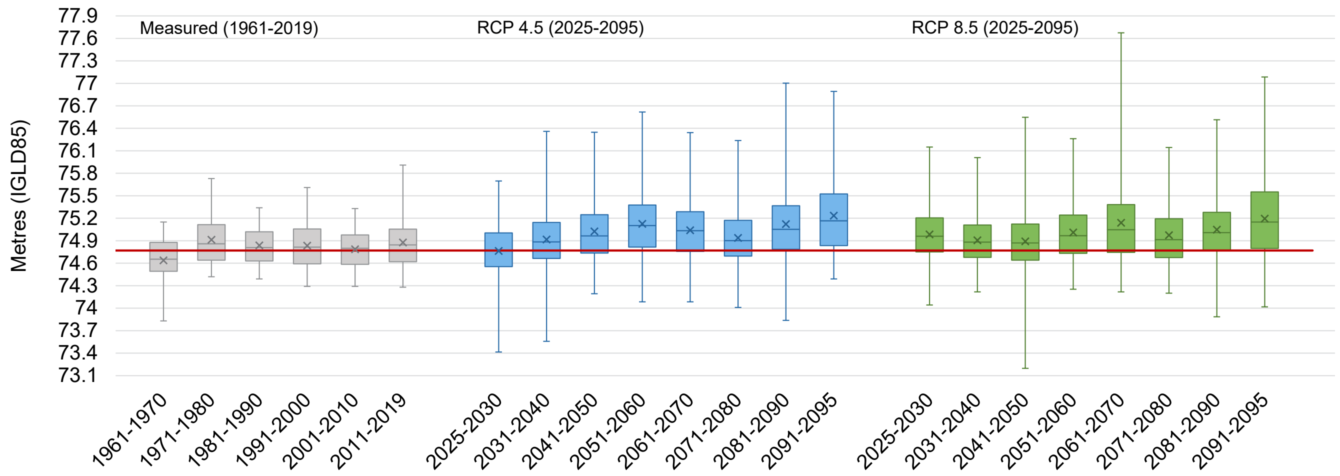
c) Lake Erie



d) Lake St. Clair



e) Lake Ontario



These graphs illustrate the cyclical nature of Great Lakes water level fluctuations, with some high periods and some low periods. The minimum and maximum values projected under both climate scenarios show the full range of possible lake levels that could be observed over each time period, including the most extreme values. Figure 5 illustrates a high degree of variation within each time period, signaling the potential for more frequent and severe extreme high and extreme low water levels in the coming decades. The lakes that are unregulated (i.e. lakes Michigan-Huron, Erie, and St. Clair) show a great degree of variation in future lake levels. Projections for Lake Ontario also indicate a great degree of variation. While outflows from Lake Ontario are regulated, inflows are uncontrolled (McNeil, 2019). There are also limits to the amount of outflow that can be released from Lake Ontario due to the flow capacity of the St. Lawrence River.

Figure 6 presents another set of graphs showing historical and projected lake levels for each lake under both climate scenarios averaged by month and time period (historical, 2030s, 2050s, and 2080s). These graphs illustrate the anticipated changes in lake levels averaged over the short, medium, and long-term future compared to measured historical data (1961-2019) across the two climate scenarios. The 5th and 95th percentile values are presented to highlight the range of possible average lake levels for each month. These ranges are anticipated to grow in the coming decades (i.e. there will likely be higher highs and lower lows), indicating once again that more frequent and severe extreme high and low water levels can be expected across all lakes in the future. Significant increases in 95th percentile lake levels are anticipated under RCP 8.5, while significant increases in 95th percentile lake levels are also anticipated under RCP 4.5 for lakes Superior and Ontario.

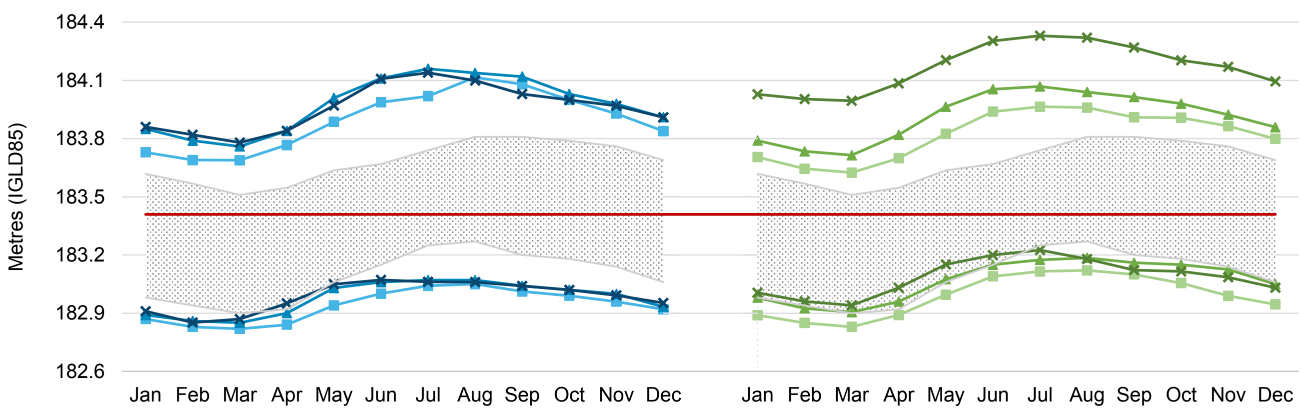
Seasonal variation in Great Lakes water levels is well defined with relatively low water levels in the winter months, rising water levels in the spring and summer, and decreasing water levels in the late summer and early fall with less precipitation and increasing lake evaporation (Quinn, 2002; Gronewold and Stow, 2014). This seasonal variation seems to be persistent under both climate scenarios in the coming decades.

Tables 6 and 7 present average lake level values in metres (IGLD85) and deviation from the lake-wide, long-term averages (1918-2019) for each lake.

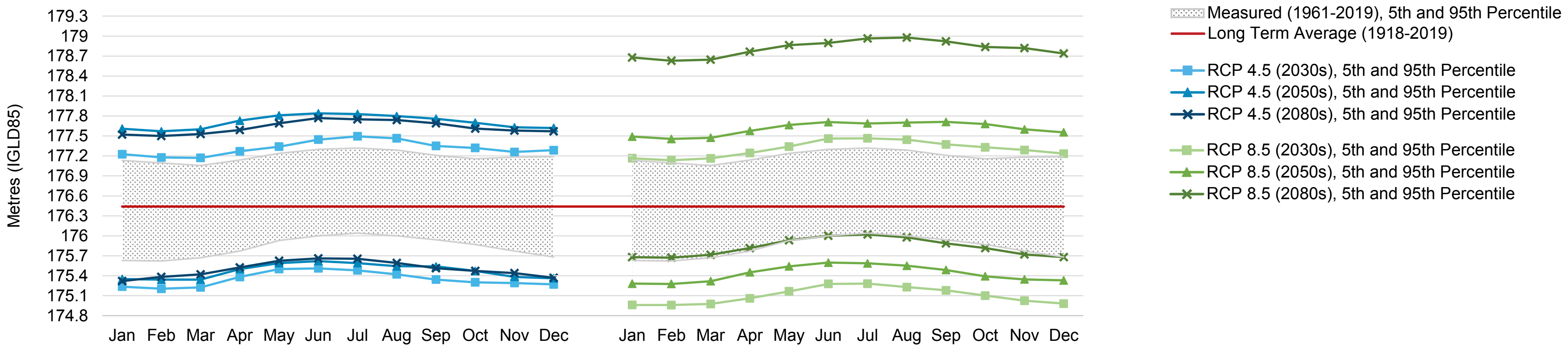
Figure 6: Historical and projected average lake levels under RCP 4.5 and 8.5 by month and time period for:

a) Lake Superior, b) Lake Michigan-Huron, c) Lake Erie, d) Lake St. Clair, and e) Lake Ontario. Projected lake levels under both climate change scenarios are presented side by side with RCP 4.5 on left and RCP 8.5 on the right. The dotted grey area shows historical lake levels averaged by month between 1961 and 2019 that fall within the 5th and 95th percentile range. The red line shows the long-term average reported for each lake between 1918 and 2019 as a point of reference. Future lake levels are projected for three time periods: 2030s, 2050s, and 2080s, with each represented by a different colour and pattern. The top lines represent the 95th percentile of the projected values under six RCP 4.5 model runs and seven RCP 8.5 model runs, respectively, and the bottom lines represent the 5th percentile.

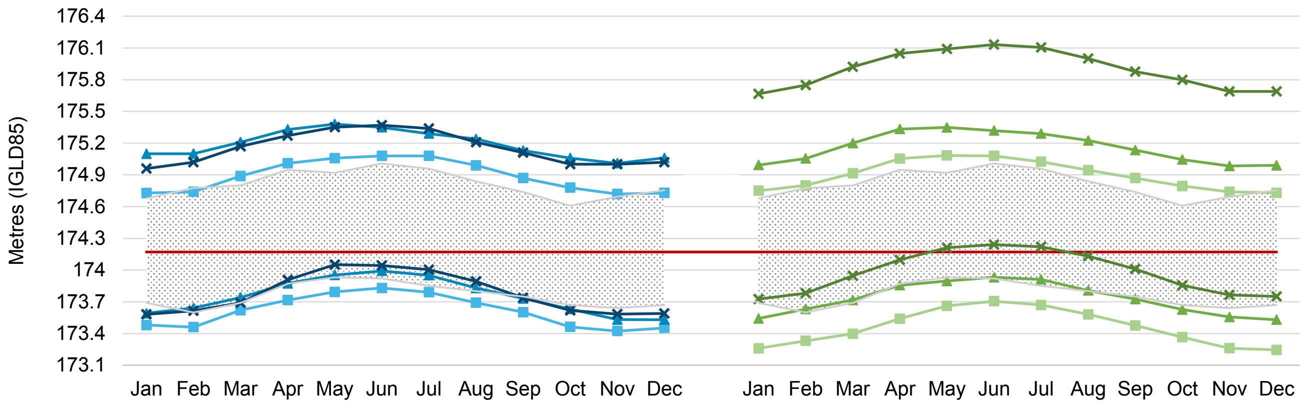
a) Lake Superior



b) Lake Michigan-Huron

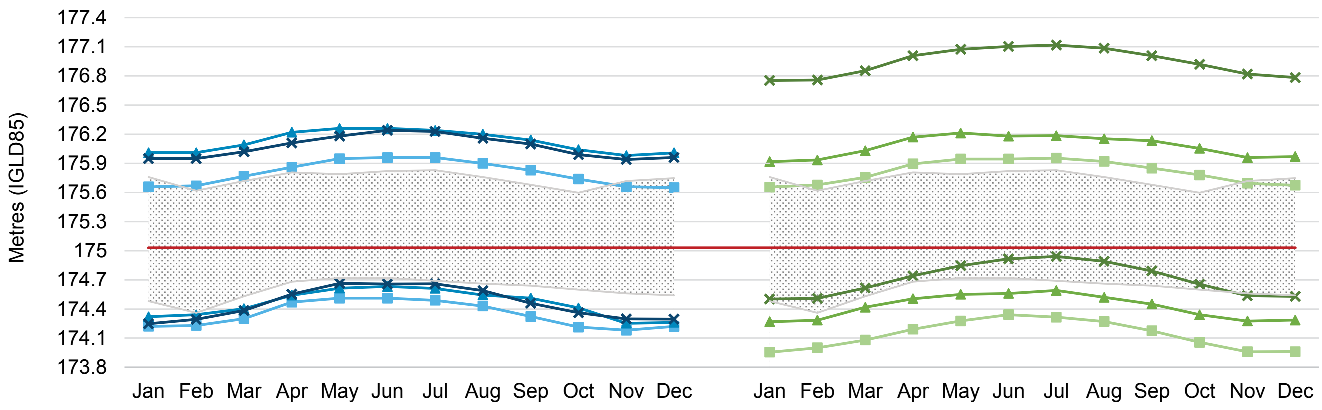


c) Lake Erie



Heron on Lake Erie

d) Lake St. Clair



e) Lake Ontario

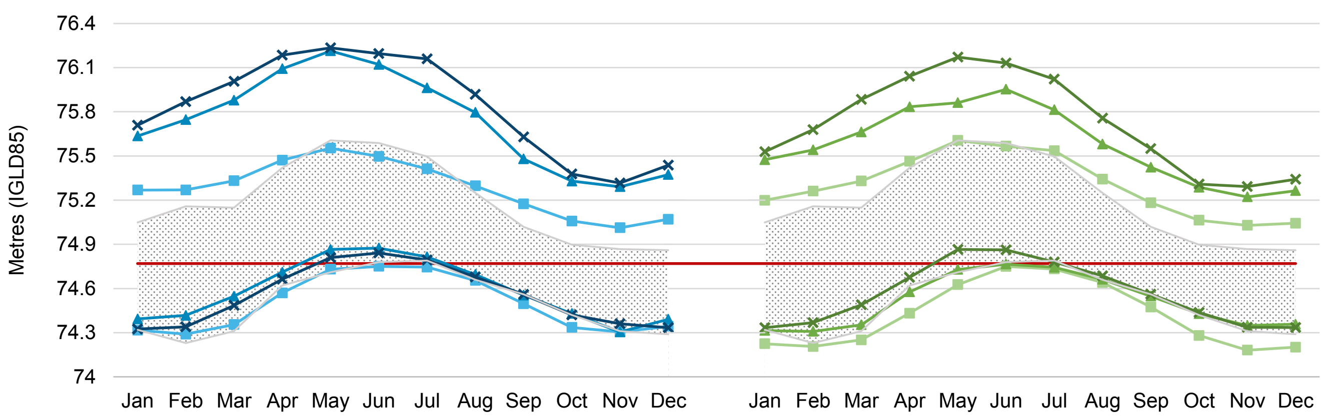


Table 6: Historical and projected annual lake levels under RCP 4.5 by time period

LAKE AND TIME PERIOD	Historical and Projected Values Under RCP 4.5 (m IGLD85)			Difference from Corresponding 1961-2000 Values (m IGLD85)		
	5th	Average	95th	5th	Average	95th
LAKE SUPERIOR						**LONG TERM AVERAGE: 183.41 M**
Historical (1961-2000)	183.2	183.4	183.7	-	-	-
2030s (2006-2035)	182.9	183.4	184.1	-0.3	0	0.4
2050s (2036-2065)	182.9	183.5	184.2	-0.3	0.1	0.5
2080s (2066-2095)	182.9	183.6	184.1	-0.3	0.2	0.4
LAKE MICHIGAN-HURON						**LONG TERM AVERAGE: 176.44 M**
Historical (1961-2000)	175.9	176.6	177.2	-	-	-
2030s (2006-2035)	175.0	176.4	177.5	-0.9	-0.2	0.3
2050s (2036-2065)	175.4	176.8	177.8	-0.5	0.2	0.5
2080s (2066-2095)	175.2	176.8	177.7	-0.7	0.2	0.5
LAKE ERIE						**LONG TERM AVERAGE: 174.17 M**
Historical (1961-2000)	173.8	174.3	174.8	-	-	-
2030s (2006-2035)	173.3	174.3	175.1	-0.5	0	0.3
2050s (2036-2065)	173.6	174.6	175.4	-0.2	0.3	0.6
2080s (2066-2095)	173.5	174.6	175.4	-0.3	0.3	0.6
LAKE ST. CLAIR						**LONG TERM AVERAGE: 175.03 M**
Historical (1961-2000)	174.6	175.2	175.8	-	-	-
2030s (2006-2035)	174.0	175.1	176.0	-0.6	-0.1	0.2
2050s (2036-2065)	174.3	175.4	176.3	-0.3	0.2	0.5
2080s (2066-2095)	174.2	175.4	176.2	-0.4	0.2	0.4
LAKE ONTARIO						**LONG TERM AVERAGE: 74.77 M**
Historical (1961-2000)	74.4	74.8	75.3	-	-	-
2030s (2006-2035)	74.1	74.9	75.6	-0.3	0.1	0.3
2050s (2036-2065)	74.3	75.1	76.2	-0.1	0.3	0.9
2080s (2066-2095)	74.3	75.1	76.3	-0.1	0.3	1.0

Table 7: Historical and projected annual lake levels under RCP 8.5 by time period

LAKE AND TIME PERIOD	Historical and Projected Values Under RCP 4.5 (m IGLD85)			Difference from Corresponding 1961-2000 Values (m IGLD85)		
	5th	Average	95th	5th	Average	95th
LAKE SUPERIOR						**LONG TERM AVERAGE: 183.41 M**
Historical (1961-2000)	183.2	183.4	183.7	-	-	-
2030s (2006-2035)	182.9	183.4	184.1	-0.3	0	-0.4
2050s (2036-2065)	182.9	183.5	184.1	-0.3	0.1	0.4
2080s (2066-2095)	182.9	183.6	184.3	-0.3	0.2	0.6
LAKE MICHIGAN-HURON						**LONG TERM AVERAGE: 176.44 M**
Historical (1961-2000)	175.9	176.6	177.2	-	-	-
2030s (2006-2035)	175.0	176.4	177.5	-0.9	-0.2	0.3
2050s (2036-2065)	175.0	176.7	177.9	-0.9	0.1	0.7
2080s (2066-2095)	175.6	177.1	179.1	-0.3	0.5	1.9
LAKE ERIE						**LONG TERM AVERAGE: 174.17 M**
Historical (1961-2000)	173.8	174.3	174.8	-	-	-
2030s (2006-2035)	173.3	174.3	175.1	-0.5	0	0.3
2050s (2036-2065)	173.4	174.5	175.4	-0.4	0.2	0.6
2080s (2066-2095)	173.7	174.8	176.1	-0.1	0.5	1.3
LAKE ST. CLAIR						**LONG TERM AVERAGE: 175.03 M**
Historical (1961-2000)	174.6	175.2	175.8	-	-	-
2030s (2006-2035)	174.0	175.1	176.0	-0.6	-0.1	0.2
2050s (2036-2065)	174.1	175.3	176.3	-0.5	0.1	0.5
2080s (2066-2095)	174.4	175.7	177.2	-0.2	0.5	1.4
LAKE ONTARIO						**LONG TERM AVERAGE: 74.77 M**
Historical (1961-2000)	74.4	74.8	75.3	-	-	-
2030s (2006-2035)	74.1	74.8	75.6	-0.3	0	0.3
2050s (2036-2065)	74.2	75.0	76.2	-0.2	0.2	0.9
2080s (2066-2095)	74.4	75.1	76.3	0	0.3	1.0

Overall, annual average lake level projections indicate variations from historical lake levels (1961-2000) for all lakes. Under both climate scenarios, Lake Michigan-Huron is expected to see the greatest variation in possible average annual lake levels in the future, which aligns with historical observations (Wuebbles et al. 2019).

2.4 Ice Cover (CCR Projections)

KEY FINDINGS:

- Ice cover projections indicate significant decreases in future lake ice cover across all lakes, especially in the months of February and March under the high-emissions scenario.
- Projections indicate the potential for more years with little to no ice cover and shorter ice seasons. For deeper lakes such as lakes Superior and Huron, ice growth may also peak earlier (in February instead of March).
- Average ice cover over lakes Superior and Erie show the greatest declines, followed by Lake Huron.
- Lake Michigan is expected to see the greatest decline in the average length of the ice season between December and May, followed by lakes Erie and Ontario.

Ice cover refers to the amount of ice that forms on the surface of the Great Lakes. Common metrics of ice cover include: area or percentage of the lake surface that is covered in ice; the length of time that the lake stays frozen; maximum annual ice cover; and the thickness of the ice that forms over the lake surface.

Historically, sections of the Great Lakes typically freeze every winter though the amount of ice cover and length of the ice season vary from year to year (NOAA, 2021b; US Environmental Protection Agency [US EPA], 2021a). NOAA-GLERL has been monitoring and analyzing Great Lakes ice cover since the early 1970s, using the ice products developed by the U.S. National Ice Center and the Canadian Ice Service (NOAA, 2021b). Ice cover data for each lake is available dating back to 1973 (US EPA, 2021a).

The formation and melting of ice cover can be characterized by three stages: freeze-up, ice growth, and break-up (Brown and Duguay, 2010). In general, ice typically begins to form in the lakes in early December and can grow until mid-February to early March (Wang et al. 2018). By late April to late May, ice typically melts away completely. In presenting historical and future ice cover in this section, December to May is considered part of the same year (or ice season).

The extent and duration of ice cover can vary due to differences in the lakes' latitude, orientation, depth (and therefore heat storage), as well as turbidity (which can affect the amount of light reflected off the lake's surface, known as albedo; Wang et al. 2018). Compared to the deeper lakes, shallow lakes such as lakes St. Clair and Erie store less heat and typically have more ice cover and experience an earlier ice season (i.e. earlier freeze-up and break-up; US EPA, 2021b; Wang et al. 2018).

In addition to the morphometry of the lakes, ice cover can also be influenced by air temperature, precipitation, wind, and solar radiation, as well as multi-year and multi-decadal climate patterns such as the El Niño and Southern Oscillation and North Atlantic Oscillation, and the Atlantic Multidecadal Oscillation and Pacific Decadal Oscillation (US EPA, 2021b; Wang et al. 2018).

Overall, Great Lakes ice cover has been declining rapidly since the 1970s. Researchers at NOAA have found that, on average, maximum annual ice cover has been decreasing by 5 percent per decade (NOAA, 2018). This report focuses on changes in annual average ice cover and length of the ice season between December and May.

Figure 7 presents a series of graphs showing historical and projected ice cover for each lake under the high-emissions scenario averaged by month and time period. These graphs illustrate the anticipated changes in ice cover over the medium (2040-2059; left), and long-term (2080-2099; right) future under RCP 8.5 compared to observed historical data (1980-2019). The 5th and 95th percentile values across the model runs are presented to highlight the range of possible ice cover over the lakes for each month. Table 8 presents the projected values of percentage ice cover under RCP 8.5.

Figure 7: Historical and projected average ice cover under RCP 8.5 by month and time period for:

a) Lake Superior, b) Lake Michigan, c) Lake Huron, d) Lake Erie, and e) Lake Ontario. Projected ice cover under the high-emissions scenario is presented. The dotted grey area shows historical ice cover averaged by month between 1980 and 2019 that fall within the 5th and 95th percentile range. Future ice cover is projected for two time periods: 2040-2059 (left) and 2080-2099 (right), with each represented by a different colour side by side. The top lines represent the 95th percentile of the projected values under six RCP 8.5 model runs, and the bottom lines represent the 5th percentile.

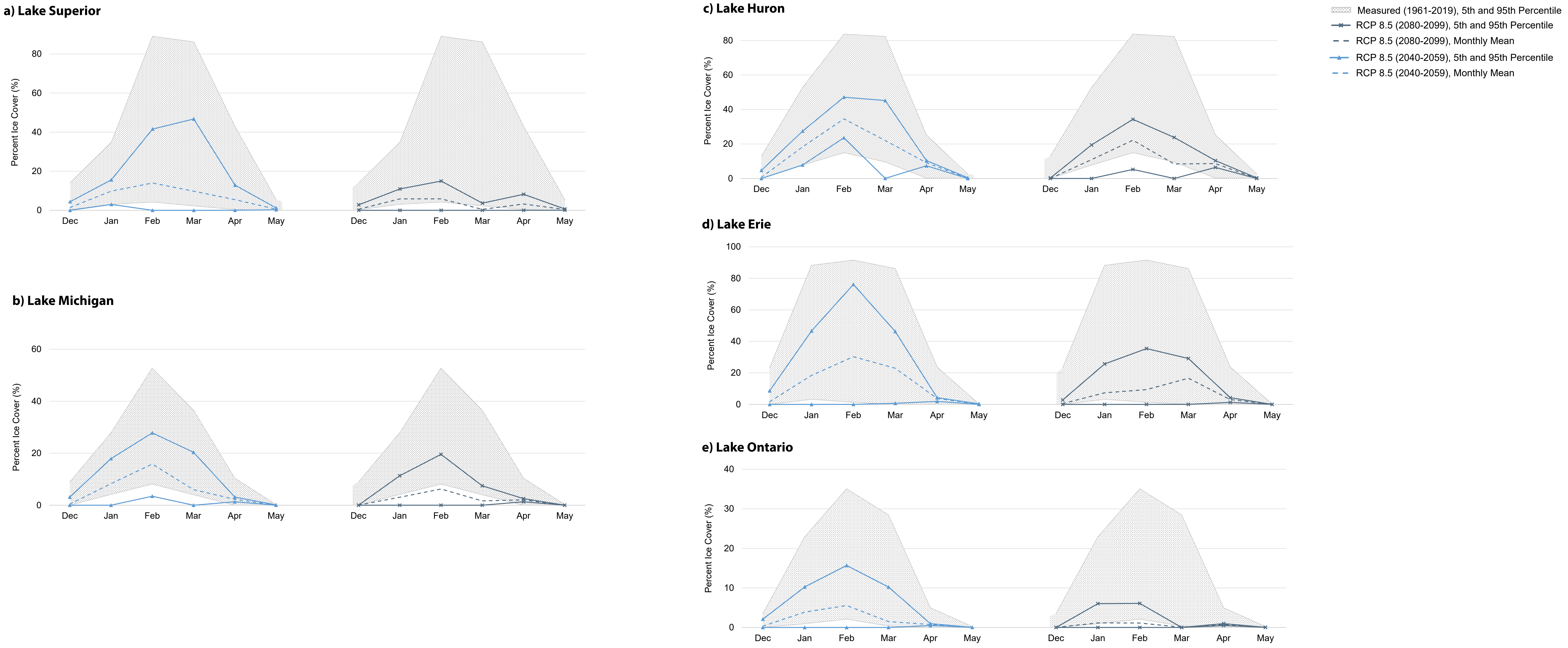


Table 8: Historical and projected average ice cover by ice season (December to May) and season under RCP 8.5 by time period

LAKE AND TIME PERIOD	Historical and Projected Values Under RCP 8.5 (%)			Difference from Corresponding 1980-1999 Values (%)		
	Ice Season	Winter (DJF)	Spring (MAM)	Ice Season	Winter (DJF)	Spring (MAM)
LAKE SUPERIOR						
Historical (1980-1999)	20.6	22.0	19.3	-	-	-
2040-2059	6.9	8.5	5.3	-14%	-13%	-14%
2080-2099	2.7	4.1	1.4	-18%	-18%	-18%
LAKE MICHIGAN						
Historical (1980-1999)	10.8	21.1	6.7	-	-	-
2040-2059	5.5	8.3	2.8	-5%	-7%	-4%
2080-2099	2.2	3.2	1.2	-9%	-12%	-5%
LAKE HURON						
Historical (1980-1999)	22.3	38.0	17.8	-	-	-
2040-2059	14.3	18.1	10.5	-8%	-9%	-7%
2080-2099	8.4	11.2	5.7	-14%	-16%	-12%
LAKE ERIE						
Historical (1980-1999)	25.3	50.9	14.8	-	-	-
2040-2059	13.0	17.1	8.9	-12%	-19%	-6%
2080-2099	6.2	5.8	6.6	-19%	-30%	-8%
LAKE ONTARIO						
Historical (1980-1999)	6.1	12.6	3.5	-	-	-
2040-2059	2.0	3.3	0.8	-4%	-6%	-3%
2080-2099	0.5	0.8	0.3	-6%	-8%	-3%

As Figure 7 illustrates, average ice cover is anticipated to decrease during winter and spring across all lakes, especially in the months of February and March under the high-emissions scenario. These changes suggest that less ice cover may form over the Great Lakes; there may be more years with little to no ice cover; and ice growth may peak earlier, especially in deeper lakes such as lakes Superior and Huron (see Section 3.0 for the impacts of these changes). Average ice cover over lakes Superior and Erie show the greatest declines, followed by Lake Huron.

Historically (1980-1999), average ice cover during winter and spring ranged from 25.3 percent over Lake Erie to 6.1 percent over Lake Ontario. Under RCP 8.5, average ice cover during winter and spring could decrease by 19 percent over Lake Erie and 6 percent over Lake Ontario by the end of the century, compared to the historical period (1980-1999). These projections indicate significant decreases in average ice cover across the Great Lakes basin.

The greatest declines in average ice cover are projected for the winter months compared to average seasonal values between 1980-1999. Under RCP 8.5, average ice cover in the winter could decrease by 8 to 30 percent by the end of the century across the Great Lakes. While average ice cover in the spring could decrease by 3 to 18 percent by the end of the century across the Great Lakes.

Table 9 presents the historical and projected length of the ice season between December and May for each lake in days. The 5th and 95th percentile values are included to highlight the range of possibilities for the length of the ice season, which may vary from year to year. On average, the length of the ice season ranged from 106 days to 139 days across the Great Lakes between 1981-1999 (1980 was excluded because December 1979 data was not analyzed). Under RCP 8.5, the average length of the ice season could range from 47 days to 124 days across the Great Lakes by the end of the century. For the most part, the number of days where the lakes are covered in ice is expected to decrease in the future though some years could still see an increase compared to the historical period.

By the end of the century, Lake Michigan is expected to see the greatest decline in the average length of the ice season, decreasing by 72 days compared to 1981-1999. This is followed by Lake Erie and Lake Ontario, which may see a decrease by 66 and 50 days, respectively, by the end of the century compared to 1981-1999. These projections indicate a significant reduction in the average ice season across the Great Lakes basin during winter and spring.

Table 9: Historical and projected ice season length between December and May under RCP 8.5 by time period

LAKE AND TIME PERIOD	Historical and Projected Ice Season Length During Winter and Spring Under RCP 8.5 (days)			Difference from Corresponding 1981-1999 Values (days)		
	5th	Average	95th	5th	Average	95th
LAKE SUPERIOR						
Historical (1981-1999)	105	139	166	-	-	-
2041-2059	126	134	139	20	-5	-27
2081-2099	112	124	138	7	-15	-28
LAKE MICHIGAN						
Historical (1981-1999)	104	126	157	-	-	-
2041-2059	74	84	93	-30	-42	-64
2081-2099	29	54	66	-75	-72	-91
LAKE HURON						
Historical (1981-1999)	105	131	156	-	-	-
2041-2059	109	118	126	4	-13	-30
2081-2099	65	93	118	-41	-38	-38
LAKE ERIE						
Historical (1981-1999)	67	112	145	-	-	-
2041-2059	63	87	104	-4	-26	-41
2081-2099	0	47	86	-67	-66	-58
LAKE ONTARIO						
Historical (1981-1999)	87	106	129	-	-	-
2041-2059	79	85	94	-8	-21	-35
2081-2099	38	57	73	-48	-50	-56

3.0 Climate Change Impacts

Across the Great Lakes basin, the impacts of climate change are already being felt.

Changes in climate and water levels impact people, infrastructure, and ecosystems across the Great Lakes region. Impacts can range from costly damages to infrastructure and property, threats to human health and safety, changes to ecosystems and biodiversity, and impacts on businesses and local economies. These impacts will be experienced differently by different people, depending on socio-economic factors and geographic location.

Climate change also acts as a threat multiplier, exacerbating the impacts of existing stressors such as pollution, invasive species, coastal development, and inequality. This section highlights some of the major impacts of climate change that are already being felt by communities across the Great Lakes basin based on a review of published literature, including peer-reviewed articles, reports, and news articles. The impacts observed include the following: warmer surface water temperatures; ice cover reduction; flooding, erosion, and storms; impacts on industries and livelihoods; and impacts on ecosystems and biodiversity.

3.1 Impacts of Warmer Water Temperatures

With warmer air temperatures and reduced ice cover, summer surface water temperatures are warming across the Great Lakes (Allan et al. 2013). In the upper Great Lakes, especially Lake Superior, summer water temperatures are warming even faster than regional air temperatures (Austin and Colman, 2007; O'Reilly et al. 2015). Surface water temperature has warmed fastest around the coastline and the eastern portion of Lake Superior (Bartolai et al. 2015; see Box 6). Meanwhile, warming of the other lakes has primarily been observed in the north-central (Lake Michigan) and eastern regions (lakes Huron, Erie, and Ontario). Warmer water temperatures inhibit the mixing of lake waters, increase oxygen depletion, promote the growth of harmful algal blooms, and lead to the decline of cold-water species. Many of these processes are interconnected and reinforce one another.

Stratification of lake waters is occurring earlier with shorter winters and earlier warming in the spring (see Figure 8; Kling et al. 2003; Allan et al. 2013). In turn, stratification may last for a longer period of time and become established at shallower depths. Stratification refers to the layering and separation of warmer surface waters from cooler waters at the bottom of the lake (Kling et al. 2003). It prevents the mixing of water in the water column and oxygenation of water at greater depths, which can lead to more widespread and longer periods of bottom anoxia (i.e., depletion of oxygen) or dead zones (when oxygen is consumed by organisms). Persistent dead zones can result in massive fish kills, damage to fisheries, toxic algal blooms, and impacts on drinking water (see Box 6).

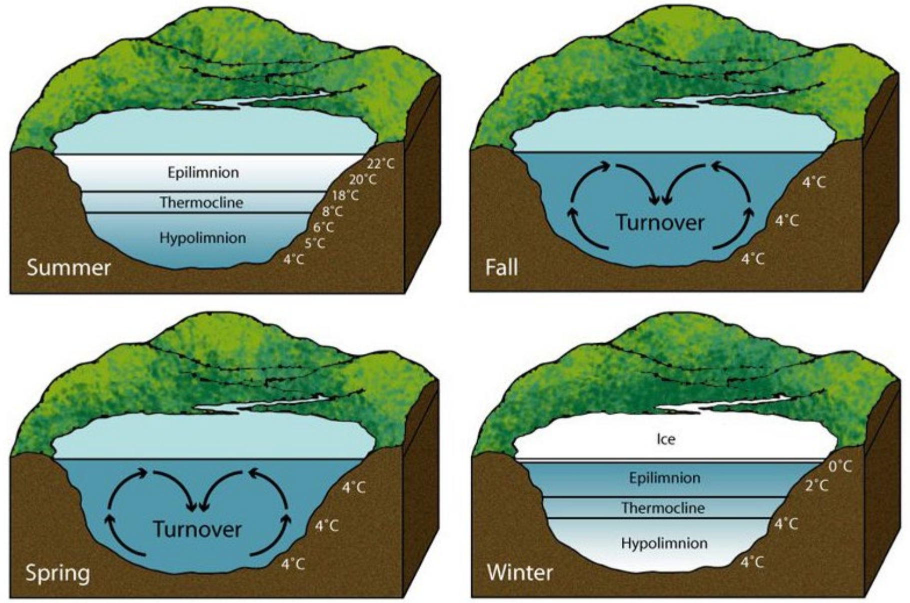


Figure 8: Lake mixing and stratification (credit: Tim Gunther).

The mixing of lake waters generally occurs when surface water cools from its maximum temperature in the year, typically in September, and begins to mix with warmer and less dense water at greater depths (Wuebbles et al. 2019). This mixing continues until water reaches a 4°C (or 39.2°F) threshold (the point at which fresh water reaches maximum density). However, when surface water temperature stays above 4°C, the lake may not mix fully to bring nutrients up from the bottom of the lake and bring down critical dissolved oxygen to deeper waters for fish and zooplankton species (Bartolai et al. 2015). This lack of mixing further contributes to increased thermal stratification and enhanced warming of surface water temperatures. Parts of southern Lake Michigan and Lake Ontario reportedly had surface temperature that stayed above 4°C during the winters of 2011/12 and 2016/17 (Wuebbles et al. 2019). As the smallest lake by surface area, Lake Ontario is particularly sensitive to this effect.

BOX 5: WHY IS LAKE SUPERIOR WARMING MORE QUICKLY THAN OTHER LAKES?

A study by O'Reilly and others in 2015 found Lake Superior to be the second fastest warming lake in the world, behind a lake in Sweden. While smaller lakes might be expected to warm more quickly, several factors may be driving the increase in warming in lakes similar to Lake Superior (Chung, 2015). Lakes that are normally covered with ice in the winter are experiencing earlier ice melt in the spring, which exposes the lakes to more solar radiation and increases the amount of heat absorbed by the lake. Summer stratification is also occurring earlier, which reinforces itself by inhibiting the mixing of colder water located at greater depths.

Higher water temperatures promote the growth of certain types of bloom-forming algae and cyanobacteria (Wuebbles et al. 2019). When water temperatures are above 20°C (or 68°F), the growth rates of many bloom-forming cyanobacteria increase (e.g. Microcystis, Anabaena, and Cylindrospermopsis), which can lead to more severe harmful algal blooms (HABs). Of these, the Microcystis and Anabaena species are of greatest concern because they produce toxic chemicals that can damage the liver and nerve tissues, respectively (Michalak et al. 2013). Contact with and consumption of water contaminated with cyanobacteria have been associated with skin and eye irritation, respiratory illness, gastrointestinal illness, and liver and kidney damage (Angel et al. 2018). Given these public health risks, restrictions on fisheries, coastal recreation, and drinking water are usually put in place when HABs occur (Sharma et al. 2018). Even nontoxic algal blooms can have significant impacts on the lakes, making lake water smell and taste bad and sometimes dangerous to drink, depleting oxygen, killing fish, and driving chemical processes that prime the lakes for larger blooms in the future (Michalak et al. 2013; Filippelli and Ortiz, 2020). In recent years, the normally pristine waters of Lake Superior have also experienced algal blooms near the Apostle Islands, an indication of the potential challenges that we might continue to expect under climate change (Wuebbles et al. 2019; Briscoe, 2019c). Meanwhile in Lake Erie, the severity of blooms has generally been on the rise since the early 2000s (Hartig et al. 2020).

Warmer and lower oxygen waters promote increased microbial decomposition and the subsequent release of nutrients (e.g. phosphorous) and contaminants (e.g. mercury and other heavy metals) from bottom sediments (Kling et al. 2003). Heavy metals such as mercury become more soluble (and bioavailable) in the absence of oxygen because oxygen binds with these elements to form insoluble compounds that sink to the bottom of the lake. This may lead to increased uptake by aquatic organisms, leading to increased accumulation of mercury and other contaminants in the aquatic food chain, impacting people and wildlife. When low-oxygen water interacts with Lake Erie's bottom sediments and clay, heavy metals such as manganese and iron are released into the water (Briscoe, 2019a). Low oxygen water is also more corrosive and can damage water pipes, causing foul-smelling and poor-tasting water, and increases the release of trace metals from pipes, which may also pose threats to human health.

BOX 6: LAKE ERIE'S DEAD ZONE POSES RISKS TO MUNICIPAL DRINKING WATER

Lake Erie's dead zone is situated mostly in deep, offshore waters and can cover an area the size of Connecticut (Briscoe, 2019a). However, northeastern winds can push this water toward Ohio's shoreline, where it threatens a number of major municipal drinking water intakes from Lorain (approximately 48 km or 30 mi west of Cleveland) to Ashtabula (approximately 97 km or 60 mi to the east). This occurred in Westlake, Ohio, on August 9, 2006, when northeastern winds blew across the lake, which led warm, low-oxygen offshore waters to engulf the crib structure protecting the municipal drinking water intake, and subsequently enter three of the four water treatment plants at the Crown Water Treatment Plant. This lasted up to 12 days and manganese concentrations at the Crown Treatment Plant rose above 1 milligram per litre (mg/L) at times, exceeding the thresholds recommended by the Environmental Protection Agency (EPA) of no more than 0.3 mg/L for pregnant and nursing women, and no more than 1 mg/L for healthy adults. Manganese causes water discolouration and has been linked to permanent neurological issues.

Warmer water temperatures also mean less available habitat for coldwater fish species (e.g. lake trout, brook trout, whitefish, emerald shiners, and rainbow smelt) and coolwater species (e.g. northern pike and walleye; Alofs et al. 2014, 2015; Dove-Thompson et al. 2011). For smaller and shallower lakes such as Lake Ontario, the increase in water temperatures can result in a significant loss in the volume of cold bottom water, constraining coldwater fish species to increasingly narrower bands in the water column where oxygen levels are sufficient and where the temperature is bearable (Briscoe, 2019b). As water temperatures increase, coldwater fish species will likely decline, and may be increasingly replaced by warmwater species (see Section 3.4 for implications on commercial, recreational, and subsistence fishing).

3.2 Impacts of Ice Cover Reduction

While ice cover over the Great Lakes is variable from year to year, Great Lakes ice cover has been declining rapidly since the 1970s (NOAA, 2018; see Section 2.4). In coastal areas, lake ice helps to protect shorelines by reducing wave action and is important for communities that rely on ice roads, and for winter recreation.

Ice cover helps to reduce wave energy/erosion that drives up against the coast. It also offers insulation and protection for spawning habitats in shallow areas for species that spawn during the fall and winter (Bartolai et al. 2015). With reduced ice cover in early and late winter and the potential for more frequent extreme high water levels, increased erosion risks can be anticipated especially for sandy beach systems found in southern Lake Huron, and much of lakes Michigan, Erie, and Ontario (Wuebbles et al. 2019). There is also increased potential for overwash and breaching of barriers, affecting barrier-protected and diked/impounded coastal wetlands, particularly at vulnerable locations, such as Presque Isle and Long Point on Lake Erie, and along baymouth barriers enclosing Sodus Bay and Hamilton Harbour on Lake Ontario. Coastal wetlands and shorelines at Point Pelee, Hillman Marsh, Rondeau, and Long Point have been damaged and breached by wind-driven waves during high lake levels. Diked coastal wetlands in Lake St. Clair have also been degraded.

For many people across the Great Lakes region, lake ice is an integral part of life and contributes to a sense of place and identity (Briscoe, 2020a). For communities that rely on ice roads, ice cover provides mobility and access during the winter to essential resources such as food, gas, and other necessities. Ice cover is also important for winter recreational activities, such as snowmobiling and ice fishing. Declining ice cover can therefore result in the loss of essential transportation for some communities (see Box 7), and the loss of winter recreation and culture, as well as posing risks to people's safety when they travel on unsafe ice conditions. In recent winters, it has been reported that more than 200 people have been rescued, and over three dozen have died in ice accidents on the Great Lakes and nearby waterbodies.

BOX 7: THE ICE ROAD CONNECTING BAYFIELD AND MADELINE ISLAND IN LAKE SUPERIOR

Historically, lake ice forms across much of Lake Superior, creating an approximately 3-km (or 1.9-mi) ice road that bridges Bayfield, Wisconsin and Madeline Island (Briscoe, 2020a). This ice road provides free, year-round access for residents of Madeline Island to and from the mainland for food, gas, and other necessities. With declining lake ice cover, the ice road never formed in 2020. As a result, locals had to pay to take the ferry, which represents an additional cost of living. At the same time, the Madeline Ferry Line was losing money because ferrying a few passengers during the off-season is not enough to offset the cost of operation. To mitigate losses, the company added a winter surcharge, which in turn further increased the cost of transportation for residents of Madeline Island.

3.3 Impacts of Flooding, Erosion, and Storms

Flooding and erosion are already causing devastating impacts across the Great Lakes basin. On the western shores of Lake Michigan, for example, houses have begun to slip into the lake because of eroding coastal dunes (O'Connell, 2020b). The frequency and severity of flooding and erosion will likely increase under climate change, with more frequent and intense precipitation, earlier spring snowmelt, more precipitation falling as rain instead of snow, earlier ice breakup, and potentially more frequent extreme high water levels. Increased flooding and erosion can cause damage to infrastructure and property, pose risks to human health and safety, and impact people's mental health and well-being. Flooding and erosion can also increase the resuspension of contaminated sediments and increase the risk of waterborne diseases (Gagnon et al. 2019).

Recent high water levels across the Great Lakes have led to the flooding of homes, driveways, roads, and trails, as well as shoreline erosion, and the loss of beaches and vegetation (McNeil, 2019). Lake Ontario experienced a record-high water level in 2017 of 75.88 m IGLD85 (or 248.95 ft IGLD85), which was subsequently exceeded just two years later in 2019, with a new record of 75.92 m IGLD85 (or 249.09 ft) (IJC, 2019). Areas that were particularly impacted in both years include portions of Toronto Island, Clarington, Brighton, Prince Edward County, the Thousand Islands shoreline area, and the Bay of Quinte in Ontario, Canada (McNeil, 2019). Numerous states of emergency were declared across Canada and the U.S., and the resulting damages and necessary repairs have been costly (see Box 8 for examples of such costs). For residents and business owners along the Lake Ontario shoreline, the events of the past few years have not only brought significant financial impacts but also emotional and mental health impacts (O'Connell, 2020a). As more high and low water levels are anticipated across the Great Lakes under a changing climate, there is need to prepare for both high and low water level conditions (e.g. 2013 record-low water levels in Lake Michigan-Huron).

Erosion damage is not limited to buildings, bluffs, and dunes (Eng, 2019). It can also affect the lakebed by digging out the bottom of the lake, which in turn increases the risk of larger waves that can cause more erosion damage along the coast. In efforts to protect their properties against erosion and high waves, homeowners have erected their own barriers, but this piecemeal approach can exacerbate erosion of neighbouring properties.

More frequent and intense precipitation is also anticipated to increase storm-induced runoff and associated nutrients and contaminants. Land surface runoff from the Great Lakes drainage basin contributes approximately half of the supply of fresh water to the lakes (Cherkauer and Sinha, 2010). Nutrients can accumulate rapidly in a small number of intense rain events (Wuebbles et al. 2019). Agricultural runoff is a major threat to the Great Lakes, particularly to Lake Erie where agricultural runoff is estimated to account for up to 89 percent of the phosphorous entering the lake (US EPA, 2018). In urban watersheds, more than 60 percent of the annual load of all contaminants are transported during storm events (Patz et al. 2008). Several locations along Lake Ontario are particularly vulnerable to nutrient inputs, including the Bay of Quinte, Hamilton Harbour, and the Toronto Waterfront (Ontario Ministry of the Environment, Conservation and Parks, 2020). Increase in nutrient loading will likely lead to an increase in algal blooms, which negatively impact the health of the lakes and pose threats to drinking water (see Section 3.1). Heavy precipitation can also increase combined sewer overflows, leading to the release of untreated sewage into the lakes, which lead to higher levels of E. coli bacteria (a public health threat), and beach closures (Patz et al. 2008; Wuebbles et al. 2019).

Island Flooding - Toronto Ontario

BOX 8: EXAMPLES OF THE COSTS ASSOCIATED WITH FLOODING, EROSION, AND STORMS

- In 2017, the direct and indirect damages to the City of Toronto, Ontario, due to the closing of Toronto Island Park as a result of high lake levels were estimated to be CA$8 million (McNeil, 2019).
- In 2018, flooding and erosion from spring storms caused CA$3.5 million in damage to 400 homes and cottages between Point Pelee and Wheatley in Ontario (Baxter, 2019).
- In 2019, following recent high water levels on Lake Huron, the Town of Goderich, Ontario, is spending CA$1.5 to 2 million to protect its treatment plant for drinking water, which is located less than 30 m (or approximately 98 ft) from the water's edge (Lupton, 2019).
- A group of Great Lakes mayors has estimated that in 2019, high water levels, flooding, and erosion have caused US$500 million worth of damage in cities throughout the region (O'Connell, 2020b).
- In 2019, the City of Grosse Pointe, Michigan, spent more than US$100,000 to address problems associated with high water levels on Lake St. Clair (Gray, 2020). Another US$50,000 is needed to fix an eroded stormwater outlet into the lake, and a project to reconstruct a seawall damaged by high water levels is expected to cost up to US$12 million.
- In 2020, nine Michigan communities adjacent to Lake Michigan anticipate that US$30 million in projects are needed to address the erosion caused by high water levels (Gray, 2020).

3.4 Impacts on Industries and Livelihoods

The industries and people who rely on the Great Lakes can also be affected by changing climate conditions within the Great Lakes basin. These include impacts to shipping, hydropower production, commercial, recreational and subsistence fishing, agriculture, tourism, and recreation (Hartmann, 1990; Wuebbles et al. 2019).

The Great Lakes/St. Lawrence Seaway serves as a major transportation system and is one of the busiest shipping areas in the world. Shipping can be impacted by both low and high water levels. Low water levels can lead to unsafe conditions for shipping and navigation, especially in the shallower portions of the Great Lakes' channels and harbours. More trips will likely be required in order to move the same amount of cargo, increasing shipping costs and traffic. The dredging of harbours and channels may also be required, which already costs approximately US$20 million per year (Bartolai et al. 2015). High water levels can produce faster moving water in portions of the Seaway that also present unsafe conditions for shipping (Great Lakes-St. Lawrence River Adaptive Management [GLAM] Committee, 2018). This occurred in Lake Ontario during the 2017 high water levels where record outflows of up to 10,400 m3/s (or 367,272 ft3/s) were observed. Any impacts to the shipping industry will have direct impacts on other industries that depend on the Great Lakes for transport (e.g. iron, steel, and grain; Hartmann, 1990).

Lake waters are extensively used for hydropower production. In Ontario, the Great Lakes help generate 80 percent of Ontario's electricity (Ontario Ministry of the Environment, 2016). In the Midwest U.S., most energy production infrastructure are located along waterways (Wuebbles et al. 2019). The Great Lakes provide water for hydropower production as well as the water needed to cool power plants. With more frequent extreme low water levels and warmer water temperatures, less water is available for hydropower production and water levels could more frequently drop below water intake levels. Increased water temperatures also reduce their effectiveness for cooling power plants. As current energy infrastructure has been designed and built based on historical water levels and temperature regimes, changing climate conditions could potentially interrupt or decrease regional power generation.

Freight ship entering the Welland Canal via Lake Ontario, St Catharines Ontario Canada

Commercial, recreational, and subsistence fishing can be affected by the impacts of climate change on fish species and populations, such as the loss of coldwater and coolwater habitats, increase in algal blooms and dead zones, loss of safe breeding/spawning habitats, and increase in invasive species. For some, the loss of opportunities to harvest coldwater fish species may be offset by increased opportunities to harvest warmwater species (Alofs et al. 2014, 2015; Dove-Thompson et al. 2011). However, for many Indigenous peoples, the decline of some fish species can impact their livelihoods and way of life, as well as traditional knowledge, food, and culture (Wuebbles et al. 2019; Briscoe, 2020b). For example, the fishing communities of Saugeen First Nation and Chippewas of Nawash are finding that higher winds, loss of ice cover, and warmer temperatures are affecting populations of lake whitefish in Lake Huron and Georgian Bay, which many rely on for their livelihoods (Johnson, 2019).

Climate change can have both positive and negative impacts on agriculture, which accounts for a third of the basin's land use (Wuebbles et al. 2019). A longer growing season would be beneficial to agriculture. However, these benefits may be offset by more extreme weather events, more variable precipitation, and an increase in pests and diseases. For example, the range of the bean leaf beetle, a pest for soybeans, already appears to be shifting northward (Kling et al. 2003). Additionally, increased evapotranspiration during the growing season may reduce water stored in the landscape, increasing soil moisture deficits in the fall, as well as demand for irrigation (Wuebbles et al. 2019).

Climate change may also bring positive and negative impacts on tourism and recreation. For example, more frequent extreme high and low water levels can limit recreational opportunities such as boating and canoeing. Warmer winters and less snow and ice conditions on average will result in fewer opportunities for winter recreation, including skiing, snowmobiling, snowshoeing, and ice fishing. Although opportunities for warm weather recreation may increase, the loss of traditional cold-weather recreation is a loss in way of life and culture for many. Communities that depend on winter recreation and related tourism will likely be significantly impacted. Impacts on nature attractions such as beaches, ice caves, and parks can further impact tourism (Dawson and Scott, 2010; Briscoe, 2020a).

3.5 Impacts on Ecosystems and Biodiversity

Climate change can impact plants and animals across the Great Lakes basin, from species abundance, distribution, genetic composition, behaviour, and survival. Changing seasonal patterns can affect breeding, spawning, and other behaviours. For example, in Lake Erie, greater variability in spring warming has been associated with more variability in spring spawning species such as walleye (Wuebbles et al. 2019). Changes to one species can impact another through species interactions and dependencies (e.g. predator and prey relationships; Dove-Thompson et al. 2011).

With climate change, habitat ranges will likely continue to expand for some plant and animal species as warming continues, while ranges shrink or shift northwards for others. For example, smallmouth bass have historically been limited in their northern distribution due to colder temperatures (Alofs et al. 2014, 2015). However, with warmer water temperatures and longer ice-free season, populations of smallmouth bass have proliferated. As voracious predators, their expansion has reportedly led to the reduction of more than 25,000 populations of northern redbelly dace, finescale dace, fathead minnow, and pearl dace throughout lakes in Ontario. With warmer surface waters and reduced ice cover, shallow water habitats in many of the Great Lakes have also become more suitable for invasive species (e.g. carp, round goby, quagga mussel, and zebra mussel; Taylor et al. 2006).

The distribution of forests will also likely change as warmer temperatures lead to the shrinking of boreal forests, and the northward shift of many tree species (e.g. birch, aspen, balsam fir, and black spruce) that will likely be replaced by more southerly species (Great Lakes Integrated Sciences and Assessments [GLISA], 2014). Currently, forest cover makes up approximately 60 percent of land cover within the basin and forms an important part of the Great Lakes ecosystem (Bartolai et al. 2015). As temperatures warm and as the distribution of forests changes, pests and diseases (e.g. LDD moth) are also anticipated to increase, posing further threats to the health of trees and forests across the basin (Kling et al. 2003).

Climate change also poses threats to coastal wetlands, which provide essential habitat for a large variety of plants and animals (Mortsch, 1998; Wuebbles et al. 2019). Over half of all Great Lakes fish species use wetlands for spawning and nursery habitat. It has also been reported that 30 species of waterfowl, 155 breeding bird species, and 55 species of reptiles and amphibians are supported by coastal wetlands across the basin. Coastal wetlands are particularly vulnerable to changing climate conditions and water levels. For example, open shoreline wetlands are vulnerable to high water levels and storm surges that lead to erosion of protective sand spits and bars at barrier-protected wetlands, and loss of wetland habitat. Low water levels can lead to the shrinking of wetlands and reduce hydraulic connectivity. Coastal wetlands are also being affected by coastal erosion.

For example, it has been reported that more than 160 hectares of coastal wetlands have disappeared in Rondeau Bay in Chatham-Kent, Ontario, due to the eroding barrier beach (Zuzek, 2020). Currently, ECCC is undertaking a study to assess coastal wetland vulnerability and enhance wetland resilience through adaptation. The vulnerability assessment will provide a better understanding of the climate-related impacts on coastal wetlands and recommend adaptation strategies and actions for enhanced coastal wetland resilience. These results and recommendations will be made available when the study is completed in 2022.

4.0 Looking Ahead

If climate change continues at its current pace, the Great Lakes will be very different by the time our children and grandchildren grow up.

By the end of the century, the climate, water levels, and ice cover over the Great Lakes are anticipated to change significantly.

Over-land air temperatures are expected to increase significantly across the basin compared to 1961-2000. The greatest temperature increases are projected for the fall and winter seasons. Changes in average over-land air temperatures are expected to bring warmer winters, more extreme heat, a longer growing season, heavier precipitation, and less ice cover. The greatest increases in over-land air temperatures are expected for lakes Superior and Michigan-Huron.

Over-lake precipitation is anticipated to increase in all seasons and over the year under both climate scenarios for all lakes, although the increase is generally less in the summer season. Changes in seasonal over-lake precipitation is anticipated to vary by lake and climate scenario. With warmer winters, snowfall is expected to decrease on average, with more precipitation falling as rain instead of snow. The greatest increases in over-lake precipitation are expected for lakes Superior and Ontario.

Lake levels are anticipated to increase in variability as the climate changes, with more extreme high and extreme low values becoming possible with greater changes in global average temperatures. Lake level projections indicate significant deviations from lake-specific, long-term averages (1918-2019) across the basin with a slight upward trend on all lakes apparent in the latter half of the century. Lake Michigan-Huron is expected to experience the greatest variation in lake levels and has historically been the most variable among the Great Lakes (Wuebbles et al. 2019). Lakes Erie, St. Clair, and Ontario are also expected to see significant variations in lake levels.

Ice cover is expected to decline across all lakes, especially in the months of February and March under the high-emissions scenario. In the future, there may be more years with little to no ice cover and shorter ice seasons during winter and spring. Average ice cover over lakes Superior and Erie show the greatest projected declines, followed by Lake Huron. Ice growth may also peak earlier for deeper lakes such as lakes Superior and Huron.

Changes to the climate system over the Great Lakes basin can cause wide-ranging environmental, social, and economic impacts. These impacts are cumulative, compounding, and interactive, which can in turn lead to even more severe consequences. Based on the climate projections and impacts discussed in Sections 2.0 and 3.0, the following are key climate change risks identified for the Great Lakes basin that could be considered by resource managers to help reduce the negative impacts of climate change and build climate resilience. These include:

- More frequent extreme high and low water levels
- Increase in flooding and erosion
- More variable and intense precipitation
- Increase in storm-induced runoff carrying nutrients and contaminants into the lakes
- Increase in combined sewer overflows
- Increase in extreme weather events
- More toxic and non-toxic algal blooms and dead zones
- Increased stress on drinking water infrastructure
- Increase in unsafe ice conditions for travel and recreation
- Increase in the resuspension of contaminated sediments that can accumulate up the aquatic food chain
- Increase in invasive species, pests, and diseases
- Potential for reduced or interruptions to shipping and hydropower generation
- Loss of cold/coolwater fish species habitat
- Loss of wildlife habitat (e.g. breeding, spawning, and nursery), including essential habitats such as coastal wetlands
- Loss of Indigenous traditional ways of life
- Loss of sense of place and identity
- Loss of livelihoods and local economic drivers

This list is not intended to be exhaustive but rather to highlight important risks that could serve as a starting point to make informed decisions on adaptation planning.

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Rocky Cliff Overlooking Lake Superior

Appendix A: Detailed Description of the Methodology Used by Environment and Climate Change Canada to Develop the Climate and Water Level Projections

As noted in Box 1, this Appendix provides a more detailed summary of the methodology used by Environment and Climate Change Canada (ECCC) to develop the climate and water level projections included in this report. The information presented in this summary is based on a report by Seglenieks and Temgoua (2021, in review).

The modelled climate data used by ECCC came from the Coupled Model Intercomparison Project Phase 5 (CMIP5), which were available from NA-CORDEX, the North American component of the International Coordinated Regional Downscaling Experiment program sponsored by the World Climate Research Program (WCRP). These datasets are based on dynamically downscaled future climate simulations driven by Global Climate Models (GCMs).

Downscaling refers to the process of deriving higher resolution, regional climate data from GCMs, which divide the earth up into large grid cells that are often larger than 100 km by 100 km. Dynamic downscaling is one of two types of downscaling, which produces what is known as Regional Climate Models (RCMs). This involves running a high resolution model over a smaller area of interest, rather than the entire globe, to derive simulations on a scale of tens of square kilometres. Since the climate over the area of interest is influenced by processes outside the boundaries of that area, RCMs rely on GCMs to simulate the boundary conditions for the area of interest. At this higher resolution, RCMs offer better representation of the Great Lakes and most are able to capture lake processes, such as lake evaporation.

Statistical downscaling is the other type of downscaling, which relies on an understanding of the historical relationships observed between local climate variables (e.g., precipitation) and large-scale variables (e.g., atmospheric pressure). Mathematical equations are used to define these statistical relationships that have been observed historically and these equations are then applied to projections from GCMs to derive local climate projections.

NA-CORDEX was the only known source of RCM data that was publicly available at the start of ECCC's coastal wetland vulnerability assessment project that had the necessary variables and temporal resolution to accurately calculate water levels. Seven RCMs were included as part of the NA-CORDEX project, and each RCM was driven by a subset of the 6 GCMs. Among these RCMs, ECCC selected ones that had over-lake precipitation, basin temperature, and lake evaporation output available. As a result, 13 RCM-GCM combinations were included in ECCC's study (see Table A-1). Most of these RCMs use a one-dimensional lake model called FLake, which helps to derive more realistic simulations of lake dynamics compared to the absence of any lake model.

Table A-1: List of RCM-GCM Combinations and Associated Details

NO.	RCM	GCM	SCENARIO	RESOLUTION	LAKE MODEL
1	CRCRM5	CanESM2	RCP 4.5	0.22° X 0.22°	FLake
2	CRCRM5	CanESM2	RCP 8.5	0.22° X 0.22°	FLake
3	CRCRM5	CNRM-CM5	RCP 4.5	0.22° X 0.22°	FLake
4	CRCRM5	CNRM-CM5	RCP 8.5	0.22° X 0.22°	FLake
5	CRCRM5	GFDL-ESM2M	RCP 4.5	0.22° X 0.22°	FLake
6	CRCRM5	GFDL-ESM2M	RCP 8.5	0.22° X 0.22°	FLake
7	CRCRM5	MPI-ESM-LR	RCP 8.5	0.22° X 0.22°	FLake
8	CanRCM4	CanESM2	RCP 4.5	0.22° X 0.22°	None – prescribed from driver
9	CanRCM4	CanESM2	RCP 8.5	0.22° X 0.22°	None – prescribed from driver
10	RCA4	CanESM2	RCP 4.5	0.44° X 0.44°	FLake
11	RCA4	CanESM2	RCP 8.5	0.44° X 0.44°	FLake
12	RCA4	Earth_SMHI	RCP 4.5	0.44° X 0.44°	FLake
13	RCA4	Earth_SMHI	RCP 8.5	0.44° X 0.44°	Flake

Lake level projections were developed based on the following factors, including the Net Basin Supply (NBS) of each lake, the inflow of water from the upstream lake, and the outflow to the downstream lake. The NBS refers to the net volume of local water supply coming into each lake. One way of calculating the NBS is by taking the sum of total over-lake precipitation and runoff into the lake from its surrounding drainage basin, and subtracting the evaporation from the lake (or over-lake evaporation). This is known as the component NBS. Each of the three components of the NBS were calculated separately for each lake and then combined into a single NBS for each lake.

Data for both over-lake precipitation and over-lake evaporation were taken directly from the datasets available from the NA-CORDEX study. Over-lake precipitation refers to precipitation that falls on the lake's surface. Meanwhile, over-lake evaporation refers to the amount of evaporation from the lake's surface.

The use of a hydrological model was necessary in order to determine runoff into the lake from its surrounding drainage basin. Runoff into the lake refers to the sum of water flowing into the lake from all of its surrounding rivers, excluding water from the upstream lake if there is one. While the RCMs provided runoff from each grid cell of the RCM, there is no direct calculation of the amount of flow into each lake. Hence, ECCC used a hydrological model called, WATFLOOD, to calculate runoff into each lake, which is able to route the flow from each grid cell down the river network and into each connecting lake to ensure proper timing of the runoff. This model has been used successfully in the Great Lakes for many years and there is an established method to calculate runoff into each of the Great Lakes. It uses hourly temperature and precipitation data as input to calculate the separation of runoff into surface runoff, interflow, and baseflow. The temperature and precipitation data that were used in the hydrological model were available from the NA-CORDEX project.

The Coordinated Great Lakes Routing and Regulation Model (CGLRRM) was used to calculate the lake levels and flow of the connecting channels for the upper lakes (i.e., Lake Superior to Lake Erie). The CGLRRM uses the NBS for each lake as input and considers the regulation of Lake Superior outflows in calculating the flow from connecting channels. This model has shown good results in simulating historical lake levels and flows when run with historical NBS. In order to calculate the connecting channel flow, the CGLRRM makes assumptions about the conveyance of these channels. As the effects of climate change on the conveyance of connecting channels are unknown, it was assumed that the channels would remain stable and that conveyance relationships would be constant throughout all simulations.

For Lake Ontario, a separate regulation plan simulation model was used to calculate outflow from Lake Ontario based on the current regulation plan – Plan 2014. This model has been developed by ECCC and considers the flow of the Ottawa River and other tributaries that enter the St. Lawrence River downstream of Lake Ontario.

As noted in Section 2.3, some projections for Lake Ontario under two RCP 8.5 models resulted in extremely high values due to the potential over-exaggeration of water accumulation from all Great Lakes flowing into Lake Ontario in the future and therefore have been excluded from our analysis. These extreme values have been excluded because it is impossible to anticipate what actions might be taken to alter flows out of the system if extremely high inflows were to occur in Lake Ontario in the future. The excluded values were from the following two RCM-GCM combinations:

1. CRCRM5-GFDL-ESM2M (November 2060 to the end of 2095) – number 6 in Table A-1
2. CRCRM5-MPI-ESM-LR (December 2066 to the end of 2095) – number 7 in Table A-1.

It is important to remember that projections of climate parameters and lake levels are based on current understanding of the climate system and assumptions made about the future behaviour of society, which will result in the amount of carbon that will be put into the atmosphere. There are many uncertainties and assumptions that are inherent in these projections and thus the projections are most useful in showing general trends of what could happen in the future.

A Note on Bias Adjustment

Bias correction was performed by ECCC for the following variables: over-lake precipitation, over-lake evaporation, runoff, and NBS. Bias correction refers to the process of adjusting simulated data to improve fit against observed data. It is well accepted that bias correction needs to be done in hydrological studies in order to obtain realistic output. However, it is important to note that the bias-corrected data is not meant to perfectly mimic the reference data over the specified time period, rather it is designed to have the same overall characteristics as the reference data.

Bias correction was performed on projected over-lake precipitation, over-lake evaporation, and runoff because the RCMs will typically show bias for some variables and time periods. ECCC used a multivariate bias correction function and selected the time period of 1961-2000 as the reference historical period because it captures both wet and dry conditions while not overlapping with ramp-up periods used in the climate projections (i.e., 2006-2095), which could skew comparisons. For each individual dataset, the bias correction was completed for the current climate and then applied for the future climate. This is based on generally accepted practice whereby the bias in the simulation of the current climate is assumed to be the same in the simulation of the future climate.

Bias correction was also performed on future NBS. This was done by using another method to calculate the NBS, known as residual NBS. The residual NBS is determined based on the change in water level and the difference between the incoming flow and the outgoing flow. As these levels and flows are based on measured values, they have lower uncertainty than the different components used to determine component NBS (i.e., over-lake precipitation, runoff into the lake, and over-lake evaporation). The residual NBS is therefore generally considered to have lower uncertainty than the component NBS, and while the two methods calculate the NBS differently, their resulting values should be the same. Hence, the coordinated residual NBS was used as the reference dataset to bias-correct the future component NBS that has been calculated based on simulation data.

Appendix B: Detailed Description of the Methodology Used by the Nelson Institute Center for Climatic Research to Develop the Ice Cover Projections

As noted in Box 1, this Appendix provides a more detailed summary of the methodology used by the Nelson Institute Center for Climatic Research (CCR) to develop the ice cover projections included in this report. The information presented in this summary is based on peer-reviewed articles by Notaro and others (2015; 2016).

The modelled climate data used by CCR also came from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Simulations from six GCMs were dynamically downscaled according to RCP 8.5 using one RCM – RegCM4 (see Table B-1). RegCM4 has a resolution (or a "grid cell") of 25 km by 25 km and was interactively coupled with a one-dimensional energy-balance lake model and lake ice submodel to produce ice cover projections (among other variables) that capture the dynamics of the Great Lakes.

Table B-1: List of RCM-GCM Combinations and Associated Details

NO.	RCM	GCM	SCENARIO	NOTES
1	RegCM4	ACCESS1-0	RCP 8.5	Leap year included
2	RegCM4	CNRM-CM5	RCP 8.5	Leap year included
3	RegCM4	GFDL-ESM2M	RCP 8.5	Adjusted to incorporate leap years
4	RegCM4	IPSL-CM5-MR	RCP 8.5	Adjusted to incorporate leap years
5	RegCM4	MIROC5	RCP 8.5	Adjusted to incorporate leap years; Missing data for 1989
16	RegCM4	MRI-CGCM3	RCP 8.5	Leap year included

The RCM outputs ice thickness for each lake grid cell. When ice thickness is 2 cm or more, 100 percent of ice cover was assumed for that grid cell. Otherwise it was set to 0 percent. Downscaled daily percentage lake ice cover was produced for three time periods: 1980-1999, 2040-2059, and 2080-2099. Given the volume of daily data, the time periods only cover 20 consecutive years. Only data from December to May was analyzed in this report, which represents the typical ice season across the Great Lakes.

A Note on Bias Adjustment

Bias adjustment was performed by the Ontario Climate Consortium (OCC) as the RCM-lake model used in the downscaling process tends to produce excessive ice cover. A simple delta change method was used by adding the difference between the observed historical and modelled historical data to modelled future data. This is again based on the generally accepted practice whereby the bias in the simulation of the current climate is assumed to be the same in the simulation of the future climate.

The delta change method was applied at the monthly scale. Monthly means between 1980-1999 were calculated for the six RCM-GCM simulations and the observed historical data obtained from NOAA-GLERL. The delta was calculated by taking the difference between the observed historical and modelled historical data for each of the six RCM-GCM combinations. These monthly deltas were then added back to the aggregated monthly modelled data (for both historical and future). When the percentage lake ice cover was a negative value, 0 percent ice cover was assumed.

The length of the ice season between December and May was calculated for each year using daily ice cover data. The annual length of the ice season was then aggregated over the three periods, covering 1981-1999, 2041-2049, and 2081-2099. The years 1980, 2040, and 2080 were not included because December data from the previous year was either not available for the modelled data (i.e. December 2039 and December 2079) or not included for the observed data for consistency (i.e. December 1979).

The same delta change method was applied to the average length of the ice season for the two future periods. The delta was calculated by taking the difference between the observed historical average length of the ice season and the modelled historical average length of the ice season for each of the six RCM-GCM combinations. The deltas were then added back to the modelled future average length of the ice season for 2041-2049 and 2081-2099. When the average length of the ice season was negative, 0 days was assumed.

Waves of Lake Huron at Kincardine, Ontario, Canada on a sunny fall day