


The background of the cover is a photograph of a lake. In the foreground, there are large, dark, wet rocks. The water is calm with some ripples. In the distance, a city skyline is visible across the water under a hazy sky. A blue wavy line separates the top image from the text area.

Lake Ontario Prospective

A Summary of Anticipated Future Climate and Lake Level Conditions

Great Lakes Integrated Sciences and Assessments (GLISA)
September 2022

A close-up photograph of a rocky shoreline. The rocks are covered in green and yellow algae. The water is dark and has some white foam from a wave. A blue wavy line separates the text area from the bottom image.

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a Summary of Anticipated Future Climate and Lake Level Conditions

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Alex Cannon, Environment and Climate Change Canada
Steve Clement, Environment and Climate Change Canada
Jennifer Day, National Oceanic and Atmospheric Administration
Jenessa Doherty, Environment and Climate Change Canada
John Haugland, Environmental Protection Agency
Shaffina Kassam, Environment and Climate Change Canada
Doug Kluck, National Oceanic and Atmospheric Administration
Sharon Lam, Toronto and Regional Conservation Authority
Glenn Milner, Climate Risk Institute
Biljana Music, Ouranos
Michael Notaro, University of Wisconsin
Frank Seglenieks, Environment and Climate Change Canada
Ram Yerubandi, Environment and Climate Change Canada

GLISA Contributors

Kim Channell
John DelPizzo
Laura Briley
Richard Rood
Jenna Jorns
Kate Hutchens

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Table of Contents



1.0 Impacts of Changing Climate Trends on the Great Lakes	1
1.1 Lake Temperature and Ice Cover	1
1.2 Stratification, Algal Blooms, and Hypoxia	2
1.3 Meteorology	2
1.4 Species and Habitats	3
1.5 Water Levels	3
2.0 Future Climate Projections	5
2.1 Climate Modeling in the Great Lakes	5
2.2 Model Choice	5
2.3 Bias Implications.	6
3.0 Analysis of Future Climate Projections for Lake Ontario.	7
3.1 Air Temperature.	8
3.2 Net Basin Supply and its Components.	9
3.3 Lake Levels	10
4.0 Uncertainty and Bias Considerations	12
4.1 Understanding Model Bias	12
4.2 Bias Analysis of Ensemble Results.	13
5.0 Considerations for Decision Making	15
5.1 Future of Great Lakes Climate Modeling	15
5.2 Scenario Planning as a Complementary Approach	15
6.0 Concluding Statements.	18
References	19
Appendix.	25
A1: Ensemble of NA-CORDEX Projections Utilized in This Report	25
A2: Representative Concentration Pathways (RCPs)	27
A3: Climate Model Biases.	28

Summary and Overview



The Great Lakes Water Quality Agreement ([Agreement](#)) is a commitment between the governments of the United States and Canada. First signed in 1972 and most recently amended in 2012, the two countries have coordinated to advance protection and restoration of the Great Lakes for 50 years. Promoting research and advancing the understanding of and communicating about climate change impacts was added to the Agreement with the 2012 amendments as [Annex 9: Climate Change Impacts](#). This Lake Ontario summary, along with similar reports for each of the five lakes, and their [retrospective counterparts](#), were developed to mark the 50th anniversary of the signing of the Agreement in 1972 and provide an overview of future climate trends and impacts for each lake and its basin. These reports were created through Annex 9 to serve the work being done by the [other annexes](#) of the Agreement (in particular the Lakewide Action and Management Plans or LAMPs), and by natural resources managers and decision makers across the Great Lakes region.

Given the effects of climate change on lake temperatures, ice cover, and many other variables, the physical dynamics of the lakes are not the same today as they were in decades past, nor will they be the same in the future. Climate models can be a helpful tool in identifying important information about direction change and estimated magnitude of future trends. Each lake-specific prospective report includes an overview of impacts in the basin, and utilizes a multimodel ensemble of climate model simulations to analyze future projections for lake levels, overlake precipitation, air temperature, evaporation, and runoff. The report also examines uncertainty and model biases, so that potential users can make an informed decision about utilizing these results in their applications.

The projections utilized in this report indicate the following changes for Lake Ontario:

- Basin **air temperature** is projected to continue rising in the future, particularly in the winter.
- Increases in **precipitation** are anticipated year-round.
- Springtime increases are anticipated for **runoff**.
- **Evaporation** is projected to increase in the fall and early winter and decrease in the summer.
- Increased variability in **lake levels** is anticipated, with increased potential for individual years to surpass historical record extremes.

1.0 Impacts of Changing Climate Trends on the Great Lakes

The Great Lakes region has already begun experiencing the effects of a changing climate, including increased annual and extreme precipitation, warming air and lake temperatures, and declining lake ice coverage. The results discussed in [Section 3.0](#) project a continuation of these trends into the future, amplified by further warming. To put these projected changes into perspective, this section will detail the wide-ranging societal, economic, recreational, and environmental impacts that these trends already have on the Great Lakes region as a whole, with a few examples from the Lake Ontario basin.

1.1 Lake Temperature and Ice Cover

Following the trend of increasing air temperature, Lake Ontario summer lake surface temperatures increased by an average of 1.6°C (2.9°F) between 1968 and 2002 (Dobiesz and Lester 2009). This can be partially attributed to earlier spring ice melt which allows for longer periods of lake stratification and more exposure to solar radiation (McCormick and Fahnenstiel 1999). Warming surface temperatures affect ecosystems, biodiversity, lake stratification, and ice cover.

Warmer lake surface temperatures can lead to delays and declines in lake ice formation during the winter months. Lake Ontario and the Great Lakes have all had less ice cover on average during the last 20-30 years compared to earlier years, prior to the 1990s (Mason et al. 2016, Van Cleave et al. 2014). However, there remains strong year-to-year variability, meaning that years with very little ice and years with a lot of ice are still possible.

There is strong evidence to suggest that the Great Lakes region will continue experiencing warming air temperatures into the future, especially during winter (Pryor et al. 2014). How the Great Lakes will respond to this warming is less certain. In a warming world, there is less potential for large amounts of ice cover, but there are many forces at play

(e.g., cold arctic air blasts) that can still usher in winters of extreme cold, potentially leading to unprecedented high seasonal mean ice cover. Predicting specific weather drivers, like the El Niño-Southern Oscillation (ENSO) and Arctic Oscillation (AO), that affect weekly to seasonal temperatures in the Great Lakes Region is also very challenging. Practitioners should prepare for increased variability – high ice cover years followed by low ice cover years, and vice versa. Ice will continue to form first where it always has, in protected areas near the shore, but it may not persist for as long (Barnes and Polvani 2015).

This increase in interannual ice cover variability and overall decline of ice cover impacts regional recreation, shipping and navigation, and lake ecosystems. Ice cover provides protection for certain fish species and wetlands, it serves as a platform for ice fishing, snowmobiling, ice caves, and other winter recreation, and provides access to necessities for communities that rely on ice roads (Borunda 2020, Briscoe 2020). Years with low ice (and snow) cover can lead to declines in winter tourism activities and previously-reliable revenue for the surrounding region (Burakowski and Magnusson 2012, Chin et al. 2018, Dawson and Scott 2010). Less ice cover can also leave shorelines exposed and more susceptible to erosion during high wind and wave events of winter storms (Mackey et al. 2012). Such conditions have already caused millions of dollars in damages to shoreline communities around Lake Ontario (McNeil 2019, Duffy 2020). The amount and timing of ice cover formation also heavily impacts the shipping industry; with a shorter ice season, the shipping season can operate longer and/or start earlier (Millerd 2011). The shipping industry cannot, however, rely on such conditions year-to-year, and should plan for increased variability between ice years.

Ice cover is also tied to water levels due to its relationship with temperature and evaporation. Ice acts as a reflector for incoming solar radiation that prevents additional warming of the lake. Water temperatures at the start of



Ice cover on Lake Michigan-Huron. Photo by Dan Brown

the fall season determine the magnitude of evaporation from the lake surface, which has a cooling effect on the water and leads to higher amounts of ice cover (Spence et al. 2013, Van Cleave 2012, Lenters et al. 2013). The temperature difference between the cold fall air and warm lake surface water accelerates evaporation, particularly when coupled with the strong winds that occur in the fall and early winter. Evaporation removes latent heat from the surface, resulting in a cooling of the surface, and the potential for greater ice cover. For the northern lakes, ice cover strongly influences the timing of surface layer warm-up (stratification) of the lakes the following spring (Austin and Colman 2007). Changes in the amount and duration of ice cover can therefore impact the magnitude and timing of seasonal water level fluctuations.

1.2 Stratification, Algal Blooms, and Hypoxia

During the winter months, colder layers of lake water become stratified into separate layers that have very little mixing. During the spring, the seasonal warming of the lake begins a process of overturning, or mixing of these different layers, which allows nutrients to mix between different layers of the lake. In the Great Lakes, warming surface water temperatures, and earlier spring warming are causing stratification to occur earlier and last longer (Kling et al. 2003, Hondzo and Stefan 1993, McCormick and Fahnenstiel 1999). When nutrients like phosphorus runoff into the lake from surrounding agricultural lands and then sit in warm surface waters, algae can feed and grow, forming algal blooms. With more stratification and warmer water temperatures, those nutrients stagnate in the warm surface waters where algae then feed and grow out of control to form harmful algal blooms (HABs). More rainfall, and specifically earlier shifts in spring rains and

increases in extreme rain events, increase runoff from farmland, which then increases phosphorus loading in the lakes (Scavia et al. 2014; Michalak et al. 2013). HABs use up dissolved oxygen in the water, creating hypoxic dead zones where fish cannot survive, and putting further stress on biomass productivity in the lake and wetlands (Michalak et al. 2013).

These effects of HABs have a damaging impact on fishing, recreational boating, and drinking water supply. Algal blooms have been occurring for many years, but the factors that lead to their formation are enhanced by regional changes in temperature and precipitation, as described above. They have been a persistent problem for warm, shallow bodies of water like Lake Erie and the U.S. Gulf Coast, but HABs now occur annually in Lake Ontario, particularly in Sodus Bay, Bay of Quinte, and Hamilton Harbor (Carmichael and Boyer 2016). With lake temperatures and rainfall expected to continue increasing into the future, more frequent occurrences of the conditions needed for HABs formation is anticipated (Michalak et al. 2013).

1.3 Meteorology

The Great Lakes play an integral role in the climate and meteorological conditions of the region, from regulating air temperature to serving as a large source of moisture for storm systems. Warming air holds more water vapor and contributes to increases in annual precipitation and extreme precipitation events (Grover and Sousounis 2002). Lake effect snow in the region has increased in the recent decades, in part due to a combination of warmer lake temperatures and less ice cover (Burnett et al. 2003). In a warmer, more open lake, more moisture can be picked up by cold air masses as they move across the lake, producing more lake effect snow on the other side. Outside of the lake effect zones, the basin has seen declines in snowfall as rising winter temperatures mean that more of winter's precipitation falls as rain. The trend of increasing lake effect snow is expected to shift to a decreasing trend in the future, when higher winter temperatures will cause it to shift to lake effect rain more frequently (Notaro et al. 2015). The Lake Ontario basin could also see shifts to earlier spring snowmelt, given the seasonal temperature increases. This could lead to earlier runoff into the lakes, potentially affecting the timing of the spring high water level peak.



Snow on the coast of Lake Superior. Photo by Dan Brown



Sandpiper. Photo by Dan Brown

1.4 Species and Habitats

The Great Lakes already face threats to biodiversity of fish, plants, and other wildlife from rising invasive species. Invasive species such as the zebra mussel, sea lamprey, and alewives cause habitat degradation to native Great Lakes species by outcompeting them for essential nutrients and food (Taylor et al. 2006, Madenjian et al. 2008). The effects of climate change further amplify ecological and biological impacts, from increased likelihood of hypoxic conditions from algal blooms, declines in ice cover that protects wetlands and breeding zones, and changing thermal conditions affecting lake habitats (Wuebbles et al. 2019, Mortch 1998). Rising basin air temperatures and lake surface temperatures diminish the available habitat for certain cold water fish species (Dove-Thompson et al. 2011, Alofs et al. 2014, 2015). Changing temperature, precipitation, and seasonal conditions contribute to northward shifts in species of mammals, birds, fish, and plants as their habitats become less suitable (Parmesan and Yohe 2003, Woodall et al. 2009).

Changes to the length and severity of winter conditions in the region impact the timing and extent of seasonal migration for several species of birds (Notaro et al. 2016). Warming winter air temperatures, decreases in snowfall, and decreases to the length of the ice season all contribute to shifts in the timing of migration patterns of birds, with earlier south-to-north migration and later north-to-south migration (Schummer et al. 2010). Bird migration routes will shift more northward with changing temperatures (Notaro et al. 2016).

1.5 Water Levels

Lake levels fluctuate based on the opposing dynamics of how much water enters the lake versus how much water leaves the lake. The main drivers are precipitation, evaporation, and runoff, which make up the lake's net basin supply (NBS). Any future changes in lake levels will depend on how one or more of these competing physical processes will balance another. There will still be periods of highs and lows in the future, with climate-driven changes to the hydrologic cycle influencing those fluctuations. As with ice cover, practitioners should prepare for increased variability in water levels on Lake Ontario: higher highs, lower lows, and potentially more rapid shifts between high and low than were observed in the past (Gronewold and Rood 2019).

Low water levels, high water levels, and rapidly fluctuating water levels all have unique impacts on a range of sectors in the Great Lakes region. Issues in shipping and navigation arise during periods of low water levels, as some ships are too large or deep to travel in certain areas (Wang et al. 2012). For every inch of water level decrease, cargo capacity on freighters decreases by several hundred tons and tens of thousands of dollars in daily shipping profits per ship (Marchand et al. 1988). Recreational boating can also be adversely affected by low water levels, particularly in already shallow areas (Buttle et al. 2004). Low water conditions increase the need to dredge marinas and canals to make them usable and safe (Changnon 1993, Bartolai et al. 2015). Hydropower electricity

generation is also vulnerable to low water levels; slower water movement turns generator turbines more slowly, and thus weakens the capacity to generate electricity (Buttle et al. 2004, Hartmann 1990).

Periods of high water levels contribute to shoreline flooding and coastal erosion, particularly during high wind and wave events (Mackey et al. 2012, Bartolai et al. 2015). Damage from these events spans residential properties, public shorelines, private and public docks, breakwaters, bridges, shoreline trails, public beaches and parks, roads, and other infrastructure, causing hundreds of millions of dollars in damages across the Great Lakes region (McNeil 2019, Flesher 2021). Large ships navigating narrow channels during periods of high water levels also run a higher risk of causing shoreline erosion damage from the waves they generate (GLAM 2018). Coastal wetlands are vulnerable to erosion and prolonged periods of high or low water levels, which can reduce the size of wetlands and other natural habitats that serve as breeding zones for birds and fish (Mortsch and Quinn 1996).

Many of these trends and impacts are already occurring in the Great Lakes region, and are expected to further amplify under changing climate conditions into the future, detailed in [Section 3.0](#).



Freighter on Lake St.Clair. Photo by Dan Brown

2.0 Future Climate Projections

2.1 Climate Modeling in the Great Lakes

In order to interpret and utilize the climate projections presented in the following section (3.0), it is necessary to understand how climate models generate these results and what their limitations are.

Climate processes in the Great Lakes region are difficult to simulate due to the complexity of the lakes' interactions with the atmosphere and the other components of the climate system. Many Global Climate Models (GCMs) do not include the Great Lakes as water bodies in their computations because of their coarse resolution (often hundreds of square kilometers per grid cell). When the Great Lakes are included, their representation is greatly simplified. **Given that the regional climate is highly influenced by the presence of the lakes and their physical interactions with the air and land , deficient representation of the lakes contributes to the uncertainty of future climate projections (Briley et al. 2021, Briley et al. 2015).** Currently, the most credible simulations of Great Lakes regional climate are derived from combining Regional Climate Models (RCMs), which offer a higher resolution simulation of local climate features, with GCMs through a process called dynamical downscaling (Delaney and Milner 2019). In this procedure, a GCM that simulates global-scale climate processes is used to generate the boundary conditions for a RCM which produces simulations with a much finer resolution over a smaller area.

In addition, RCMs better capture integral lake-driven climate trends and feedback when they are two-way coupled with a lake model. Lake models range from simple one-dimensional configurations that represent vertical lake dynamics to more sophisticated 3-D lake models that incorporate horizontal and vertical dynamics and better capture variables like lake ice formation, lake effect

precipitation, moisture fluxes, and lake temperature (Xue et al. 2017).

Global and regional climate models can also be used to produce the inputs that are needed for developing water level projections using hydrologic lake routing models. Such models consider the flow of connecting channels between the lakes, the NBS of each lake, and regulation of lake outflows. For a more thorough summary of current and future climate and lake level modeling efforts in the Great Lakes region, refer to [GLISA's 2021 Great Lakes Climate Modeling Workshop report](#).

2.2 Model Choice

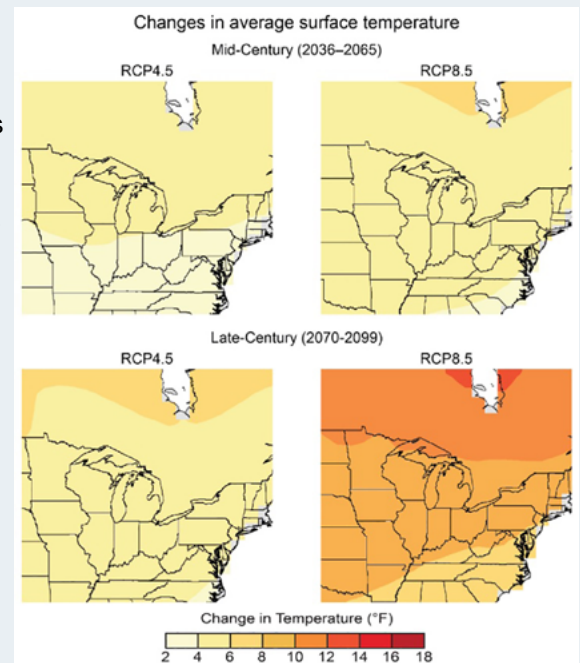
To characterize uncertainty, it is useful to consider multiple sets of RCM-GCM pairs, or an ensemble of models (Gates and Rood 2021). An ensemble characterizes uncertainty associated with climate projections by looking at the full range of projections across different models rather than relying on any individual model. This technique addresses, for example, the uncertainty associated with trade-offs that model developers make in model construction. There are currently a wide variety of climate models and ensembles to consider, but not all are easily accessible, or include reliable representations of Great Lakes climate.

At the time of publication, the North American component of the International Coordinated Regional Downscaling Experiment ([NA-CORDEX](#)) was the only source of dynamically-downscaled RCM data with subsequent lake level projections that fit all of the parameters required for use in this report (see [Appendix 1](#) for full description of the ensemble and parameters used). The 13 models in the ensemble come from GCMs in the Coupled Model Intercomparison Project Phase 5 (CMIP5) coupled to several different RCMs, and are utilized in this report to illustrate one example of regional climate projections

Representative Concentration Pathways (RCPs)

RCPs are radiative forcing scenarios intended to analyze different potential outcomes of climate change in the short term (present-2035) and long term (2100+) (van Vuuren et al. 2011). RCPs are developed based on quantitative evolutions of future emissions and concentrations of greenhouse gasses, aerosols, chemically active gasses, and land use and land cover change (GLISA 2021). Different levels of radiative forcing, and the paths taken to reach them, determine the varying levels of climate warming associated with each RCP. Each RCP represents only one potential path among many that would reach the same radiative forcing level endpoint. Even with major reductions in GHGs under the lowest scenarios, global temperatures will still rise, as there is a certain amount of delayed warming already built into the earth system from current GHG levels (Meehl et al. 2005). These radiative forcing scenarios are not meant to predict future socio-economic and climate conditions, but rather to present a range of possible futures that are useful in planning and decision making. For more information on RCPs, see [Appendix 2](#).

This image displays projected changes in annual average surface temperatures (°F) across the Great Lakes region for the two RCPs used in this report: RCP 4.5 (left) and RCP 8.5 (right). Changes are the difference between the average for mid-century (2036–2065; top) or late-century (2070–2099, bottom) and the historical average (1976–2005). Each map depicts the weighted CMIP5 multimodel mean. Figure adapted from the Climate Science Special Report Figure 6.7 (USGCRP, 2017). See GLISA's [Practitioner's Guide to Climate Model Scenarios](#) for more information on RCPs.



(Taylor et al. 2012, Seglenieks and Temgoua 2022). Two climate forcing scenarios are used to represent a range of plausible outcomes from moderate (RCP 4.5) and high (RCP 8.5) future radiative forcing (see box for more details).

2.3 Bias Implications

The ensemble results presented in this report are bias adjusted, or statistically calibrated to better match historical model simulations to the observed data from that same time period. Bias adjustment methods are generally intended to allow climate models to be used as inputs for other types of modeling (e.g., impact and hydrological) (Christensen et al., 2008, Sharma et al., 2007). In this case, bias adjustment was applied in order to use the model outputs in the Coordinated Great Lakes Regulation and Routing Model (CGLRRM), originally developed by GLERL, to obtain lake level projections (Quinn 1978; Clites and Lee 1998). **Though bias adjustment allows a model to better trace the observations, it does not solve the underlying problems with representation of physical processes, but rather hides them. This has implications for how well a model simulates future climate changes, challenges the interpretation and credibility of results, and impacts the ability to use the models in planning**

of adaptation and climate change mitigation strategies (Piani et al. 2010, Sørland et al. 2018). Bias is particularly important to consider in lake level projections because they are based on the combination of multiple simulated variables and multiple models that may introduce new errors and propagate into larger biases in the NBS and lake level projections.

[Section 3](#) discusses bias adjusted results of the ensemble outputs for temperature, NBS components, and water levels for Lake Ontario. Potential users of this information need to first assess whether it fits their needs. Part of that assessment is understanding the quality of the information and determining if the physical representations of the model are realistic enough for individual applications of the data. To help users assess the usability of these results for their work, [Section 4](#) examines the biases in the ensemble, specifically for Lake Ontario's hydrological components, alongside the bias-adjusted outputs. In our evaluation, we found that the biases for some of the ensemble variables are large (>100%), which limits their use quantitatively. Ultimately, this depends on the sensitivity of a particular application to the quantitative model results. However, GLISA recommends a complementary approach of scenario planning that can utilize these results as guidance, further explained in [Section 5.2](#).

3.0 Analysis of Future Climate Projections for Lake Ontario

The ensemble of NA-CORDEX models utilized in this analysis ran simulations from 2006 to 2100. To complement its [retrospective counterpart](#) that summarizes observed climate trends from the last several decades, this report examines Lake Ontario climate trends for a 30-year period in the middle of the 21st century (2036-2065). The historical reference period for these models is 1961 to 2000, which will be used to compare observed climate and lake data with model results, and also to perform a bias analysis in [Section 4.2](#).

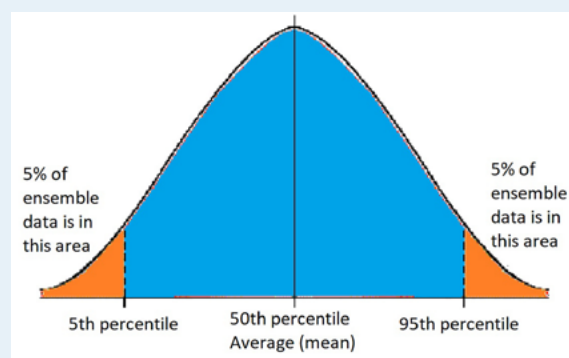
The historical lake observations were retrieved from the NOAA-Great Lakes Environmental Research Laboratory (GLERL) [Great Lakes Monthly Hydrologic Data](#) and

the US Army Corps of Engineers (USACE) [Great Lakes Water Level Data](#) (Hunter et al. 2015, USACE 2022). Model data for the base period was used to help frame the future projections relative to a historical reference period, to quantify the biases in these models, and to understand associated uncertainties. This section provides an examination of the bias-adjusted outputs for air temperature, NBS, precipitation, evaporation, runoff, and lake levels from the ensemble projections under RCP 4.5 and RCP 8.5 scenarios.

Understanding the Data: Percentiles, Multi-Model Mean, and Model Spread

Many figures in this section utilize percentiles, displayed as black dashed lines. The 5th (95th) percentile represents the value below which 5 (95) percent of the data falls. When considered together, they represent where 90% of all data lies. Percentile range is important for climate data, as it removes the extreme values that will occur 5% of the time on either side of the distribution, which could otherwise skew the resulting analysis. What lies outside (below 5% or above 95%) of the data distribution is statistically improbable, though not impossible.

Figures in this section also display the multi-model averages as red and blue lines. These lines represent the mean across all models within the full ensemble of RCP 4.5 (6 models) and RCP 8.5 (7 models) scenarios. Model spread (or 'range') is displayed as red and blue shaded areas. These ranges are obtained by taking the overall maximum and minimum value out of all models in each scenario. For figures that display monthly averages (e.g., Figures 2-7), these ranges are calculated using the minimum and maximum of the monthly average of the individual models. These ranges account for model spread within RCP 4.5 and RCP 8.5 separately, while the percentiles are calculated from the entire ensemble, taking both RCPs into account.



3.1 Air Temperature

Global average surface temperatures have been rising for decades, a trend that is expected to continue due to increasing levels of atmospheric greenhouse gas concentrations. Annual average air temperature in the Lake Ontario basin is consistent with the global trends of recent decades, and the following analysis examines projections for how it will change in the future.

The ensemble of models suggests that the Lake Ontario basin will see significant warming in the coming years, as shown by air temperature anomalies in Figure 1. These anomalies are calculated as the difference between the historical reference period average (7.1°C/44.8°F) and the annual average values across all models. The anomalies displayed in these figures grow larger over the period of 2036 to 2065 and represent significant departures from

historical average temperatures in the basin. The average temperature anomaly at the beginning (2036) and end (2065) of the RCP 4.5 time series is 1.7°C (3.1°F) and 3.2°C (5.8°F), and the average temperature anomaly at the beginning and end of the RCP 8.5 ensemble is 2.4°C (4.3°F) and 4.8°C (8.6°F). Both RCP scenarios show increases in temperature through this 30-year time period, with RCP 8.5 demonstrating a more rapid rate of change than RCP 4.5.

Future air temperatures in both RCP ensembles are projected to make their largest departures from historical averages in the winter months of December, January, and February, with smaller increases projected in summer and fall (Figure 2). This follows a historical trend of greater warming, on average, during winters than during other seasons (USGCRP 2017). These seasonal temperature projections are summarized in Table 1.

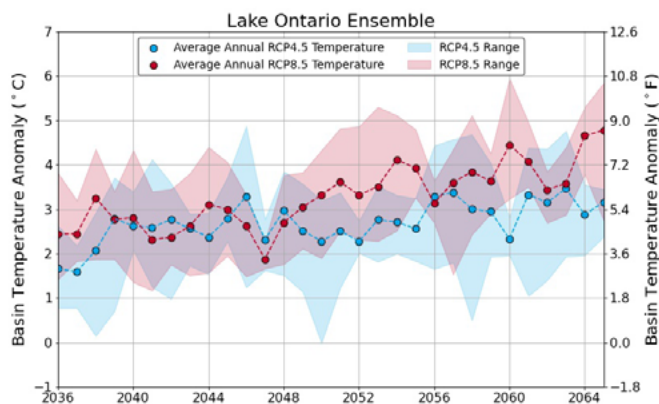


Figure 1: Air temperature anomalies in the Lake Ontario basin for RCP 4.5 (blue) and RCP 8.5 (red). Anomalies displayed are the difference between the multi-model average annual temperature and the long-term average temperature for the historical reference period of 1961-2000. The shaded areas represent the range of all model results from the RCP 4.5 ensemble (6 models, shown in blue), and from the RCP 8.5 ensemble (7 models, shown in red). These are bias-adjusted results.

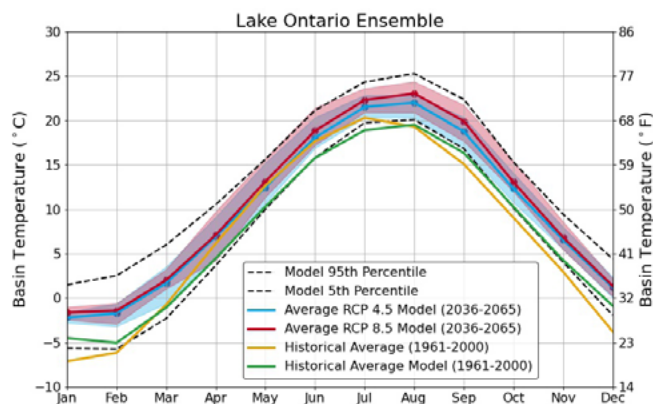


Figure 2: Monthly average Lake Ontario basin air temperature, with the multi-model average of RCP 4.5 (blue) and RCP 8.5 (red) scenarios compared to the observed historical average (yellow), the modeled historical average (green), and the 5th and 95th percentiles (black). The shaded areas represent the range of all averaged model results in the RCP 4.5 (blue), and RCP 8.5 (red) scenarios. These are bias-adjusted results.

Basin Air Temperature (°C/ °F)										
	Annual		Spring		Summer		Fall		Winter	
Observed (1961-2000)	7.1	44.8	6.0	42.8	19.1	66.4	9.0	48.3	-5.7	21.8
Projected (2036-2065) - RCP 4.5	9.8	49.6	7.0	44.6	20.5	69.0	12.6	54.6	-0.9	30.3
Projected (2036-2065) - RCP 8.5	10.4	50.7	7.4	45.3	21.4	70.5	13.3	55.9	0.1	32.1

Table 1: Average observed and projected Lake Ontario basin air temperatures. Annual and seasonal average temperatures are displayed in Celsius (left columns) and Farenheit (right columns). As climatological winter is defined as December, January, and February, December of the previous year is used to compute winter averages.

3.2 Net Basin Supply and its Components

Water levels on the Great Lakes are predominantly driven by each lake's water balance. The portion of the water balance originating in each lake basin, known as the net basin supply (NBS), is defined as overlake evaporation subtracted from the sum of overlake precipitation and basin runoff, demonstrated in the following equation (Decau et al. 2012).

$$\text{NBS} = \text{Precipitation} + \text{Runoff} - \text{Evaporation}$$

Each of these variables is affected by climate change. For example, warming temperatures enhance evaporation over the lakes and in the drainage basin, and can lead to more years with low lake ice cover. Increases in evaporation coupled with reduced ice cover duration can subsequently lead to lower water levels. Warmer temperatures can also reduce snowpack and soil moisture contributing to weaker runoff and lower water levels. Conversely, increases in precipitation frequency and intensity could contribute to rising water levels. Future water level changes will depend on how these processes will balance one another in the future. Inflows from upper lakes and outflows to lower lakes are also important components of a lake's total water supply, but are not part of the lake's NBS and therefore are not included in this analysis.

Precipitation, runoff, and evaporation projections generated by the NA-CORDEX data were used to calculate the lake's NBS. The NBS projections were then bias-adjusted with observational data and used as inputs to run a Great Lakes regulation and routing model to calculate lake level projections. In order to interpret the lake level projections obtained from this ensemble and assess the associated biases, it is necessary to examine the NBS of Lake Ontario, the three components that make up the NBS, and the subsequent biases of each. All NBS components, particularly precipitation, are considerably more difficult to model than temperature. Therefore, there is more variability between the different models and higher uncertainty associated with NBS components.

Net Basin Supply

Monthly average NBS for each RCP ensemble is shown in Figure 3. The ensemble indicates that average NBS will be higher than the historical average from approximately December to April, with the highest increases occurring in the spring months when the impacts of springtime changes in runoff (Figure 5) are especially evident.

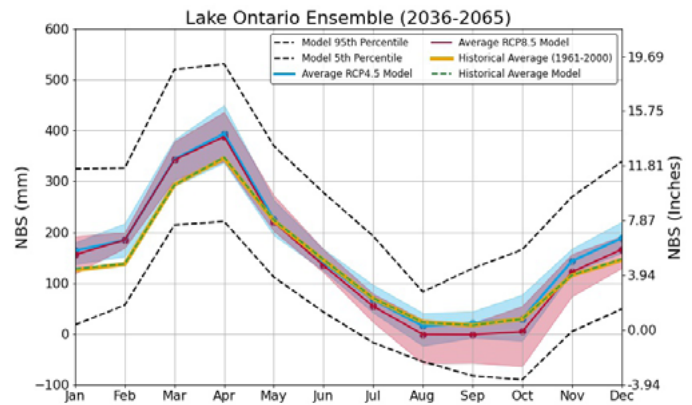
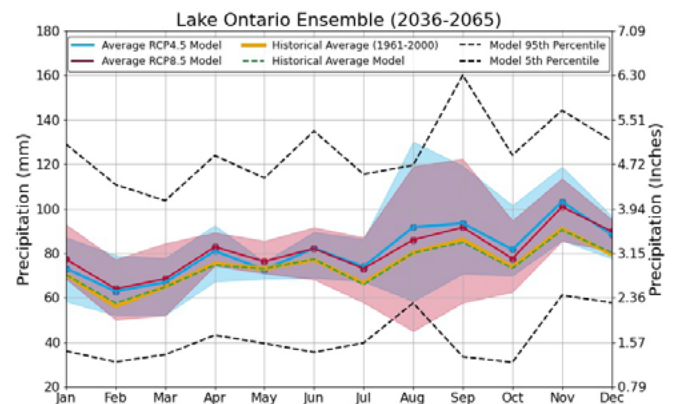


Figure 3: Monthly average net basin supply (NBS) for Lake Ontario, with the multi-model average of RCP 4.5 (blue) and RCP 8.5 (red) scenarios compared to the observed historical average (yellow), the modeled historical average (green), and the 5th and 95th percentiles (black). The shaded areas represent the range of all averaged model results in the RCP 4.5 (blue), and RCP 8.5 (red) scenarios. These are bias-adjusted results.

Precipitation

Overlake precipitation totals are expected to increase, on average, due in part to the ability of warmer air to hold more water vapor (moisture) and hence, increase precipitation. In most months, each RCP scenario shows higher Lake Ontario precipitation totals than the historical average, with the largest increases in the months of August and November (Figure 4).



Monthly average overlake precipitation totals for Lake Ontario, with the multi-model average of RCP 4.5 (blue) and RCP 8.5 (red) scenarios compared to the observed historical average (yellow), the modeled historical average (green), and the 5th and 95th percentiles (black). The shaded areas represent the range of all averaged model results in the RCP 4.5 (blue), and RCP 8.5 (red) scenarios. These are bias-adjusted results.

Runoff

Runoff consists of overland flow from rivers and streams, which are partially fed by rainfall, snowmelt, and groundwater. In addition, groundwater enters and leaves a lake through the subsurface of the surrounding land, a process known as direct discharge. Runoff and groundwater are affected by physical factors including land use, vegetation, soil type and moisture, topography, drainage systems, and elevation. Runoff reaches its highest levels in the spring when the Lake Ontario basin's snowpack melts. The ensemble results indicate that peak runoff in the Lake Ontario basin will still occur in April, but at a higher rate than the historical average (Figure 5). The runoff increase may be associated with an earlier shift in spring snowmelt from warmer winter temperatures (Dudley et al. 2017). The greatest range in models occurs during months associated with a large change in runoff (March and April).

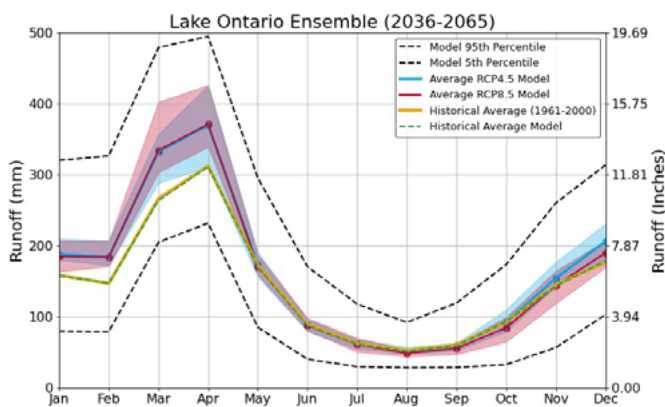


Figure 5: Monthly average runoff for the Lake Ontario basin, with the multi-model average of RCP 4.5 (blue) and RCP 8.5 (red) scenarios compared to the observed historical average (yellow), the modeled historical average (green), and the 5th and 95th percentiles (black). The shaded areas represent the range of all averaged model results in the RCP 4.5 (blue), and RCP 8.5 (red) scenarios. These are bias-adjusted results.

Evaporation

Evaporation from the lake surface is mainly driven by large differences between the water temperature and air temperature, high wind speeds, and low relative humidity. This peaks in the fall when lake temperatures are still warm from the summer and air temperatures are cooler, creating a temperature gradient ideal for evaporation. The ensemble projects the largest increases in average evaporation in the months of October to December, with decreases in the summer months, as shown in Figure 6. Evaporation is affected by warming air temperatures, and

even more so by warming lake temperatures, which also reduce ice formation on the lakes. Lake Ontario usually has lower ice coverage compared to the upper Great Lakes. If more of Lake Ontario's surface area remains ice-free, more evaporation can occur throughout the winter months. These results for the 13-model ensemble are generally consistent with an analysis of the full ensemble of NA-CORDEX models in Mailhot et al. (2019), which found overall increases in NBS, precipitation, runoff, and evaporation, with differences between seasonal trends.

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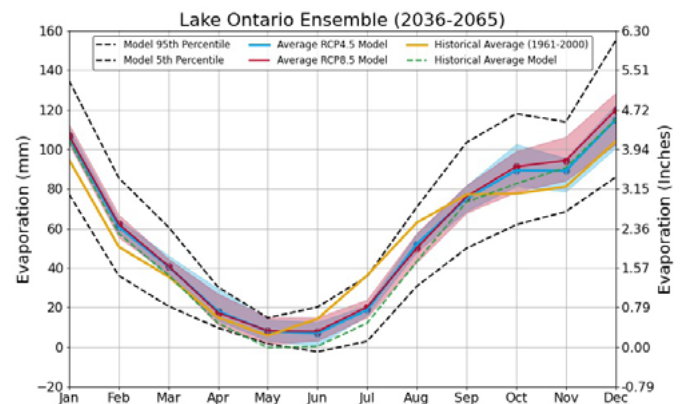


Figure 6: Monthly average overlake evaporation for Lake Ontario, with the multi-model average of RCP 4.5 (blue) and RCP 8.5 (red) scenarios compared to the observed historical average (yellow), the modeled historical average (green), and the 5th and 95th percentiles (black). The shaded areas represent the range of all averaged model results in the RCP 4.5 (blue), and RCP 8.5 (red) scenarios. These are bias-adjusted results.

3.3 Lake Levels

Lake level projections were obtained from the bias-adjusted ensemble NBS outputs through use of a routing model. These results, however, cannot be quantified simply as increasing or decreasing in the future, given the variable nature of water level fluctuations on the Great Lakes. In addition to long-term averages, it is necessary to consider changes in extremes, variability, and seasonality.

The ensemble of lake level projections follows the usual seasonal cycle of summertime highs and fall/winter lows. Figure 7 displays monthly averages of each RCP ensemble over the entire 2036-2065 time period, compared to

historic records and averages. The annual ensemble average of both RCPs remains above the historical average. Most of the individual model averages are also above the historic average. Given that these results are averaged over 30 years, this indicates that more individual years exceeding historic records are possible. Low-water years are also still anticipated as lake levels continue to fluctuate, but all individual model averages are well above record lows and closer to record highs. The largest increases are projected in the months of February to July, likely due in part to the combined effects of increased springtime precipitation and runoff. The seasonal lake level projections are summarized in Table 2.

The annual variability of the ensemble projections is evident in Figure 8, but it should be noted that projections should not be used to predict conditions in any individual

year or used to demonstrate specific extremes. Even if a particular model generates very high or low results, that does not indicate that these levels will occur in the future with certainty, so it is important to focus on the averages and trends in the model data. The annual averages of the RCP 4.5 and 8.5 ensembles are largely above the historical average, with only a handful of slightly below-average years. This figure illustrates the continued importance of interannual variability; lake levels do not continuously rise or fall, but fluctuate. Projections also indicate longer, extended periods of higher than average lake levels than in the past.

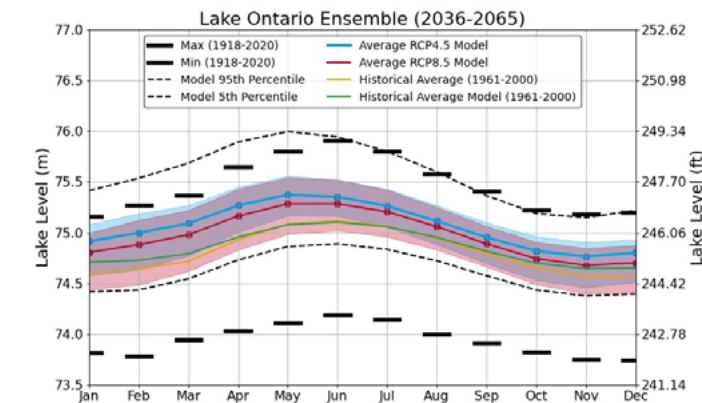


Figure 7: Monthly average Lake Ontario water levels, with the multi-model average of RCP 4.5 (blue) and RCP 8.5 (red) scenarios compared to the observed historical average (yellow), the modeled historical average (green), the 5th and 95th percentiles (black dashed), and the observed historical record monthly maximums and minimums (black horizontal lines). The shaded areas represent the range of all averaged model results in the RCP 4.5 (blue), and RCP 8.5 (red) scenarios. These are bias-adjusted results.

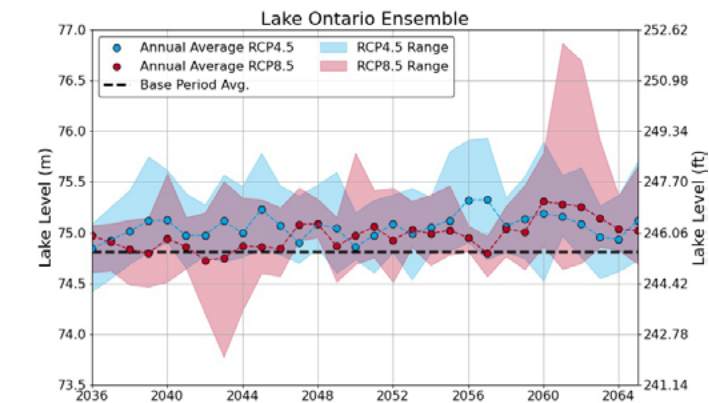


Figure 8: Annual water levels for Lake Ontario, with the multi-model average of RCP 4.5 (blue) and RCP 8.5 (red) scenarios compared to the long-term average lake level for the historical reference period of 1961-2000 (black dashed). The shaded areas represent the range of all averaged model results in the RCP 4.5 (blue), and RCP 8.5 (red) scenarios. These are bias-adjusted results.

Lake Levels (Meters/Feet)										
	Annual		Spring		Summer		Fall		Winter	
Observed (1961-2000)	74.8	245.4	74.9	245.8	75.0	246.2	74.7	245.0	74.6	244.8
Projected (2036-2065) - RCP 4.5	75.1	246.3	75.2	246.9	75.2	246.9	74.9	245.6	74.9	245.7
Projected (2036-2065) - RCP 8.5	75.0	246.0	75.1	246.5	75.2	246.7	74.8	245.3	74.8	245.4

Table 2: Average observed and projected Ontario lake levels. Annual and seasonal average lake levels are displayed in Meters (left columns) and Feet (right columns). As climatological winter is defined as December, January, and February, December of the previous year is used to compute winter averages.

4.0 Uncertainty and Bias Considerations

Before utilizing these results in planning or other applications, users should understand the uncertainties associated with the ensemble of models and how well they capture underlying physical processes. Uncertainty in climatological observations and models exists in several forms. Climate projections include three types of uncertainty: model uncertainty, scenario uncertainty, and natural variability (Latif 2011). The combination of these represents the total uncertainty associated with climate projections. Uncertainty levels vary over time, and generally are greater when looking at a regional or local scale, and lower at a global scale (Gates and Rood 2021).

It is important to consider uncertainty in climate projections when evaluating whether the outputs from a climate model are reliable for use in planning and decision making. There is high certainty - supported by observations and theory - that global temperatures will continue to warm and that there will be complex responses to the warming. The climate model simulations utilized in this report attempt to provide a more detailed look at plausible futures across the Great Lakes region, but these details are accompanied by the uncertainties inherent in both the climate forcing scenarios used and the models themselves.

4.1 Understanding Model Bias

How well a model simulates past weather and climate, when compared with observational data, contributes to its uncertainty. Systematic differences between quantified historical observations and historical model simulations are defined as model bias, which can vary by season and location (Maraun 2016). Biases can have substantial impacts on the interpretation of the future, as well as on the ability to use the models in planning of adaptation and climate change mitigation strategies (Sørland et al. 2018).

In a bias adjustment process, observational data are used to adjust the outputs of the model (Maraun 2016).

This leads to a better fit with observations; however, this process does not correct the underlying error that caused the modeled data to poorly represent the observations in the first place (Rood and Gates 2021). Hence, we define this as an adjustment, not a correction.

Bias is related to how well a particular quantity is simulated, and different climate variables (e.g., temperature or precipitation) may exhibit different amounts of bias in the same model. Large bias adjustment may indicate a large underlying error likely due to deficiencies in model representation of important physical atmosphere, land, lake, and ocean processes (Maraun, 2016). **Though bias adjustment allows a model to better trace the observations, it does not solve the underlying problems with representation of physical processes, but rather hides them. This has implications for how well a model simulates future climate changes and challenges the interpretation and credibility of results** (Piani et al. 2010). GLISA generally characterizes biases of less than 10% as small or incremental, and biases over 100% as large. Such large biases suggest that model results may not be credible for direct, quantitative use in certain applications (Gates and Rood 2021). When it comes to practical use in planning and decision making, what qualifies as 'large' bias depends on the parameter and the use.

Even with the best available models, certain variables are difficult to simulate because scientists are still working to understand the physical relationships and how to represent them through numerical modeling. Part of the uncertainties surrounding these simulations also stems from the observational data that are used in bias adjustment and skill assessment for the models. There are particular variables that have higher uncertainties because of less reliable measurement methods. Variables like overlake precipitation and overlake evaporation have higher uncertainty than land-based observations because lake observations are sparse (Fry et al. 2022). These sparse observations are interpolated to create lake-wide data,

without consideration for the impacts of lake-atmosphere stability, which renders the lake observations less reliable (Holman et al. 2012). Data discontinuities at the US-Canadian border also present challenges (Gronewold et al. 2018). This complicates the estimation of overlake evaporation, precipitation, and tributary runoff.

4.2 Bias Analysis of Ensemble Results

To describe uncertainty and fully assess the usability of these results, we consider the model output before bias adjustment was applied and how it compares to observational data.

Figure 9 displays the original NBS output from the model simulation of the historical reference period (1961-2000) compared with the observational NBS data from that time period, and the bias-adjusted model output. The bias-adjusted outputs very closely resemble the observations that are used in the bias adjustment process, as is the intent of the procedure. This allows the models to produce salient results that stand up to historical ranges, but it does not eliminate the errors associated with the original model projections. In fact, bias adjustment hides any physical errors in the model from the user.

If we start by investigating biases in NBS, Figure 9 shows that the original model output overestimates NBS in most of the months, and underestimates NBS in the months of March and April. Since NBS is an integrated quantity, calculated from three primary components (Precipitation + Runoff - Evaporation), errors in these underlying components are obscured. That is, the nature

and magnitude of the underlying model biases are not discernable as systematic positive and negative errors can compensate each other when they are added together.

To examine these underlying biases, we break down the analysis by individual components.

Figure 10 displays this breakdown by presenting biases for each NBS component as a percent of the quantity simulated. For example, if the model average precipitation in a given month is 100mm and the average precipitation bias for that same month is 25mm, then the percent bias is 25%. By examining the biases of individual components we can better define and describe the model errors in the NBS equation, which are not discernable from the total bias of NBS shown in Figure 9.

Figure 10 demonstrates how the magnitude of bias varies by month for each component, with the largest monthly biases associated with evaporation in 6 of the months (mainly winter and spring) and runoff in the other 6 months (mainly summer and fall). Large evaporation biases could be due to inadequate physical representations of lake ice and/or lake-atmosphere interactions in the 2-D lake model. Overestimations of evaporation can amplify the downward influence on water levels in the projections. In January, evaporation bias is larger than the simulated amount of evaporation (e.g., biases are >100%). It should, however, be noted that evaporation in the spring and summer months is typically very small, so even small differences from the model output appear very large. See [Appendix 3](#) for a more in-depth look at individual model biases.

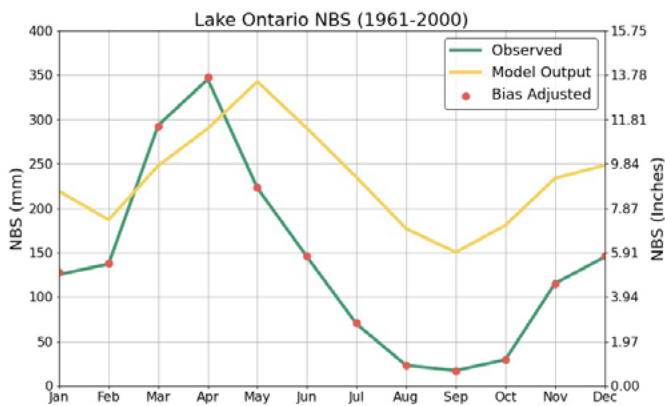


Figure 9: Monthly average net basin supply (NBS) for Lake Ontario, with the full ensemble mean of the original (pre bias-adjustment) model output (yellow), the observational data (green), and the bias-adjusted model results (red dots).

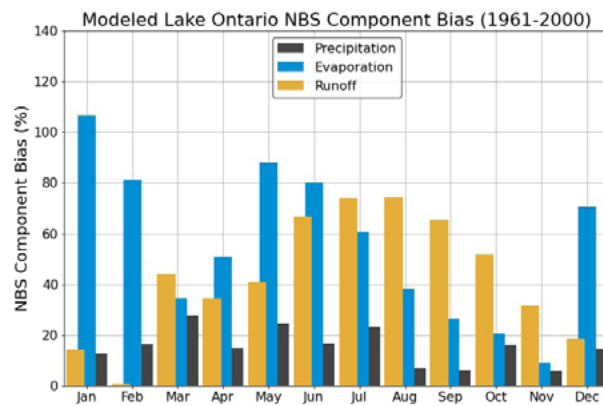
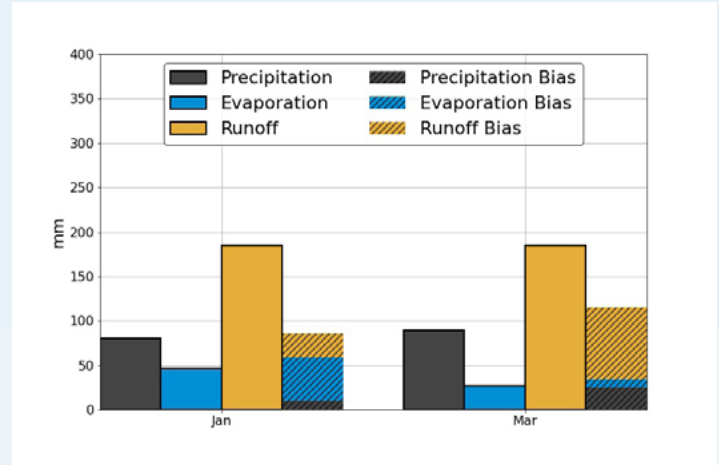
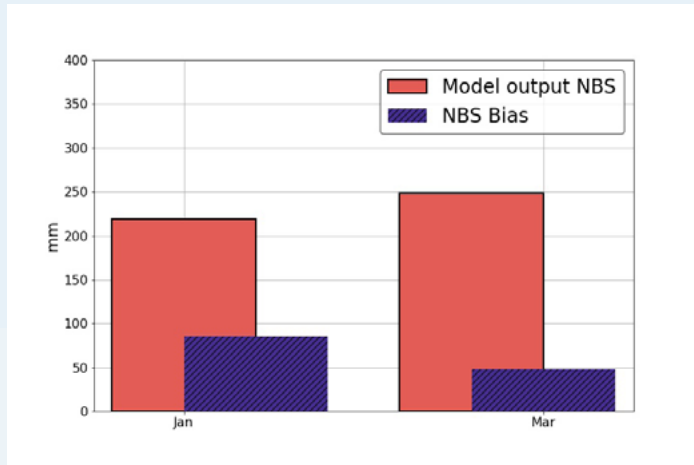


Figure 10: Monthly average bias of precipitation (gray), evaporation (blue), and runoff (yellow) as a percentage of the total modeled component magnitude.

NBS vs. Components Bias Breakdown



Select months are shown demonstrating NBS bias (left plot) compared to individual NBS component bias (right plot). On the left, it would appear that January NBS bias (purple) is larger than March NBS bias. On the right, for those same months, the total January component bias (diagonal bar) is smaller than that for March. So, model errors are greater during March than January but this is not apparent by looking at the NBS bias alone. This is because even though evaporation and runoff errors are quite large, they “cancel” each other out when used in the NBS equation ($P - E + R$). Incorrect conclusions about model quality and credibility could be drawn from considering NBS bias alone. In many months, the sum of component biases (diagonal bar) is comparable to the magnitude of the other components (solid bars).

In this consideration of biases, the uncertainties associated with the observations should not be forgotten. NBS data comes from residual NBS observations (computed from change in storage inflows and outflows), which are considered far more reliable than NBS component estimates because they are more easily observed (Fry et al. 2022). The individual components of overlake precipitation, evaporation, and runoff are much more difficult to measure and have higher associated uncertainties (Holman et al. 2012, Fry et al. 2022). The bias adjustment of model outputs was performed on both the NBS, using residual NBS observations, and on the individual components, using observational data. Lake level results were derived from the NBS outputs that were bias-adjusted with the more reliable residual NBS observations, not the component observations.

This adjustment may make the model results align more closely with the historical averages, statistically, but does not make the simulations more physically realistic. Bias

adjustment, which uses historical observations, relies on the assumption that the adjustment factor(s) for the past will be the same in the future in order to carry adjustments forward into future projections (Reichler and Kim 2008). In other words, bias adjustment procedures assume climate relationships and processes remain stationary, or the same, through time. However, given the effects of climate change on lake temperatures, ice cover, and many other variables, the physical dynamics of the lakes are not the same today as they were in decades past, nor will they be the same in the future (Briley et al. 2015). Therefore the adjustment factor of the past is changing, so applying the historic adjustment factor to the future may not produce salient results in our region. Though the NBS simulations are bias-adjusted with historical observation before obtaining lake level projections through the routing model, the bias adjustment process does not eliminate underlying errors or deficiencies in how the model simulates physical processes.

5.0 Considerations for Decision Making

Though models are not able to represent a definitive picture of the future, they can convey important information, such as the direction and the estimated magnitude of change. **The presence of uncertainty and bias in climate models does not necessarily render their outputs unusable. We recommend that scientists disclose data issues and model biases, as we have done in this report, so users can make an informed decision. We can state whether or not we consider the model simulations to be credible, having a defensible scientific basis. Ultimately, the choice to use model data (e.g., projections) or bias-adjusted data in practice is up to the user and whether they can justify use of such data in their application.**

5.1 Future of Great Lakes Climate Modeling

The state of climate modeling in the Great Lakes region is limited by multiple factors, including computing power, resources, and cost of generating more sophisticated models. Modelers in the region are currently making advances to better represent the lake-land-atmosphere interactions that are essential to realistic simulations of Great Lakes climate (Delaney and Milner 2019, Briley and Jorns 2021). Such advances ultimately strive to reduce bias and uncertainty and to improve the usability of models in planning and decision making.

This section summarizes recommendations and ongoing efforts to improve climate models (further details available in GLISA's 2021 [Great Lakes Climate Modeling Workshop Report](#), funded by Annex 9). Ongoing updates from modelers in the Great Lakes region include efforts to devise new 3-D coupled lake-atmosphere-land models for the Great Lakes region. These more sophisticated models show improvements over the previous 1-D coupled lake simulations, including those used in this report's ensemble.

One key recommendation for future efforts is to enhance data collection and conduct targeted field studies on lake climatology, which can feed into and validate climate models, and also enhance spatial-temporal data coverage. Regardless of how sophisticated the models are, initial conditions are critical as they are boundary conditions for model simulations. Newly published estimates of monthly water balance components from 1950 to 2019 for the Great Lakes can be used for researching changes in water availability or benchmarking new hydrological models. Other recommendations for Great Lakes climate modeling include: 1) capture the advanced and complex processes of the Great Lakes in climate models by including lake simulations, particularly 3-D simulations, when available; 2) develop guidance for the evaluation of physical climate processes in models prior to bias adjustment, and also evaluate model bias to determine if the bias adjustment adds value or conceals major model uncertainties; 3) utilize large (50+ member) ensembles when available to evaluate regional climate change, variability, and extremes; and 4) develop multiple tiers of model diagnostics, based on the sophistication of the models being addressed to better understand where improvements still need to be made.

5.2 Scenario Planning as a Complementary Approach

This report utilizes an ensemble of climate models to examine projections of future climate conditions, and we have demonstrated how uncertainty (i.e., errors) in quantified model projections can be large. In our evaluation, we found that the biases for some of the ensemble variables are so large (>100%), as to question their use in quantitative applications. When the errors are this large, it is important, from an ethical perspective, not to overstate our certainty about future climate conditions. Even in the case of large bias relative to the observations,

the model's internal representation of precipitation, evaporation, and runoff should be physically plausible and provide guidance for developing scenarios.

Fortunately, simulations are just one of several tools available for planning and decision making. Future projections of climate change, lake levels, or any other simulations, can be used in scenario planning processes that account for future uncertainty and frame projection information in more usable formats for real-world use. Scenario planning has been used by the U.S. military, the energy sector, and NASA (Cann 2010, Cornelius et al. 2005). Scenario planning creates a framework to consider several novel situations, not just what may be expected based on the past, leading to increased preparation for any plausible future. Most importantly, scenario planning is a process that brings together practitioners, who need science-based information about the future, and experts, who can translate and communicate available relevant science.

GLISA's scenario planning approach (described in detail on their [website](#)) uses climate model projections in combination with other sources of information, including research, expert guidance, and local knowledge and

experience, as guidance to inform their scenario planning process. GLISA's approach considers multiple plausible futures and accounts for uncertainty in planning. For example, a climate model ensemble may simulate decreasing ice cover over the next 50 years, but this does not mean that stakeholders should only plan for less ice cover. Due to natural variability and the prevalence of cold air outbreaks from the arctic, there will still be individual years where high ice cover is possible. To explore this future uncertainty, one scenario may include a year with high ice cover and related impacts. Scenario planning allows decision makers to plan for extreme conditions and disruptions that span a range of likely outcomes, while still taking into account outputs of climate models to inform the scenarios themselves (not to be confused with RCP scenarios described in [Section 2.2](#)). Planning for multiple plausible futures, including extremes, can increase the robustness of planning and preparedness for climate change impacts. An example case study of scenario planning applied to lake levels can be found on the following page, to help illustrate this.

Scenario Planning: a Lake Ontario Case Study

In 2021, GLISA and New York Sea Grant facilitated a scenario planning workshop with practitioners from Wayne County, NY, as part of a project to advance community-level resilience to Lake Ontario flooding. GLISA developed a set of three plausible scenarios for the workshop around high lake level conditions. The scenarios were informed by climate and lake level projections, historical trends, and the physical properties of the Great Lakes system. Four breakout groups were assigned different scenarios that they built onto with events and impacts. The following is an example from one group.

Break out group example: Cold air outbreak scenario for septic systems with a coastal erosion event

In this scenario, water levels are already above average. Then, a cold air outbreak associated with arctic oscillation occurs, causing very cold temperatures. The lakes freeze, evaporation shuts off, and the ground is frozen with snow cover. Water levels that were above average become extremely high. The group assigned to this scenario focused on the impacts on septic systems and planning. They chose to add a coastal erosion event to this scenario as they discussed the goals and actions outlined below.

GOAL #1: Ensure septic systems are working properly by 2031

Actions:

- An integrated strategy to inventory and assess septic systems' risk of inundation, including a regional coastal plan and participation from all agencies in order to reduce barriers in coordination.
 - Properties will be audited and assessed, with municipalities and inspection agents performing a coordinated inspection and audit.
- Code enforcement officers should perform stress tests on new home purchases. In some cases of septic along eroded shorelines, houses may not be livable.
 - In these worst-case scenarios, houses would require a state or federally funded buyout.

GOAL #2: Ensure access to community financial fund for cost share

- Federal investment in pilot programs for relocation and house buybacks
- Replicate and adopt model local septic laws to demonstrate seriousness and local commitment to federal and state agencies
- Find integrated local/state/federal funding solutions to erosion that may require federal investment in buyouts.

For more information about this workshop and the scenarios used, refer to the [workshop summary report](#). Funds for this project were provided through the Climate and Societal Interactions COCA/SARP competition by the National Oceanic and Atmospheric Administration Climate Program Office

6.0 Concluding Statements

The Great Lakes have already begun to experience the impacts of changing climate trends, and such trends are expected to accelerate into the future. Given the effects of climate change on lake temperatures, ice cover, and many other variables, the physical dynamics of the lakes are not the same today as they were in decades past, nor will they be the same in the future. Climate models can be a helpful tool in identifying important information about direction change and estimated magnitude of future trends.

Under both RCP scenarios examined in this report, Lake Ontario basin air temperature is projected to continue rising in the future, particularly in the winter. Springtime increases are anticipated for runoff, while increases in precipitation are anticipated year-round. Evaporation

is projected to increase in the fall and early winter and decrease in the summer. Such changes affect the lakes NBS and subsequently, lake levels. Increased variability in Ontario lake levels is anticipated, with increased potential for individual years to surpass historical record extremes. Such changes will amplify existing societal, economic, recreational, and environmental stressors and present new challenges for the basin. Despite the presence of uncertainty and bias in all climate models, their results can still offer guidance to planning and applications, particularly when used with complementary approaches such as scenario planning. Such approaches can help increase preparedness and promote resilience for future change.



Lake Ontario shoreline, Mississauga. Photo Credit Mustang Joe

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Appendix

This appendix provides additional details on the ensemble used in the report, representative concentration pathways, and model biases.

[A1: Ensemble of NA-CORDEX Projections Utilized in This Report](#)

[A2: Representative Concentration Pathways \(RCPs\)](#)

[A3: Climate Model Biases](#)

A1: Ensemble of NA-CORDEX Projections Utilized in this Report

The climate projection data utilized in this report was developed by ECCC using the North American component of the International Coordinated Regional Downscaling Experiment ([NA-CORDEX](#)). This section provides a more detailed summary of the projection data and methodologies, based on a report by Seglenieks and Temgoua (2022).

At the time of publication, NA-CORDEX was the only source of dynamically-downscaled RCM data that fit all of the parameters required for use in this report. These parameters included the need for the data to be publicly available, have multiple GCM-RCM pairs, at least 2 RCPs, the presence of a lake model, the availability of overlake evaporation as a simulated output, and the availability of lake level projections obtained through use of a routing model. These models come from GCMs in the Coupled Model Intercomparison Project Phase 5 (CMIP5) coupled to several different RCMs and are utilized in this report to illustrate one example of regional climate projections (Taylor et al. 2012). There are newer regional climate models that can perform as well as or even better than NA-CORDEX for the region, but not all are publicly available or fit all the needs for this report.

In order to obtain lake level projections, only RCM-GCM pairs that were coupled to a lake model with evaporation as a usable output were chosen for the ensemble. There are seven RCMs in this subset of NA-CORDEX models, and each RCM is driven by a set of six GCMs. The spatial resolutions of these models are not identical; the finest resolution available for each model was utilized. All but two of these RCM-GCM couplings use FLake, a one-dimensional lake model, which is a simple representation of lake-atmosphere dynamics (Mironov 2008). Table A-1 contains a list of details for each of the seven RCMs and six GCMs in the ensemble.

The ensemble produced projections for precipitation, runoff, and evaporation, and these projections were used to estimate the lakes' NBS (see Section 3.2). Lake evaporation data are not included in the publicly-available version of the NA-CORDEX dataset and so was obtained from the model teams directly. Runoff data was obtained by using the temperature and precipitation projections from the ensemble runs to calculate river flow into each lake with the hydrological model WATFLOOD (Kouwen et al. 1993, Wijayarathne and Coulibaly 2020). A multivariate bias adjustment function was performed on the NBS estimates using residual NBS observations from the historical reference period of 1961-2000 (Cannon 2016).

Lake level projections were calculated by using the NBS simulations as input to the Coordinated Great Lakes Routing and Regulation Model (CGLRRM, see figure A-1). More information on the routing model is available from GLERL. The CGLRRM calculates flow in connecting channels between the lakes, and considers the regulation of outflows from Lake Superior in its calculation of lake levels. A separate regulation model was used to calculate Ontario lake levels that takes into account its current regulation plan (Plan 2014). It should be noted that these modes are based on observed flow characteristics of the past, which may not be maintained under extreme conditions in the future.

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

Table A-1: Details of RCM-GCM Combinations used in the ensemble

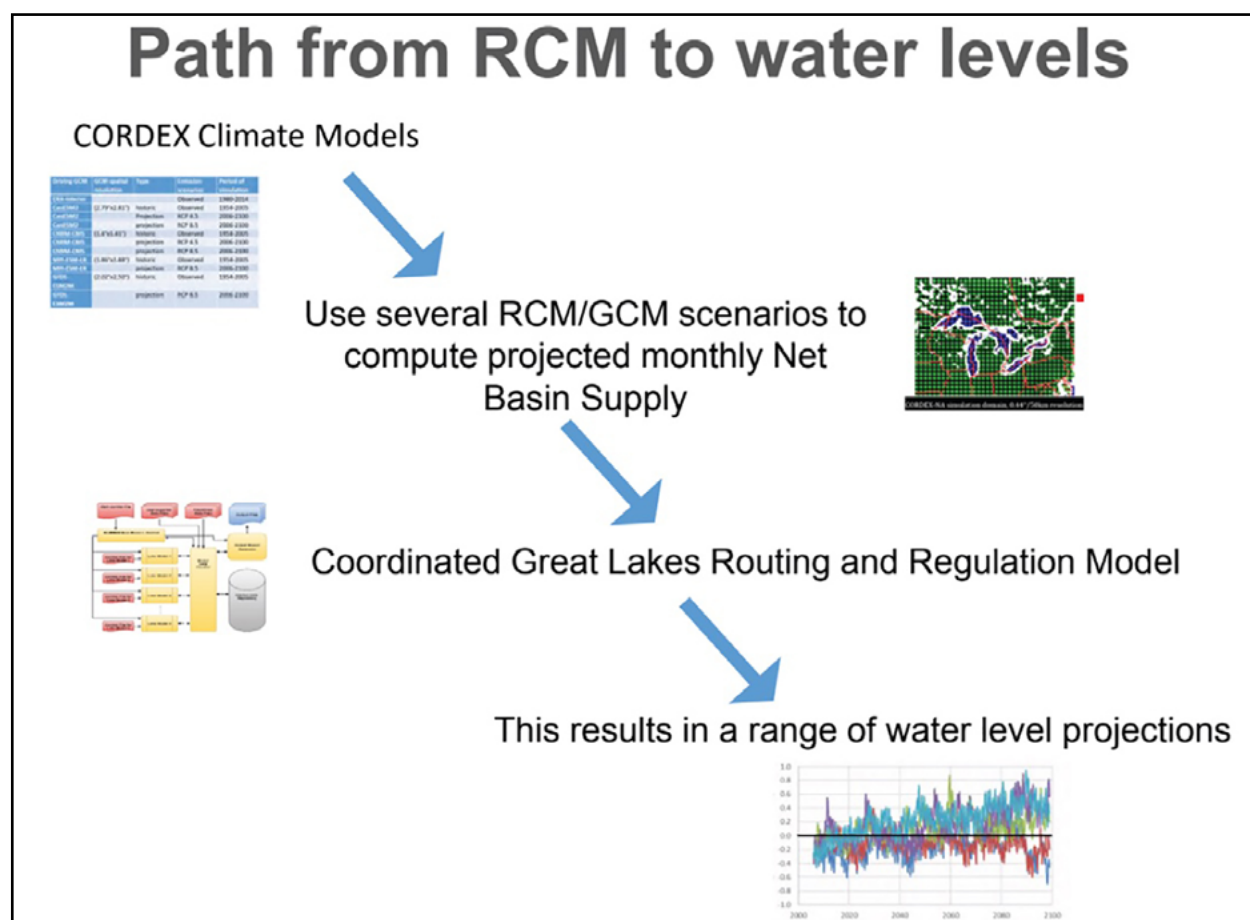


Figure A-1: Example modeling pathway depicting how lake levels are derived from climate model projections.

Source: Frank Seglenieks (ECCC)

A2: Representative Concentration Pathways (RCPs)

Investigation of future climate depends on representation of atmospheric greenhouse gasses and other environmental and societal factors in climate modeling. The Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report and the 4th US National Climate Assessment utilized representative concentration pathways (RCPs) to represent these futures and force GCM simulations (IPCC 2014, USGCRP 2018). RCPs are radiative forcing scenarios intended to analyze different potential outcomes of climate change in the short term (present-2035) and long term (2100+) (van Vuuren et al. 2011). RCPs are developed based on quantitative evolutions of future emissions and concentrations of greenhouse gasses, aerosols, chemically active gasses, and land use and land cover change (GLISA 2021). Though there are hundreds of potential radiative forcing scenarios, four were approved for use in the 5th IPCC report in 2014. Each is named for their respective end-of-century radiative forcing values (change in the atmosphere's energy flux in Watts per square meter, or W/m²): RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, as shown in Figure A-2. The numbers are representative of the radiative forcing increase relative to pre-industrial conditions (e.g., RCP 2.6 represents an increase in radiative forcing of 2.6 W/m²).

Each RCP scenario provides one of many possible pathways that the Earth may take to reach that level of radiative forcing. The four RCPs are able to factor in how society may develop in the future, but some may be perceived as less achievable than others. RCP 8.5 depicts a high emission scenario due in part to slow improvements in energy efficiency and emissions that are more extreme than current trends (Riahi et al. 2011). RCP 8.5 is not the hard upper bound for what is possible (e.g., not the “worst case scenario”), as shown by the even higher possible radiative forcing scenarios in Figure 2. At the same time, RCP 8.5 includes assumptions about global income, population, and energy demand that are considered extreme by some (See Box 3 of GLISA's Practitioner's Guide to Climate Model Scenarios for a more in-depth discussion of RCP 8.5 and whether it makes sense to use it in practice). Different levels of radiative forcing, and the paths taken to reach them, determine the varying levels of climate warming associated with each RCP. Even with major reductions in GHGs under the lowest scenarios, global temperatures will still rise, as there is a certain amount of delayed warming already built into the

earth system from current GHG levels (Meehl et al. 2005). These radiative forcing scenarios are not meant to predict future socio-economic and climate conditions, but rather to present a range of possible futures that are useful in planning and decision making.

Two climate forcing scenarios are used in this report to represent a range of plausible outcomes from moderate (RCP 4.5) and high (RCP 8.5) future radiative forcing. By the end of the 21st century, RCP 4.5 projects global temperatures will increase by 1.7-3.2°C (3.1-5.8°F), and RCP 8.5 projects increases of 3.2-5.4°C (5.8-9.7°F). Note that each RCP represents only one potential path among many that would reach the same radiative forcing level endpoint, as shown in Figure A-2. Additional RCPs, such as RCP 7.0 are in development to explore intermediate forcing levels.

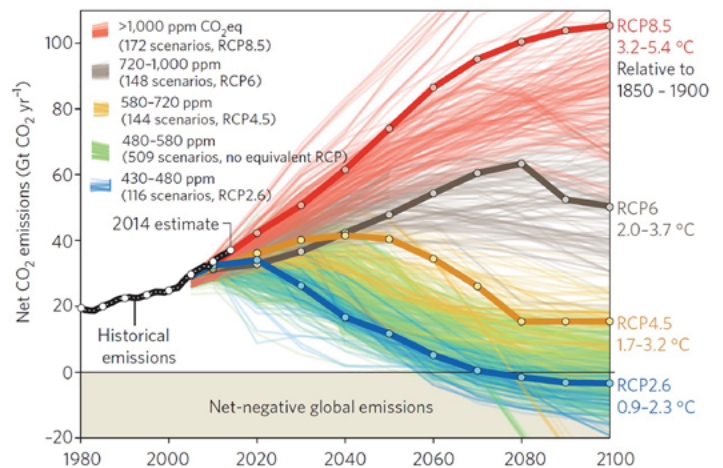


Figure A-2: Representative Concentration Pathways (RCP) scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). Thinner lines represent multiple possible emission pathways under different global emission trajectories, and the thicker lines represent the four main scenarios developed for the 5th IPCC Assessment. Data: CDIAC/GCIP/IPCC (Fuss et al. 2014).

A3: Climate Model Biases

Section 4 examined biases of the ensemble average, but to truly understand underlying model errors and physical deficiencies, an examination of individual model bias is necessary. The following tables (A-2 through A-5) contain monthly bias information (magnitude and percent difference of observations from models) of each individual model for NBS, precipitation, runoff, and evaporation. Some of the percent differences are extremely large (>1000%), and this is mainly due to the modeled value in

those months being very low. A difference between the modeled and observed values divided by a low modeled value will result in large percent biases, which is why it is important to consider both percent and magnitude bias.

This bias analysis only applies to the 13 NA-CORDEX models utilized in this report. A bias analysis for temperature and precipitation of the full ensemble of NA-CORDEX models for the entire Great Lakes region compared to other climate model ensembles is [available from GLISA](#).

	CanRCM4/ CanESM2	CRCRM5/ CanESM2	CRCRM5/ CNRM-CM5	CRCRM5/ MPI- ESM-LR	CRCRM5/ GFDL- ESM2M	RCA4/ CanESM2	RCA4/ Earth_ SMHI
January	151.34 54.72%	30.57 19.62%	83.44 39.98%	128.00 50.54%	100.27 44.46%	47.20 27.37%	59.86 32.34%
February	96.28 41.26%	6.93 5.32%	49.70 26.61%	86.47 38.68%	51.85 27.44%	11.10 7.49%	13.89 9.20%
March	38.27 11.54%	84.35 40.34%	70.42 31.57%	28.96 10.95%	79.47 37.14%	89.16 43.64%	88.67 43.30%
April	31.12 8.27%	87.96 34.17%	40.20 13.17%	34.69 11.16%	99.49 40.46%	105.53 44.00%	138.29 66.78%
May	163.15 42.28%	34.33 13.35%	165.17 42.58%	181.56 44.91%	198.53 47.13%	35.55 13.76%	18.75 7.76%
June	198.43 57.74%	46.90 24.41%	174.03 54.51%	206.57 58.72%	197.53 57.63%	74.37 33.87%	62.65 30.14%
July	250.55 78.28%	43.60 38.54%	174.92 71.56%	202.46 74.44%	175.05 71.57%	92.40 57.06%	131.77 65.46%
August	248.70 91.60%	46.82 67.25%	163.66 87.77%	154.14 87.11%	152.83 87.02%	82.42 78.33%	136.15 85.65%
September	210.55 92.56%	48.36 74.09%	126.26 88.18%	129.33 88.43%	114.78 87.16%	89.51 84.11%	138.06 89.08%
October	217.20 88.12%	46.47 61.34%	166.44 85.04%	142.48 82.95%	168.09 85.16%	100.88 77.50%	153.20 83.95%
November	179.33 60.89%	15.39 11.78%	138.99 54.68%	152.16 56.91%	145.00 55.72%	56.40 32.87%	81.60 41.46%
December	164.11 53.10%	12.21 7.77%	114.50 44.13%	141.56 49.41%	138.16 48.80%	40.71 21.93%	52.02 26.41%

Table A-2: Monthly NBS biases by model and RCP, representation by magnitude difference from the historical observations and the percent difference.

	CanRCM4/ CanESM2	CRCRM5/ CanESM2	CRCRM5/ CNRM-CM5	CRCRM5/ MPI- ESM-LR	CRCRM5/ GFDL- ESM2M	RCA4/ CanESM2	RCA4/ Earth_ SMHI
January	14.22 16.84%	11.41 13.97%	13.78 16.40%	31.69 31.09%	24.53 25.88%	15.35 27.97%	13.16 23.05%
February	11.30 16.76%	4.51 7.44%	22.39 28.53%	31.27 35.79%	19.35 25.64%	6.70 13.56%	4.71 9.17%
March	37.75 36.78%	28.00 30.14%	33.10 33.78%	29.03 30.91%	14.95 18.72%	8.67 11.79%	8.28 11.31%
April	14.43 16.08%	14.90 16.52%	22.36 22.90%	22.35 22.89%	15.20 16.80%	6.22 7.63%	5.96 8.60%
May	20.47 21.90%	21.55 22.79%	32.12 30.55%	36.48 33.31%	25.00 25.50%	21.54 22.78%	13.20 15.31%
June	9.12 13.45%	15.93 17.15%	32.30 29.57%	48.95 38.88%	15.91 17.14%	22.91 22.94%	4.86 5.94%
July	5.59 9.16%	7.05 9.57%	43.17 39.32%	49.38 42.57%	31.14 31.86%	14.89 18.27%	25.61 27.77%
August	39.78 98.28%	9.11 12.81%	29.80 27.08%	27.05 25.21%	25.80 24.33%	29.03 56.68%	6.30 8.51%
September	37.47 76.97%	7.10 7.62%	20.57 19.27%	21.88 20.25%	19.46 18.43%	23.62 37.77%	11.02 14.67%
October	4.36 6.30%	16.64 18.43%	56.53 43.42%	29.29 28.45%	41.46 36.01%	13.12 21.67%	7.77 11.79%
November	8.13 8.20%	7.82 7.91%	27.00 22.88%	29.88 24.72%	25.26 21.73%	29.12 47.06%	33.45 58.13%
December	15.76 16.56%	10.65 11.82%	34.11 30.03%	35.89 31.12%	48.43 37.87%	24.35 44.19%	28.17 54.91%

Table A-3: Monthly precipitation biases by model and RCP, representation by magnitude difference from the historical observations and the percent difference.

	CanRCM4/ CanESM2	CRCRM5/ CanESM2	CRCRM5/ CNRM-CM5	CRCRM5/ MPI- ESM-LR	CRCRM5/ GFDL- ESM2M	RCA4/ CanESM2	RCA4/ Earth_ SMHI
January	74.16 31.86%	39.44 33.09%	20.67 11.53%	47.67 23.11%	25.27 13.74%	1.83 1.17%	7.79 4.68%
February	45.66 23.74%	45.25 44.64%	10.40 7.64%	18.71 11.32%	8.44 6.11%	19.76 15.58%	17.54 13.59%
March	15.69 6.26%	117.35 78.80%	114.81 75.80%	72.48 37.40%	111.10 71.60%	101.79 61.89%	102.46 62.55%
April	8.18 2.69%	108.85 53.54%	80.89 34.97%	73.33 30.70%	131.00 72.31%	105.94 51.37%	124.65 66.47%
May	141.27 44.99%	33.35 16.18%	146.19 45.84%	158.80 47.90%	182.56 51.39%	85.99 33.24%	71.83 29.37%
June	210.77 70.18%	70.10 43.91%	193.50 68.36%	208.75 69.98%	224.16 71.45%	156.61 63.62%	161.26 64.29%
July	233.46 78.92%	56.70 47.63%	171.90 73.38%	190.12 75.30%	183.38 74.63%	165.76 72.67%	187.49 75.04%
August	226.71 81.22%	39.56 43.00%	136.23 72.21%	146.08 73.59%	136.49 72.25%	134.74 71.99%	165.00 75.88%
September	178.40 74.67%	15.32 20.21%	100.05 62.31%	114.04 65.33%	99.00 62.06%	94.24 60.89%	127.38 67.79%
October	150.26 62.00%	6.89 8.09%	108.18 54.01%	105.66 53.43%	110.19 54.47%	65.17 41.44%	106.25 53.57%
November	112.16 43.62%	32.84 29.28%	84.43 36.80%	92.25 38.88%	90.45 38.42%	21.74 13.04%	52.89 26.73%
December	88.08 33.27%	48.69 38.05%	50.93 22.38%	68.35 27.90%	53.67 23.30%	1.58 0.89%	15.33 7.98%

Table A-4: Monthly runoff biases by model and RCP, representation by magnitude difference from the historical observations and the percent difference.

	CanRCM4/ CanESM2	CRCRM5/ CanESM2	CRCRM5/ CNRM-CM5	CRCRM5/ MPI- ESM-LR	CRCRM5/ GFDL- ESM2M	RCA4/ CanESM2	RCA4/ Earth_ SMHI
January	50.62 124.46%	46.26 102.72%	36.65 67.08%	36.30 66.00%	38.13 71.72%	52.04 132.59%	52.89 137.73%
February	24.25 92.18%	18.73 58.86%	22.63 81.01%	21.40 73.39%	25.87 104.73%	22.48 80.07%	21.06 71.38%
March	14.93 69.47%	3.72 11.37%	10.01 37.88%	13.21 56.88%	15.39 73.22%	2.67 7.92%	4.23 13.15%
April	1.87 10.86%	20.76 57.51%	8.42 35.44%	10.45 40.53%	10.44 40.51%	32.55 67.98%	34.42 69.18%
May	14.97 69.30%	36.95 84.79%	29.52 81.66%	30.10 81.95%	25.41 79.31%	88.37 93.02%	82.66 92.58%
June	10.02 40.88%	45.94 76.02%	58.58 80.17%	57.93 79.99%	49.34 77.30%	111.95 88.54%	110.28 88.39%
July	1.59 4.34%	44.42 55.82%	64.42 64.69%	61.31 63.55%	63.75 64.45%	112.52 76.19%	105.60 75.02%
August	14.66 30.47%	30.75 32.88%	49.49 44.09%	66.11 51.30%	56.58 47.41%	70.41 52.87%	69.67 52.61%
September	16.53 27.48%	27.16 26.16%	47.46 38.24%	59.69 43.78%	56.78 42.55%	34.20 30.85%	31.39 29.06%
October	15.43 23.67%	19.16 19.20%	54.14 40.18%	48.35 37.49%	39.44 32.86%	7.04 8.03%	1.14 1.40%
November	18.15 29.41%	0.48 0.59%	13.33 14.30%	10.86 11.97%	11.60 12.68%	22.90 40.18%	21.27 36.30%
December	50.59 99.43%	40.56 66.59%	19.79 24.22%	27.63 37.42%	26.37 35.12%	53.80 112.88%	55.18 119.21%

Table A-5: Monthly evaporation biases by model and RCP, representation by magnitude difference from the historical observations and the percent difference.