The State of Climate Modeling in the Great Lakes Basin

A Synthesis in Support of a Workshop held on June 27, 2019 in Ann Arbor, MI

ONTARIO
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Kristina Dokoska, Ontario Climate Consortium
Nishal Shah, Ontario Climate Consortium
Greg Mayne, Environment and Climate Change Canada
Wendy Leger, Environment and Climate Change Canada
Frank Seglenieks, Environment and Climate Change Canada
Armin Dehghan, Environment and Climate Change Canada
Shaffina Kassam, Environment and Climate Change Canada
Heather Arnold, Environment and Climate Change Canada
Shivani Vigneswaran, Environment and Climate Change Canada

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Executive Summary

The Great Lakes Basin (GLB) is one of the planet's largest freshwater ecosystems and is a vital source of drinking water for over 20 million people. In recent decades, the GLB has felt the impacts of climate change. These changes include higher temperatures, increased precipitation, reduced snow cover, abrupt lake warming, decreased annual lake ice coverage, increased wind speeds and waves, fluctuating lake levels, changes in timing and quantity of precipitation events, and an increased number of extreme weather events (Wang et al., 2017). These changes are and will continue to have a significant impact on the GLB's natural assets and population including but not limited to increased flooding, erosion of shorelines, contamination of water, and/or the loss and alterations of habitats for a variety of aquatic species (Mortsch, 1998). It is thus important that sound scientific projections of these climatic changes exist to assess the extent of the impacts of climate change within the GLB, and to communicate these impacts with GLB communities and residents. This report provides a summary of the state of climate modeling in the GLB and assesses model strengths and limitations, the knowledge gaps climate modelers face, the state of climate model users and translators, and recommendations for modelers, users, and translators moving forward.

The state of climate modeling in the Great Lakes has enhanced significantly in the past few decades. Global Climate Models (GCMs) have traditionally been used to characterize the Earth's climate through the modeling of the ocean-atmosphere circulation. The coarse spatial resolution that these models operate on creates challenges for the GLB. Most climatological studies in the GLB now use Regional Climate Models (RCMs) which offer higher resolution, dynamically downscaled GCM output under a more regional climate context. This increased resolution allows for a more accurate representation of climatological variables across hydrological features, which are typically represented as land surfaces on GCMs.

Efforts have been made in creating one- and three-dimensional hydrodynamic models for specific phenomena of the Great Lakes, and many modelers have started to couple these models with RCMs or GCMs to better predict climate impacts across the GLB. While there have been significant strides in climate change projections for the GLB, there exist numerous gaps in data collection, model development, and in the general understanding of the Great Lakes and their interactions from outside influences, such as large teleconnection patterns from the Gulf of Mexico and the Atlantic Ocean.

Current State of Knowledge Gaps in Data and Monitoring, Model Development, and of the Great Lakes themselves:

The following provides a summary of the gaps identified in the literature review undertaken on climate modeling for the Great Lakes:

1. *Data and Monitoring Gaps*

- Urban and agricultural land use
- Lake surface and profile temperatures
- Ice cover and ice thickness (e.g., areas of ridging and rafting)
- Energy exchanges and interfaces of land, lakes, ice, atmosphere, and hydrologic system
- Over-lake precipitation
- Over-lake evaporation
- Evapotranspiration
- Lake depth and opacity
- Eddy flux evaporation Lake circulation patterns
- Lake-effect snow (e.g., gridded products on snowfall and snow depth)

2. *Gaps in Global, Regional, and Hydrodynamic Models in the Great Lakes Basin*

- Teleconnections from large scale storms are not well captured over the Great Lakes because atmospheric dynamics are poorly represented
- Groundwater, base flow, and rivers are not represented in models
- Snowbelt zones are often underestimated
- Ice cover can be overestimated in 1D lake models
- Seasonal stratification in lakes is not always well predicted, and the water temperatures near the bottom of the Great Lakes are often misrepresented
- Thermal stratification beneath ice cover and radiative warming and mixing of near-surface water in the spring is not well represented
- Turbulence models tend to over-predict mixing in smaller lakes
- Lake surface temperature (LST) boundary conditions are usually poorly estimated.
- Models lack the resolution required to incorporate realistic lake-effect morphology
- Most models lack the ability to model historical climate patterns over the Great Lakes
- Lack of seasonal predictions of climate; often models predict annual conditions

3. *Knowledge Gaps in Understanding the Great Lakes in General*

- Lack of understanding on the impacts of reduced ice cover and warmer LSTs on lake effect precipitation

- Lack of understanding on temporal variations in the occurrences of harmful algal blooms and their relationships to climate change
- Lack of understanding of the impacts of teleconnections (e.g., Polar vortex) and their impact on the Great Lakes, and the lack of understanding on how teleconnection patterns will change with climate change
- Lack of understanding on the water quality impacts on rivers and Great Lakes from storm dynamics as well as nutrients and chemicals from urban and agricultural land use changes.
- Lack of understanding of the future of Great Lakes water levels and how these will change with climate change.
- Lack of understanding the causes and effects of rapid warming the GLB has experienced in recent years.
- Lack of understanding of lake-effect morphology on the Great Lakes and inter-lake differences in warming trends and sensitivity.

Recommendations

From the knowledge gaps listed above, a set of recommendations have been provided for climate modelers, information translators, and practitioners moving forward, these include:

1. Increase two-way coupling of models that incorporate the atmosphere, land, and lakes and increase research and funds to 3D modeling.
2. Enhance data collection and conduct targeted field studies on lake climatology to feed into and validate climate models, and enhance spatial-temporal data coverage.
3. Develop a shared set of data collection tools for operational users, climate modelers, and weather forecasters to project socio-economic impacts to residents of the GLB.
4. Conduct continuous diverse stakeholder engagement between climate modelers, users, translators, and funding agencies.
5. Continue to emphasize the connections between climate projections and local impacts.
6. Increase communication on the comparison of various climate model ensembles to practitioners.
7. Promote the importance of consistent approaches, where possible, being applied across similar regions in the GLB.
8. Build emerging climate information into existing portals and tailor its output, where possible, for different user groups.
9. Bolster available resources and opportunities to focus funding, specifically for Great Lakes scale climate modeling initiatives.

1. Introduction

1.1 The Great Lakes Basin

The five Laurentian Great Lakes are part of one of the world's largest surface freshwater ecosystems, spanning two Canadian provinces and eight states in the United States. Together, the Great Lakes contain nearly 20% of the planet's freshwater, providing drinking water to over 30 million people. The Great Lakes Basin (GLB) provides opportunities for hydro generation, shipping, agriculture, fishing, tourism, and recreation industries, and is part of the region's physical and cultural heritage. However, the impacts of industrialization, invasive species, toxic contaminants, agricultural runoff, and climate change pose significant threats to the GLB's well-being.

1.2 Climate Change Impacts and the Need for Climate Modeling in the Great Lakes Basin

The Great Lakes play an important role in local weather patterns and climate processes due to their vast sizes, depths, and degrees of thermal inertia. The Lakes produce many benefits to the GLB, as they provide optimal environments for certain species to thrive due to the mild and cool breezes from the Lakes. However, the Lakes also have the ability to cause infrastructure damage and disrupt critical services from harsh lake-effect snow and ice storms (Sharma et al., 2018). The effects the Lakes have on the climate have been studied for decades; however, there remain many knowledge gaps on the full extent of services the Lakes provide to the region. In addition, as the climate continues to change globally, the physical behaviour of the Great Lakes will also evolve over time, making it increasingly difficult to project and predict future climates for the area. Limitations in climate modeling in the GLB can inhibit our abilities to predict and communicate localized climate hazards and impacts, which increases the vulnerability of people, ecosystems and infrastructure within the GLB.

In recent decades, the GLB has felt the impacts of climate change, generally consisting of higher temperatures, increased precipitation, reduced snow cover, decreased annual lake ice coverage, increased wind speeds and waves, fluctuating lake levels, changes in timing and quantity of precipitation events, and an increased number of extreme weather events (e.g. snowstorms, ice storms, thunderstorms, hailstorms, high wind speed events) (Wang et al. 2017). These changes in climate can cause many cascading impacts, for example, variations in lake levels may lead to increased flooding events, erosion of shorelines, contamination of water, and/or the loss and alterations of habitats for a variety of aquatic species (Mortsch, 1998).

It is extremely important to plan for anticipated climatic changes and to reduce the negative impacts they may cause. By enhancing the way we examine current conditions, projecting future climates in the GLB, and communicating this information, decision-makers and resource managers will have the necessary information to develop climate change adaptation policies to help residents of the GLB withstand the negative impacts of climate change.

1.3 Objectives of this Report and Workshop

Environment and Climate Change Canada (ECCC) initiated a collaborative workshop on climate modeling in the Great Lakes Basin to be held in Ann Arbor, Michigan on June 27, 2019 to fulfill the objectives of both Annex 7 (Habitats and Species) and Annex 9 (Climate Change Impacts) of the Great Lakes Water Quality Agreement (GLWQA). Both annexes are working to bridge the gap between climate modelers and decision makers, and to enhance collaboration and communication within the climate modeling community.

Specifically, the objectives of the workshop and this report are to:

1. Review the existing Great Lakes regional climate modeling efforts, including the strengths, limitations and credibility of climate change projections and their applicability to the Great Lakes Basin;
2. Share preliminary results from relevant studies in Canada and the U.S.;
3. Identify gaps and areas of greatest uncertainty; and
4. Develop recommendations for future work.

By identifying the current gaps in climate modeling in the GLB, climate modelers and practitioners can work together to improve these models through funding, collaboration, and engagement activities. Appendix A provides an agenda of the day on June 27, 2019, and Appendix B provides an overview of the entire workshop.

2. Background

To ensure all participants at the workshop had a foundational understanding of climate modeling, the following section provides a brief background on climate modeling and key terminologies that will be used throughout the rest of the report and during the workshop. This section discusses the differences between Global Circulation Models and Regional Climate Models, various downscaling methods, ensemble approaches, and the different climate change scenarios used in climate modeling.

2.1 Global Circulation Models (GCMs) and Regional Climate Models (RCMs)

Global Climate Models (GCMs) are coupled ocean-atmospheric models that project future changes in climate over the entire Earth surface under alternative GHG emissions scenarios (Charron, 2016; EBNFLO, 2010). These models develop climate projections with a horizontal resolution usually ranging between 150 – 300 km, on continental scales (Wang et al., 2016) and are designed to characterize future climate on an annual, seasonal and monthly basis (EBNFLO, 2010). In general, three different types of GCMs exist: Atmospheric General Models (AGCMs), Atmospheric-Ocean General Circulation Models (AOGCMs), and Earth System Models (ESMs) (Charron, 2016). AGMs were the first GCMs to be developed. These models examine the atmospheric portion of the climate and its interaction with the land surface. AOGCMs examine how the atmosphere and land interact with physical ocean models (Charron, 2016). Lastly, ESMs are the latest generation of models and include biogeochemical interactions and cycles, as well as changes in land cover (e.g., vegetation types) (Charron, 2016). Since GCMs provide projections over larger spatial scales, limitations exist. Some of the most prominent limitations to GCMs are that GCMs cannot simulate smaller scale convective storms (i.e., thunderstorms), and as a result cannot account for some extreme events at the local scale (EBNFLO, 2010). They also have deficient land-atmosphere feedbacks; they lack the integration of lakes in the models; most are deficient in the resolution of the planetary boundary layer (PBL) and do not include cloud processes; they have insufficient surface heterogeneity; and they have dampened extreme weather conditions compared to historical observations (Notaro, in person).

RCMs have emerged as an increasingly valuable climate model. RCMs are high resolution models that are used to downscale the lower (or “coarser”) resolution GCM outputs, providing a physically realistic simulation of climate projections over a smaller geographical area (ECCC, 2017; Charron, 2016). RCMs produce climate projections on a much finer scale (ranging from 10 – 50 km, some even have resolutions of 4km) and produce more regionally-relevant climate information (e.g., the effects of the Great Lakes) than GCMs that can be evaluated against historical climate observations (Whan and Zwiers, 2015; Charron, 2016). As a result, RCMs allow for a more precise representation of land features such as lakes and rivers and ensures that consistency is maintained among different climate variables (Charron, 2016). Unlike GCMs, RCMs can project smaller scale storms (e.g., finer resolution RCMs can project thunderstorms), allowing the models to incorporate future storms and extreme events (EBNFLO, 2010). As a physical model, RCMs also provide the benefit of linking the interaction of GHG emissions with other components of the climate system (Charron, 2016). Given that RCMs are dynamically downscaled models, ensuring a range of projections are used will be necessary to ensure GCM biases and errors are not amplified.

2.2 Downscaling Methods

Downscaling is the process of generating climate information from a GCM with coarse spatial resolution to a finer spatial resolution (Wilby et al., 2004; Flint and Flint, 2012). The two types of approaches, statistical downscaling and dynamical downscaling have been established to achieve detailed regional and local atmospheric data (Castro et al., 2005).

Statistical downscaling is based on a statistical model that compares large-scale climate variables from GCMs to smaller scale regional or local climate variables (Wilby et al., 2004). It relies on historical relationships (also referred to as “stationary assumption”) among climate variables at different scales (Auld et al., 2016). There are three types of statistically downscaled approaches that can be applied, including weather classification schemes, regression models, and weather generators (Wilby et al., 2004). As the impacts of climate change become more significant, using a stationary assumption (i.e. relying on historical forcing conditions) will result in greater uncertainty among the statistically downscaled data, as important feedback cycles in the climate are not accounted for in these projections (e.g., the impact of warming temperatures and lake ice will exponentially increase the rate of lake effect snow and evaporation). Thus, using a stationary assumption is not necessarily a recommended approach to be taken to account for future changes in climate, particularly for extreme weather events, and processes that are dependent on other climate forces. The approach taken in statistical downscaling is therefore not physically verifiable (Wilby et al., 2004). Since statistical downscaling relies on historic relationships among climate variables at various scales, using a statistical relationship based on present-day conditions may not hold up under different forcing conditions in future climate projections, where the principle of stationarity no longer applies (Wilby et al., 2004). In addition, it is commonly understood that most statistical downscaling methods underestimate observed extremes, however, there are some statistical techniques (e.g., the probability density function) that have been used (e.g., by the Wisconsin Initiative on Climate Change Impacts – WICCI) that reproduce observed extremes and allows for probabilistic assessments. Therefore, the type of statistical downscaling impacts the robustness of historical (and future) climates.

Dynamical downscaling is based on a spatial-scale numerical atmospheric model, commonly referred to as a RCM (Castro et al., 2005). Traditional dynamical downscaling incorporates GCM data to provide the initial conditions, lateral boundary conditions, sea surface temperatures, and initial land surface conditions (e.g., general topography, large bodies of water) (Xu and Yang, 2012). It then continuously integrates RCMs using the initial data and the boundary conditions from the GCM to develop the projections (Xu and Yang, 2012). Depending on the purpose of the dynamic downscaling, RCMs are able to develop four types of downscaling including short-term weather simulations, seasonal predictions, regional weather simulations, seasonal predictions, and climate prediction.

Both statistical and dynamical downscaling techniques rely on GCMs to drive local-scale modeling and analysis, and ideally the uncertainty associated with GCMs should be transparent through the downscaling process (Wilby et al., 2004). A summary of the key advantages and disadvantages of both statistical and dynamical downscaling are provided in Table 1.

Table 1: Key advantages and disadvantages of downscaling techniques. (adapted from Hostetler et al., 2011).

Statistical	**Dynamical**
+ fast and inexpensive (relatively)	+ true simulation of high resolution forcing and climate
+ high resolution (e.g., 4 km or less)	+ large, internally consistent set of atmospheric and surface variable
+ multiple GCMs for ensembles and different emissions scenarios	+ avoids stationary assumption (i.e. uses trends into the future that differ from the historical rates of change, and incorporates feedback cycles)
- limited ability to account for finer scale topography (reducing ability to account for features like orographic precipitation over mountain ranges, or evaporation over lakes)	- time consuming (e.g., requires debiasing)
- may not conserve mass and heat	- limited number of GCMs used
- uses stationary assumption (uses historical rates of change to model the future), and mostly only models for precipitation and temperature	- added model biases

In addition, the Great Lakes Integrated Sciences and Assessments (GLISA) team at the University of Michigan have been working to develop a downscaled climate data guide for the Great Lakes Region. This short guidance document was initiated to aid practitioners in choosing or using downscaled data for various different projects. For example, the guide explains the limitations of statistical downscaling for the Great Lakes region, it recommends dynamical downscaling when an interactive lake model is included, and it discusses spatial resolution misconceptions and techniques of how to downscale projections further. For more information on this document, please contact GLISA.

2.3 Ensemble Approach

Previous research using AOGCMs to project future changes in climate has shown that no single model exists that can determine all possible future climates (Tebaldi et al., 2004). Research has shown that the use of a single model to project climate trends increases the number of errors within the climate modeling and can result in a misinterpretation of climate trends (Auld et al., 2016). Each individual model represents specific climatological processes and comes with its own set of biases (Sheffield et al., 2013).

The ensemble, or multi-model approach uses multiple models together to produce a full range of possible climate scenarios and represents those projections using statistical distribution. Statistical distribution allows the users to interpret trends probabilistically and address the uncertainties associated with the climate modeling (Auld et al., 2016). Using a multi-model approach provides better predictions and compares more favourably to observations than a single model (Auld et al., 2016). With the ensemble approach, individual biases present in a single model tend to be reduced while the uncertainty associated with the overall process is maintained and can be disseminated through further analysis and local-scale modeling. Ensembles can consist of multiple GCMs coupled with a single or multiple RCMs, one GCM coupled with multiple RCMs, or simply running one single model with an ensemble of “runs” (running the model to multiple climate scenarios). An ensemble of RCMs requires that users first select the GCM(s) that they wish to use followed by the selection of RCMs that they would like to downscale the GCM data from (Evans et al., 2013). While there is no best future scenario that can be applied for any given situation, the use of an ensemble approach allows for a more plausible approach to capture what the future may represent (Charron, 2016).

GLISA has also created a Great Lakes Ensemble of future climate projections and guidance for practitioners in the Great Lakes region, to increase the capacity of practitioners to be informed consumers of climate information. Click here for more information on GLISA’s Great Lakes Ensemble.

2.4 Climate Change Scenarios

Another uncertainty associated with modeling and projecting climate is the future of human behaviour, technology, and of the amount of carbon in the atmosphere. Therefore, in climate modeling, there exists a series of plausible pathways, otherwise referred to as “scenarios”, or targets that embody the relationships between human behaviour, emissions, greenhouse gas (GHG) concentrations, and temperature change. The most recently produced climate change scenarios are called Representation Concentration Pathways (RCPs), which have been endorsed by the Intergovernmental Panel on Climate Change (IPCC). RCP scenarios consider the impacts of policies that may reduce GHG emissions significantly (e.g., RCP 2.6), as well as the impact of the continued heavy reliance on fossil fuels (e.g., RCP 8.5). Figure 1 demonstrates the four RCP scenario projections through time, for three different greenhouse gases.

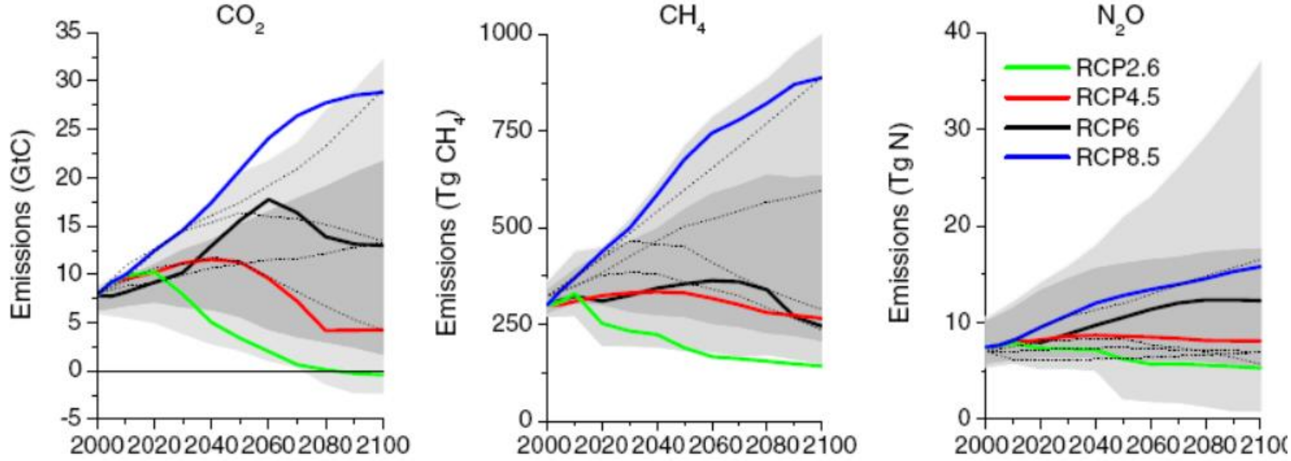


Figure 1: Graphs demonstrating the four Representative Concentration Pathways (RCPs) for carbon dioxide (CO^2) methane (CH^4), and nitrous dioxide (N$_2$O) (Van Vuuren et al., 2011).

Prior to the development of the RCP climate scenarios, climate modelers across the globe used (and some may still use) the SRES (Special Report on Emission Scenarios) climate scenarios, which do not account for all of the different mitigative futures available in the RCP climate scenarios. One of the main differences between the RCP and SRES climate scenarios is that RCP scenarios consider GHG concentrations, while SRES scenarios consider GHG emissions; this is due to the fact that carbon concentration in the atmosphere is not solely reliant on human-induced emissions, as the carbon cycle is much more complex than this (e.g., the carbon emitted from trees, the amount of carbon absorbed by oceans). Therefore, RCP climate scenarios are more commonly used, to account for the complexity of the carbon cycle into the climate models and the SRES scenarios are not generally used in the latest climate modeling exercises. Table 2 provides an overview of RCP concentration scenarios, with the comparative SRES emissions scenarios for reference throughout this report.

Table 2: The four Representative Concentration Pathways that have been used in the Fifth Intergovernmental Panel on Climate Change (IPCC) Assessment, with comparative SRES scenarios (IPCC, 2014).

Representative Concentration Pathway (RCP)	SRES Temperature Anomaly Equivalent	Definition
RCP 2.6	None	The lowest emission scenario, where peak radiative forcing is 3 Wm^{-2} and declines before 2100 (IPCC, 2014). This scenario would require all the main GHG emitting countries, including developing countries, to participate in climate change mitigation initiatives and policies.
RCP 4.5	SRES B1	The second lowest emission scenario, where stabilization without overshoot pathway to 4.5 Wm^{-2} and stabilization after 2100 (IPCC, 2014).
RCP 6.0	SRES B2	The second highest emission scenario, where stabilization without overshoot pathway to 6 Wm^{-2} and stabilization after 2100 (IPCC, 2014).
RCP 8.5	SRES A1F1	The highest emission scenario, where rising radiative forcing pathway leading to 8.5 Wm^{-2} in 2100, and continues to rise for some amount of time (IPCC, 2014). GHG concentrations are up to seven times higher than preindustrial levels.

In addition, GLISA is also developing a climate scenarios guide for practitioners, which frames SRES and RCPs as one type of scenario in a larger chain of information used to create climate change and climate impact scenarios (produced by climate impact assessment models and expert guidance). Please contact GLISA for more information on their climate scenarios guidance document.

3. An Overview of Climate Models that Incorporate Great Lakes Conditions

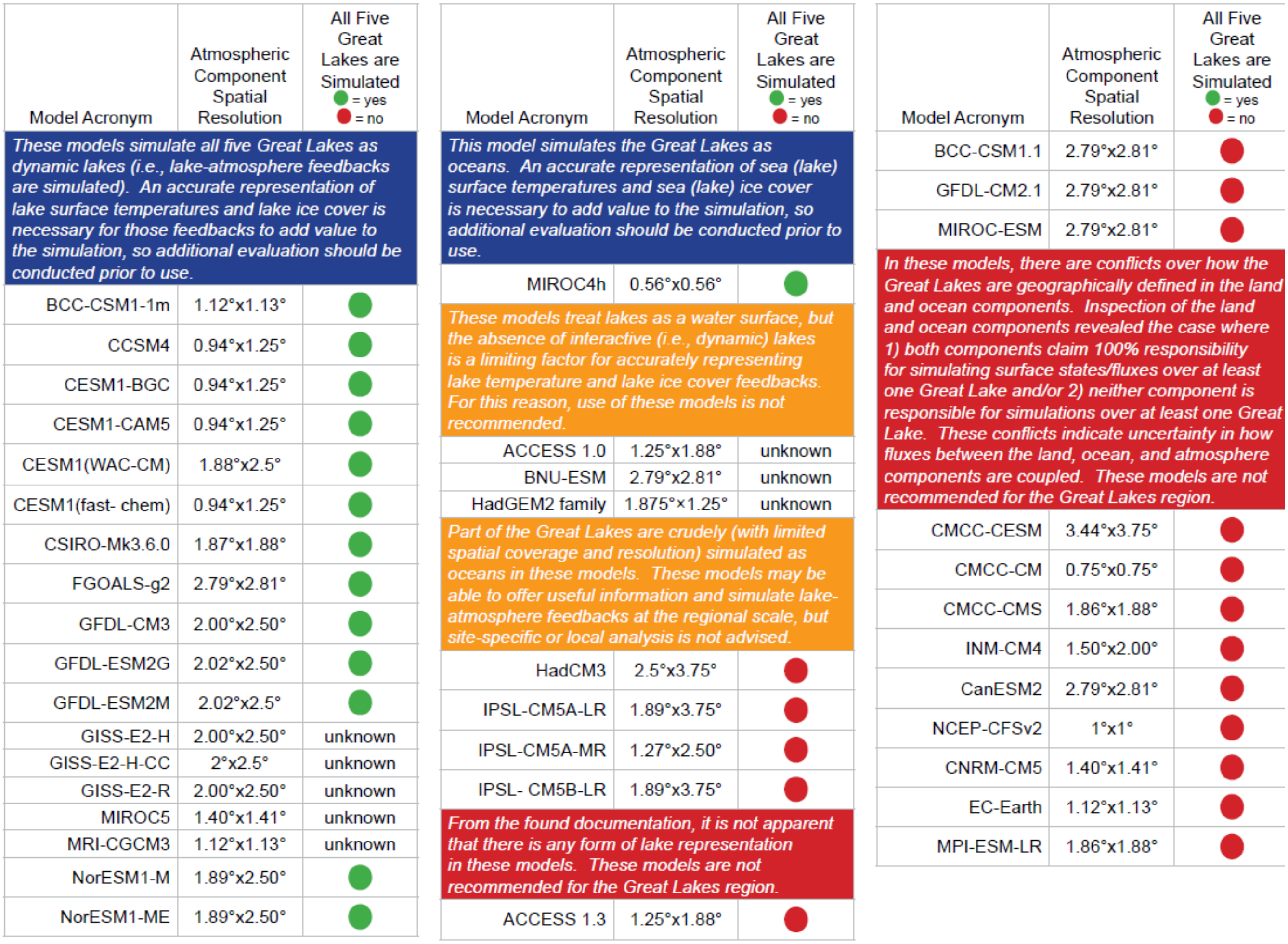
3.1 Taking Stock of Models in the Great Lakes: An Inventory

One of the key drawbacks that practitioners and planners come across when developing adaptation actions is the breadth of climate models that exist, and the complex language surrounding these. It is often difficult to choose appropriate climate models or methods to predict the future climate for a given area within the GLB. This section of the report will outline some of the GCMs, RCMs, and the more complex hydrodynamic models that have been used in the GLB to date, followed by their limitations, gaps, and uncertainties.

3.1.1 Global Circulation Models (GCMs)

Most GCMs were not designed with emphasis on lake-land-atmosphere interactions, despite the Great Lakes' influence on regional climate. As previously mentioned, GCMs usually have a horizontal resolution that varies between 150 to 300 km, limiting the ability for GCMs to appropriately account for the Great Lakes to a certain extent (e.g., the length of Lake Ontario is about 310 km). A study by GLISA (currently in review) evaluates how all 55 GCMs within the Coupled Model Intercomparison Project Phase 5 (CMIP5) models (models used in the latest IPCC report) incorporate the Great Lakes, if at all. The study showed that 18 of the GCMs simulate all five of the Great Lakes as "dynamic lakes" (i.e. models that account for certain lake-atmosphere feedbacks within the resolution of a GCM, in one-dimension), one simulates all the Great Lakes as oceans, three GCMs treat the Great Lakes as a water surface, but do not treat them as "dynamic" (i.e. do not account for lake temperature and lake ice cover feedbacks), four GCMs over simplify the geography of the Great Lakes, and treat them as low-resolution oceans, four GCMs do not have any form of lake representation, and nine had conflicts in the geographic representation of the Great Lakes and were not clear on how fluxes between land, ocean, and atmosphere were integrated (see Table 3 for more specific details). It should be noted that while this study shows which GCMs incorporate the Great Lakes, there is still uncertainty around how effective some of these models model climate in the area (e.g., some GCMs simulate all five Great Lakes as dynamic lakes, however, they may treat the lakes as shallow lakes that freeze over completely in the winter).

Table 3: Summary of Great Lakes representation in each of the Global Circulation Models in the CMIP5 Ensemble (GLISA, in review).



Model Acronym	Atmospheric Component Spatial Resolution	All Five Great Lakes are Simulated 🟢 = yes 🔴 = no
These models simulate all five Great Lakes as dynamic lakes (i.e., lake-atmosphere feedbacks are simulated). An accurate representation of lake surface temperatures and lake ice cover is necessary for those feedbacks to add value to the simulation, so additional evaluation should be conducted prior to use.		
BCC-CSM1-1m	1.12°x1.13°	🟢
CCSM4	0.94°x1.25°	🟢
CESM1-BGC	0.94°x1.25°	🟢
CESM1-CAM5	0.94°x1.25°	🟢
CESM1(WAC-CM)	1.88°x2.5°	🟢
CESM1(fast- chem)	0.94°x1.25°	🟢
CSIRO-Mk3.6.0	1.87°x1.88°	🟢
FGOALS-g2	2.79°x2.81°	🟢
GFDL-CM3	2.00°x2.50°	🟢
GFDL-ESM2G	2.02°x2.50°	🟢
GFDL-ESM2M	2.02°x2.5°	🟢
GISS-E2-H	2.00°x2.50°	unknown
GISS-E2-H-CC	2°x2.5°	unknown
GISS-E2-R	2.00°x2.50°	unknown
MIROC5	1.40°x1.41°	unknown
MRI-CGCM3	1.12°x1.13°	unknown
NorESM1-M	1.89°x2.50°	🟢
NorESM1-ME	1.89°x2.50°	🟢

Model Acronym	Atmospheric Component Spatial Resolution	All Five Great Lakes are Simulated 🟢 = yes 🔴 = no
This model simulates the Great Lakes as oceans. An accurate representation of sea (lake) surface temperatures and sea (lake) ice cover is necessary to add value to the simulation, so additional evaluation should be conducted prior to use.		
MIROC4h	0.56°x0.56°	🟢
These models treat lakes as a water surface, but the absence of interactive (i.e., dynamic) lakes is a limiting factor for accurately representing lake temperature and lake ice cover feedbacks. For this reason, use of these models is not recommended.		
ACCESS 1.0	1.25°x1.88°	unknown
BNU-ESM	2.79°x2.81°	unknown
HadGEM2 family	1.875°×1.25°	unknown
Part of the Great Lakes are crudely (with limited spatial coverage and resolution) simulated as oceans in these models. These models may be able to offer useful information and simulate lake-atmosphere feedbacks at the regional scale, but site-specific or local analysis is not advised.		
HadCM3	2.5°x3.75°	🔴
IPSL-CM5A-LR	1.89°x3.75°	🔴
IPSL-CM5A-MR	1.27°x2.50°	🔴
IPSL- CM5B-LR	1.89°x3.75°	🔴
From the found documentation, it is not apparent that there is any form of lake representation in these models. These models are not recommended for the Great Lakes region.		
ACCESS 1.3	1.25°x1.88°	🔴

Model Acronym	Atmospheric Component Spatial Resolution	All Five Great Lakes are Simulated 🟢 = yes 🔴 = no
BCC-CSM1.1	2.79°x2.81°	🔴
GFDL-CM2.1	2.79°x2.81°	🔴
MIROC-ESM	2.79°x2.81°	🔴
In these models, there are conflicts over how the Great Lakes are geographically defined in the land and ocean components. Inspection of the land and ocean components revealed the case where 1) both components claim 100% responsibility for simulating surface states/fluxes over at least one Great Lake and/or 2) neither component is responsible for simulations over at least one Great Lake. These conflicts indicate uncertainty in how fluxes between the land, ocean, and atmosphere components are coupled. These models are not recommended for the Great Lakes region.		
CMCC-CESM	3.44°x3.75°	🔴
CMCC-CM	0.75°x0.75°	🔴
CMCC-CMS	1.86°x1.88°	🔴
INM-CM4	1.50°x2.00°	🔴
CanESM2	2.79°x2.81°	🔴
NCEP-CFSv2	1°x1°	🔴
CNRM-CM5	1.40°x1.41°	🔴
EC-Earth	1.12°x1.13°	🔴
MPI-ESM-LR	1.86°x1.88°	🔴

It is important to consider the GCMs that incorporate the Great Lakes when developing a method for climate modeling for a specific area in the GLB. GLISA therefore recommends using the GCMs that treat all of the Great Lakes as dynamic lakes for climate analyses in the GLB. From these GCMs, RCMs can be derived and the large grid cells can be downscaled to a more appropriate scale to evaluate climate at the local level.

3.1.2. Regional Climate Models (RCMs)

RCMs are models derived and downscaled or reanalyzed from GCMs to a finer horizontal resolution, usually varying from 10 to 50 km grids. This section provides an overview of the most common RCMs that have been used in the GLB, and ensemble approaches that have been made available or used in climatological studies.

Firstly, there are four RCMs that appear to be more commonly used in the GLB. These are:

1. Canadian Regional Climate Model 5 (**CRCM5**) (or an earlier version of the model)
2. Regional Climate Model 4 (**RegCM4**) (or an earlier version of the model)
3. Weather Research and Forecasting model (**WRF**)
4. Canadian Regional Climate Model 4 (**CanRCM4**) (or an earlier version of the model)

The following table (Table 4) delves into more detail on each of these RCMs, such as their spatial resolutions, developers, and institutions they are hosted at. Please note that the spatial resolution of these models may vary depending on the study; the table therefore notes different studies that the models have been used in.

Table 4: Detailed descriptions of the most commonly used RCMs in the Great Lakes Basin.

Regional Climate Model	Description	Spatial Resolution	Developer	Institution	Studies where ensemble is used
CRCM5	The first CRCM was developed in 1991 at the University of Quebec at Montreal (UQAM). This version of the RCM is driven by the GCM Global Environmental Multiscale model (GEM). This RCM is an example of a collaborative effort between a modern global operational forecast provider and a university-based organization. In 2002, Ouranos was created and its Climate Simulations Team (CST) became responsible for the development of the operational versions of the CRCM and to carry out the	50 km by 50 km grids, centered on the Great Lakes, with a horizontal resolution of 0.5°	K. Winger	Université du Québec a Montréal (UQAM)	**Modeling in the Great Lakes Basin:** Goyette et al., 2000 Martynov et al., 2012 **Model itself:** Martynov et al., 2013 Scinocca and McFarlane, 2004 Šeparović et al., 2013

	climate-change projections. The Ouranos CST got strongly involved in the development of later versions of the model (CRCM4 and CRCM5)		S. Biner	OURANOS	
RegCM4	The Regional Climate Model system RegCM was originally developed at the National Center for Atmospheric Research (NCAR) in 1989 (Dickinson et al., 1989, Giorgi and Bates, 1989). Since then it has undergone major updates in 1993 (RegCM2), 1999 (RegCM2.5), 2006 (RegCM3) and most recently 2010 (RegCM4),and is now controlled by the International Centre for Theoretical Physics (ITCP). The RegCM was the first RCM to be documented in literature, and was the first model used to create the first month-long, or "climate mode" simulation (Giorgi 1990). The model is a community model, and has been designed for use by a variety of scientists in both industrialized and developing nations (Giorig et al., 2012). It is therefore public, open source, user-friendly, and has a portable code that can be applied to any region of the world. The model can also be interactively coupled to a 1D lake model, a simplified aerosol scheme, and a gas phase chemistry module. Model improvements include the development of a new microphysical cloud scheme, coupling with a regional ocean model, inclusion of full gas-phase chemistry, upgrades of some physics schemes (convection, planet boundary layer (PBL), cloud microphysics) and development of a non-hydrostatic dynamical core.	10 km by 10 km grid	Dickinson et al., 1989, Giorgi, 1990	Iowa State National Center for Atmospheric Research (NCAR)	**Modeling in the Great Lakes**: Bryan et al., 2015 Notaro et al., 2015 Bennington et al., 2014 Hostetler et al., 1993 Bates et al., 1995 Martynov et al., 2010 Holman et al., 2012 Notaro et al., 2013 **Model itself:** Giorgi et al., 2012 Elguindi et al., 2011

WRF	This is a mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. It features two dynamical cores, a data assimilation system, and a software architecture supporting parallel computation and system extensibility. The model serves a wide range of meteorological applications across scales from tens of meters to thousands of kilometers. WRF can produce simulations based on actual atmospheric conditions (i.e., from observations and analyses) or idealized conditions. WRF offers operational forecasting a flexible and computationally-efficient platform, while reflecting recent advances in physics, numerics, and data assimilation contributed by developers from the expansive research community. The model can provide a range of predictions of phenomena such as air chemistry, hydrology, wildland fires, hurricanes, and regional climate. While the WRF Model has a centralized support effort, it has become a community model, driven by the developments and contributions of an active worldwide user base.	Varying resolutions for different applications (e.g., sea surface temperature simulations can have a resolution of 5 km by 1 km, eddy-simulations can have a resolution of 50 –100 m, fire simulations can have a resolution of 200 by 800 m)	Skamarock et al., 2008	U Arizona National Center for Atmospheric Research (NCAR)	**Modeling in the Great Lakes Basin:** Anderson et al., 2018 d'Orgeville et al., 2014 Gula and Peltier, 2012 Xiao et al., 2018 **Model itself:** Skamarock et al., 2008 Powers et al., 2017 Liang et al., 2012

CanRCM4	CanRCM4 was developed by employing a new approach of "coordinated" global and regional climate modeling. This allows the model to incorporate dynamical driving parameters (e.g., wind, temperature, moisture), and allows for interpretation beyond the RCM's lateral boundaries, as it is coupled tightly with its GCM. CanRCM4 employs sea surface temperature and sea ice distributions. The RCM is paired with, and driven exclusively by, a global parent model (GCM) for all of its applications. CanRCM4's parent model is CanAM4, which forms the atmospheric component of the second generation earth system model CanESM2.	50 km by 25 km, or by 0.22° by 0.22° or 0.44°by 0.44°	Scinocca et al., 2016	Canadian Centre for Climate Modeling and Analysis (CCCma)	**Modeling in the Great Lakes Basin:** Kerr et al., 2018 **Model itself:** Scinocca et al., 2015 Scinocca et al., 2016

There are numerous RCMs that exist that offer detailed data on certain climate parameters; though it is important to note that not all have detail on all parameters. Therefore, climate modelers have begun to use ensembles of multiple RCMs or multiple RCM runs driven by different GCM boundary conditions, to capture reduce bias in the projections they want to study, and to provide more robust and reliable predictions (i.e. the more climate models that are used, the more likely the correct range of the future climate will be predicted).

3.1.2.1 RCM Ensembles Available for use in the Great Lakes Basin

The following section delves into six ensembles of RCMs that are commonly used in the GLB (NARCCAP, NA-CORDEX, Peltier Ensemble, Notaro Ensemble, USGS RCCV, University of Regina's Climate Portal, and York University's LAMPS Climate Data Portal). The section discusses the strengths and weaknesses of each of the RCM ensembles, and lists the various RCMs and GCMs used in each one. This section aims to synthesize and summarize the state of the use of climate ensembles within the GLB, to help practitioners choose a climate portal/ensemble in future climate modeling projects.

A) ***North American Regional Climate Change Assessment Program (NARCCAP) (this website provides additional information)***

The NARCCAP dataset contains high-resolution climate change scenario simulation outputs from multiple RCMs derived from multiple Atmosphere-Ocean General Circulation Models (AOGCMs) for a 30-year current and future periods. The RCMs are run at 50 km spatial resolution over a domain covering the conterminous United States and most of Canada and results are recorded at 3-hourly intervals. The driving AOGCMs are forced with the SRES A2 emissions scenario in the future period. This RCM ensemble was created to examine the combined uncertainty in future climate projections from global to regional models for North America.

NARCCAP uses five RCMs, which include:

- **CRCM4** (Canadian Regional Climate Model Version 4)
- **ECPC/ECP2 (Experimental Climate Prediction Center Regional Spectral Model)**
- **HRM3 (Hadley Regional Model Version 3)**
- **MM5I** (Fifth Generation Pennsylvania State University – National Center for Atmospheric Research (NCAR) Mesoscale Model)
- **RCM34** (International Centre for Theoretical Physics – ITCP Regional Climate Model Version 3)
- **WRFP/WRFG** (Two versions of the Weather Research and Forecasting Model)

NARCCAP also uses four AOGCMs to drive each of the RCMs listed above. These include:

- **CCSM3** (US National Centre for Atmospheric Research CCSM)
- **MRI-CGCM3** (Meteorological Research Institute CGCM Version 3)
- **GFDL CM2.1** (NOAA Geophysical Fluid Dynamics Laboratory Climate Model Version 2.1)
- **HadCM3** (UK Met Office Hadley Centre Climate Model Version 3)

Strengths:

- One of the GCMs used in the ensemble simulates all five Great Lakes as dynamic lakes (e.g., MRI-CGCM3), while another treats part of the Great Lakes as oceans (e.g., HadCM3) (GLISA, in review)
- Uses multiple RCMs and GCMs to strengthen overall results
-
- Consistent with historical observations in certain aspects (Wehner, 2012):
  - Demonstrated that the western US had higher temperatures in coastal regions (except in summer months) from 1971-2000, which is consistent with observations
  - Demonstrated that temperatures were lower over mountainous regions and the Great Plains, with a seasonal minimum in the winter, consistent with observations

Limitations:

- Some of the GCMs included in the ensemble do not show any form of representation of the Great Lakes (e.g., GFDL CM2.1) (GLISA, in review), which may impact results
- There is great variation between the models (resolution, seasonality) (Wehner, 2012)

- Comparisons between observations and model outputs showed large east-west gradients, where the eastern US had the greatest variation between the models
- Uses the previous version of CCSM (the latest model is CCSM2)
- Spatial resolution of 50 km square grid cells are too large to capture lake-effect patterns and for decision makers interested in data at a local scale (e.g., across a watershed, municipality, region, etc.)
- Uses the older climate change scenario of SRES A2

For more information on the evaluation of the NARCCAP climate ensemble with historical and future predictions, see the following resources:

- Bukovsky, 2012: *Temperature trends in the NARCCAP regional climate models*
- Bukovsky et al., 2013: *Towards assessing NARCCAP regional climate model credibility for the North American Monsoon: Current climate simulations*
- Horton et al., 2015: *Projected changes in extreme temperature events based on the NARCCAP model suite*
- Karmalkar (2018): Interpreting results from the NARCCAP and NA-CORDEX ensembles in the context of uncertainty in regional climate change projections
- Mearns et al., 2015: *Uses of results of regional climate model experiments for impacts and adaptation studies: The example of NARCCAP*
- Mesinger et al., 2006: *North American regional reanalysis*
- Sobolowski and Pavelsky (2012): *Evaluation of present and future North American Regional Climate Change Assessment Program (NARCCAP) regional climate simulations over the southeast United States*
- Wehner, 2012: *Very extreme seasonal precipitation in the NARCCAP ensemble: model performance and projections*

North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX) Ensemble (refer to this website for more information):

This is an ensemble of six dynamically downscaled RCMs, which include:

- **CRCM5** (Canadian Regional Climate Model 5)
- **RCA4** (Rossby Centre Regional Atmospheric Model 4)
- **RegCM4** (Regional Climate Model 4)
- **WRF** (Weather Research Forecasting model)
- **CanRCM4** (Canadian Regional Climate Model 4)
- **HIRHAM5** (Based on a subset of HIRLAM (High Resolution Limited Area Model) RCM and the ECHAM (European Centre developed at Hamburg) atmospheric general circulation model)

The RCMs listed above are run with six different GCMs, which include:

- **HadGEM2-ES** (U.K. Met Office Hadley Centre Earth System Model)
- **CanESM2** (Second Generation Canadian Center for Climate Modeling and Analysis Earth System Model)
- **MPI-ESM-LR** (Max Planck Institute for Meteorology Earth System Model LR)
- **MPI-ESM-MR** (Max Planck Institute for Meteorology Earth System Model MR)
- **EC-EARTH** (Irish Centre for High-End Computing EC-EARTH Model)
- **GFDL-ESM2M** (NOAA Geophysical Fluid Dynamics Laboratory Earth System Model Version 2M)

The ensemble is run for two different climate scenarios (RCP 4.5 and RCP 8.5) and the spatial resolution varies from 12km to 25-km grids (depending on the different RCMs used and the different driving GCMs).

Strengths:

- Uses a wide range of GCMs to test and validate RCM projections across North America
- One of the GCMs treats all of the Great Lakes as dynamic lakes (e.g., GFDL-ESM2M), and another treats the Lakes as a non-dynamic water surface (e.g., HadGEM2-ES) (GLISA, in review)
- All six RCMs are dynamically downscaled
- Freely accessible and accessible data portal
- Guidance documents on the use of the ensemble is provided on website
- Provides high resolution climate scenarios

Studies have shown the ensemble reproduces observed near-surface temperature and precipitation over most of North America well, and represents the Great Plains Low-Level Jet stream well (Martynov et al., 2013)

Limitations:

- Some of the GCMs included in the ensemble misrepresent the Great Lakes geographically in the models (e.g., MPI-ESM-LR, CanESM2, EC-Earth) (GLISA, in review)
- Some climate variables are not yet available for download or are in development
- Practitioners may find downloading time longer given the size of the dataset available
- Studies have shown NA-CORDEX to misrepresent precipitation in the eastern half of the U.S. in the winter, and the Great Plains in the summer (Karmalkar, 2018)
- Studies have shown the ensemble to show large variations in its ability to simulate observed temperature trends (Karmalkar, 2018)

For more information on the evaluation of the NA-CORDEX climate ensemble with historical and future predictions, see the following resources:

- Karmalkar (2018): *Interpreting results from the NARCCAP and NA-CORDEX ensembles in the context of uncertainty in regional climate change projection*

- Diaconescu et al., (2017): *Evaluation of CORDEX-Arctic daily precipitation and temperature-based climate indices over Canadian Arctic land areas*
- Giorgi et al. (2009): *Addressing climate information needs at the regional level: the CORDEX framework*
- Lucas-Picher et al., (2013): *Evaluation of the regional climate model ALADIN to simulate the climate over North America in the CORDEX framework.*
- Martynov et al., (2013): *Reanalysis-driven climate simulation over CORDEX North America domain using the Canadian Regional Climate Model, version 5: Model performance evaluation*

Peltier Ensemble (refer to this report for more information):

This ensemble was initiated out of the University of Toronto. The ensemble is composed of physics-based mini ensemble of five different physics configurations, using the U.S. Weather Research and Forecasting (WRF) Model simulations dynamically downscaled from the National Center for Atmospheric Research (NCAR) Community Earth System Model, version 1 (CESM1) GCM. The ensemble also uses the freshwater lake model (FLake) (section 3.1.3 provides additional details on this model). The spatial resolution of this ensemble is of 10-km grids, and all model runs are for the RCP 8.5 climate scenario.

Strengths:

- Incorporates the Great Lakes into models, using FLake
- Uses five physics components of the WRF to enhance climate projections
- Spatial resolution is very detailed at 10-km square grids
- Small biases in spatially-averaged temperature and precipitation (Peltier et al., 2017)

Limitations:

- Uses an outdated CCSM model (the latest version is CESM2)
- Uses one RCM and one GCM to drive climate projections
- Data is not available online as a standalone ensemble, but has been integrated into other portals and other ensembles of models (e.g., York University’s LAMPS portal, which is described on page 17)
- Strong biases in areas of higher topography (Peltier et al., 2017)
- Does not include the influence of sulfate aerosol forcing (which can further exacerbate the cold biases seen in the ensemble) (Peltier et al., 2017)

For more information on the evaluation of the Peltier climate ensemble with historical and future predictions, see the following resources:

- Peltier et al., (2017): *Uncertainty in Future Summer Precipitation in the Laurentian Great Lakes Basin: Dynamical Downscaling and the Influence of Continental-Scale Processes on Regional Climate Change*

- Gula and Peltier (2012): *Dynamical downscaling over the Great Lakes basin of North America using the WRF regional climate model: The impact of the Great Lakes system on regional greenhouse warming*
- D'Orgeville et al., (2014): *Climate change impacts on Great Lakes Basin precipitation extremes*
- Erler et al., (2015): *Dynamically downscaled high resolution hydroclimate projections for western Canada*
- Erler and Peltier (2016): *Projected changes in precipitation extremes for western Canada based upon high-resolution regional climate simulations*
- Erler and Peltier (2017): *Projected hydroclimate changes in two major river basins at the Canadian west coast based upon high-resolution regional climate simulations*

Notaro Ensemble (this website provides additional information):

This ensemble consists of one RCM, RegCM4, that downscales historical and future model output from six different GCMs listed below:

- **ACCESS1-0** (Australian Community Climate and Earth System Simulator)
- **CNRM-CM5** (Centre National de Recherches Météorologiques)
- **IPSL-CM5-MR** (Institut Pierre Simon Laplace)
- **MRI-CGCM3** (Meteorological Research Institute)
- **MIROC5** (Model for Interdisciplinary Research on Climate Version Five)
- **GFDL-ESM2M** (National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory)

The models chosen for the ensemble were based on statistical measures, resolution (e.g., the ratio between parent and child models), bias magnitude in the Great Lakes region compared to observations and climatology, range of future projections of regional temperature and precipitation, .
and representation of physical processes in the Great Lakes (e.g., hot/cold days, freeze-thaw cycles, growing season length). The ensemble has been coupled with three one-dimensional models to incorporate a lake, atmosphere, and land component (the Hostetler 1D lake model, the Pennsylvania State University National Center for Atmospheric Research Mesoscale Model (MM5), and the Biosphere-Atmosphere Transfer Scheme (BATS) – section 3.1.3 provides more information on these). The spatial resolution of this ensemble is grids of 25-km and this ensemble provides data for 30 different climate variables. All the models are run for the RCP 8.5 climate scenario, and all the GCMs that RegCM4 are ran at incorporate the effects of the Great Lakes (GLISA, in review).

Strengths:

- Three GCMs used in this ensemble treat all Great Lakes as dynamic lakes (e.g., MRI-CGCM3, MIROC5, GFDL-ESM2M), one that treats the Lakes as a non-dynamic water surface (e.g., ACCESS 1-0), and one that treats part of the Lakes as oceans (IPSL-CM5-MR) (GLISA, in review)

- 30 climate variables are available for download
- Freely accessible data and easy-to-use and interactive mapping website
- RegCM4 can reproduce the broad temporal and spatial patterns of lake ice and lake-effect snowfall in the Great Lakes Basin (Notaro et al., 2013).
- RegCM4 accurately represents historical observed lake features (e.g., maximum and minimum LSTs, ice cover, etc.) (Notaro et al., 2013).
- Thorough historical evaluations of the simulated climate and lake conditions were conducted and compared to climate observations, giving the ensemble credibility.

Limitations:

- One GCM misrepresents the Great Lakes geographically (e.g., CNRM-CM5)
- Longer downloading time (e.g., each variable for each timeframe is about 670 NetCDF files in total), however, access may can be granted to the server.
- RegCM4 is unable to simulate for remote climatic responses to the Great Lakes (e.g., beyond the eastern U.S. and southeastern Canada), and the GCMs that do simulate these have inaccurate representations of these phenomena due to their coarse grid sizes (Notaro et al., 2013).
- RegCM4 does not capture interannual variability in nlake ice and temperature (Bennington et al., 2014).

For more information on the evaluation of the Notaro climate ensemble with historical and future predictions, see the following resources:

- Bennington et al., (2014): *Improving climate sensitivity of deep lakes within a Regional Climate Model and its impact on simulated climate*
- Holman et al. (2012): *Improving historical precipitation estimates over the Lake Superior basin*
- Notaro et al. (2013): *Influence of the Laurentian Great Lakes on Regional Climate*

USGS Regional Climate Change Viewer (RCCV) (refer to this report for more information):

The USGS has completed an array of high-resolution simulations of present and future climate over Western and Eastern North America by dynamically downscaling four GCMs, using the RCM RegCM3, and using PRISM (Parameter-elevation Relationships on Independent Slopes Model) data sets (which calculates climate-elevation regressions for different elevations – gridded historical climate averages). The four GCMs used in this ensemble include:

- **NCEP** (National Centers for Environmental Prediction)
- **MPI ECHAM5** (Max Planck Institute for Meteorology (MPI) ECHAM5)
- **GENMOM** (combination of the GENESIS V3.0 and the MOM V2.0 oceanic GCM)
- **GFDL CM 2.0** (NOAA Geophysical Fluid Dynamics Laboratory Climate Model Version 2)

Simulations were run over 50- and 15-km grids. All simulations span the present (for example, 1968–1999), common periods of the future (2040–2069), and two simulations continuously cover 2010– 2099, using the A2 climate scenario. The ensemble models are also coupled with BATS (Biosphere-Atmosphere Transfer Scheme – section 3.1.3 provides more information on this model), which simulated surface processes related to vegetation (e.g., leaf temperatures, phenology, evapotranspiration).

Strengths:

- RCM used incorporates representation of 1D lakes
- Runs the RCM with multiple GCMs
- Uses PRISM, which incorporates important local topographical features into model
- Easy to use, can view the data before downloading

Limitations:

- Uses one RCM (RegCM3) which is not updated to the latest version (RegCM4)
- GCMs used comprise the CMIP3 ensemble
- Climate scenario used is A2 from SRES
- Comparisons to observed data shows that this ensemble does not accurately historical climates, there are biases from the incorporation of 3-D models into RegCM3, and the ensemble does not accurately represent for high resolution topography (USGS, 2019).
- Data only available based on political boundaries (e.g., states, counties) and hydrological units (HUC2, HUC4, and HUC8) (USGS, 2019).

- For more information on the evaluation of the USGS Regional Climate Change Viewer ensemble with historical and future predictions, see the following: USGS (2019): Model Evaluation.

University of Regina Ensemble (see Ontario Climate Change Data Portal for more information)

This ensemble is composed of RegCM4 that is driven by five different GCMs for the RCP 8.5 climate scenario:

- **CanESM2** (Second Generation Canadian Centre for Climate Modeling and Analysis)
- **HadGEM2-ES** (U.K. Met Office Hadley Centre Earth System Model)
- **GFDL-ESM2M** (NOAA Geophysical Fluid Dynamics Laboratory Earth System Model Version 2M)
- **IPSL-CM5A-LA** (Institut Pierre Simon Laplace Model CM5A-LA)
- **MPI-ESM-MR** (Max Planck Institute for Meteorology Earth System Model MR)

The ensemble also provides climate-projected IDF curves for Ontario for the RCP 4.5 climate scenario, using the PRECIS driven by the HadGEM2-ES GCM. The ensemble has a spatial resolution that ranges from 25- to 50-km grids, and projects for two climate scenarios, RCP 4.5 and RCP 8.5. The ensemble is also coupled with a one-dimensional model, which is able to simulate lake ice and lake-effect snow in the Great Lakes and allows for simulations on seasonal influences of the lakes.

Strengths:

- One of the GCMs used in the ensemble simulate all five Great Lakes as dynamic lakes (e.g., GFDL-ESM2M), while another treats lakes as water surfaces but not dynamically (e.g., HadGEM2-ES)
- RegCM4 is a flexible, portable and easy to use RCM that has been dynamically downscaled
- Provides future intensity-duration-frequency curves, which can be less common
- Data source and portal is user-friendly and freely accessible
- Data comes in text (TXT) format rather than more intensive files (e.g., NetCDF files), which can benefit practitioners with limited experience in data processing or modeling

Limitations:

- Some of the GCMs included in the ensemble misrepresent the Great Lakes in the models (e.g., CanESM2) (GLISA, in review), which could impact results
- The ensemble is based on one RCM, which could limit the range of climate projections
- IDF curves are only available for the RCP 4.5 climate scenario
- Projections only available across the Province of Ontario, and not the entire GLB at this time

For more information on the evaluation of the Ontario Climate Change Data Portal ensemble with historical and future predictions, see the following:

- Wang and Huang (2015): *Technical Report: Development of High-Resolution Climate Change Projections under RCP 8.5 Emissions Scenario for the Province of Ontario*

York University LAMPS Ensemble (see the LAMPS York University Portal for more information)

This dataset takes a slightly different approach, and contains a “super-ensemble” of 209 climate members derived from both GCMs and RCMs (47 of which have been dynamically downscaled, and 167 members have been statistically downscaled). The spatial resolution of the parameters is 10 by 10 km grids. This dataset aggregates ensembles from five different institutions, some of which have been described above: York University, Pacific Climate Impacts Consortium (PCIC), North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX), University of Regina, and the Peltier ensemble from the University of Toronto). Information is projected for all four RCP climate scenarios (e.g., RCP 2.5, 4.5, 6.0, and 8.5).

Strengths:

- The super ensemble approach allows for more robust climate outputs
- Spatial resolution of 10 by 10 km grids for all model runs
- Data source and portal is user-friendly and freely accessible

- Data in CSV. Format (easily used in Microsoft Excel)

Limitations:

- Data are available across the Province of Ontario, and not yet across the entire GLB
- Because of the numerous amounts of model runs used, there are large ranges in model outputs, which can be difficult to understand and interpret (e.g., projected annual precipitation ranging from –20 mm to + 80 mm)
- Majority of climate model runs were statistically downscaled (which is not useful for future projections of lake-effect snow as it doesn't consider changing ice cover)
- Not all RCM models used were run over the same time periods

Due to the large range of the models in the super-ensemble, historical comparisons of the models have not been conducted in a single paper. Since this portal includes NA-CORDEX, Peltier, University of Regina ensembles, please see the historical comparisons that were listed in the respective sections above.

As this section demonstrates, there are strengths and limitations to all RCM ensemble approaches within the GLB, particularly depending on whether the user of these models are also model developers and scientists, translators or users (e.g., decision-makers). As technology and data collection continues to evolve, these ensembles will continue to improve. For more information on the specific projections of these ensembles, please see Appendix F.

In general, RCMs have the spatial resolution to incorporate the Great Lakes, whereas GCMs are too coarse to resolve the Lakes. However, RCMs can be limited by the fact that lake models are excluded in most of the ensembles (e.g., the Great Lakes are sometimes interpolated based on Hudson Bay or Atlantic Ocean sea surface temperatures (SSTs)s), which are able to quantify energy and water interchanges between lakes and the atmosphere (Sharma et al., 2018). In addition, RCMs tend to be limited in nonlocal influences that span beyond the model's lateral boundaries. This can result in the exclusion of major teleconnection patterns and chemical components of the atmosphere in climate modeling, which have important influences on a region's climate (Scinocca et al., 2016). Therefore, it is extremely important to couple RCMs with hydrodynamic models to account for energy fluxes and exchanges between the lakes and the atmosphere to model more realistic climate futures in the GLB, which will be discussed in the following section.

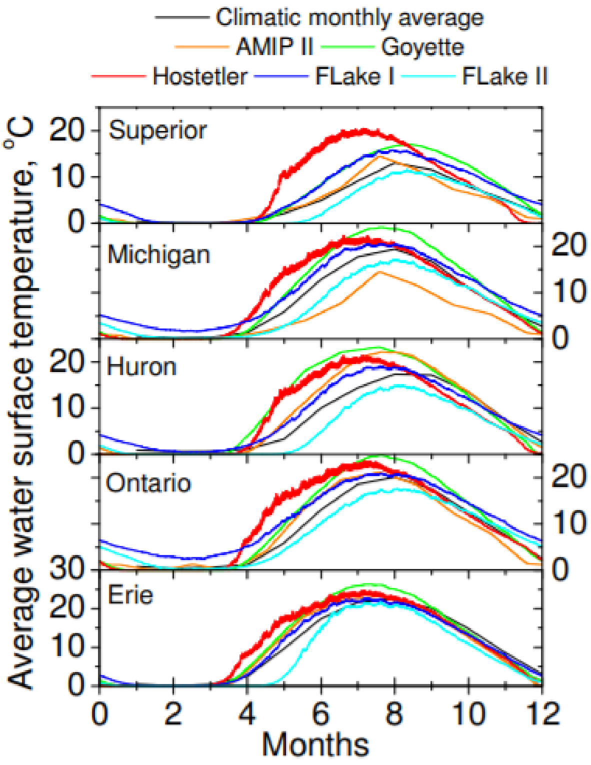


Figure 2: One-dimensional models (e.g., Goyette, Hostetler, FLake I and II) coupled with the Canadian Regional Climate Model 4 (CRCM4) for each Great Lake. Values represent 26-year-long averaged surface sea temperature values. Source: Martynov et al., 2010.

3.1.3. Hydrodynamic Models

Many of the datasets and approaches developed for use in the GLB consist of using hydrodynamic models, coupled with various RCMs or GCMs to model the Great Lakes dynamically for future climate scenarios (e.g., see Figure 2). This section provides an overview of hydrodynamic models that have been used in the GLB (please see Appendix C for a full list of 1-D models used in the GLB).

There are many specific hydrodynamic models that model various components of the Great Lakes, which can be used to evaluate lake-specific parameters, such as over-lake evaporation, LST fluxes, water vapour mixing ratios, lake heat storage, snow accumulation, and many more. The following section lists the one-, two-, and three-dimensional hydrodynamic models that have been used in the GLB (see Appendices B and C for a detailed list of these models, their characteristics and their limitations). Please note that this list does not capture every model and is not meant to be exhaustive.

One-Dimensional Models:

Many one-dimensional models have been developed in the past few decades to aid in the understanding of the physical processes of lakes and how they interact with the atmosphere and land. Some examples of lake and land models include:

Lake Models

Thermodynamic models:

- Lake Evaporation and Thermodynamics Model (**LETM**) (Croley, 1989)
- Coupled Hydrosphere-Atmosphere Research Model (**CHARM**) (Lofgren, 2004)
- Mixed Layer Model (Goyette et al., 2000)
- Lake, Ice, Snow, and Sediment Model (**CLM4-LISS**) (Subin et al., 2012)
- Canadian Small Lake Model (**CSLM**) (MacKay et al., 2017)

Two-Layer models based on the similarity theory[1]:

- Freshwater Lake model (**FLake**) (Mironov, 2008)

Thermal Diffusion models with eddy diffusivity:

- Hostetler model (Hostetler and Bartlein, 1990)

Land Models:

Many of these one-dimensional models have been coupled with a variety of GCMs, RCMs, as well as other hydrodynamic models for the prediction of climate over the Great Lakes. For example, GCMs have been coupled with 1-D models like Goyette et al.'s (2000) mixed layer model with the Canadian Regional Climate Model (CRCM). Subin et al.'s (2012) Lake, Ice, Snow, and Sediment model (LISS) has been coupled with the Community Land model 4 (CLM4). Notaro et al. (2013, 2015, and 2016) have also coupled the RCM RegCM4 with the Hostetler model, the WRF, and other one dimensional land surface models, to capture seasonal cycles and long-term trends in air temperatures, winter precipitation, lake effect precipitation, snow cover, lake temperature, lake ice, runoff, and net basin supply. Efforts have also been made to dynamically couple 1-D models together with atmospheric models. For example, the WRF model has been coupled with Community Land Model (CLM) and a one-dimensional 10-layer lake model (Gu et al., 2015; Subin et al., 2012; Xiao et al., 2016). Gula and Peltier (2012) have also attempted to couple the FLake model with the WRF in regional climate simulations.

These one-dimensional models have improved research in the GLB significantly over the past few decades, however, there are many limitations that remain in these models that do not capture all components of the Great Lakes. For example, Mallard et al. (2014) note how many of the models do not

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[1] The Similarity Theory assumes the same temperature-depth curve of stratified lake layers between the upper mixed layer and the basin bottom of a lake (Golosov and Kreiman, 1992).

accurately account for thermodynamics in the Great Lakes, especially for Lake Superior, due to its depth. Many climate modelers have also indicated that these models also generate large biases in LSTs, stratification timing, and ice cover, and they also tend to underestimate long-term limnological trends in the Great Lakes (Lofgren, 2004; Gula and Peltier, 2012; Notaro et al., 2013). Therefore, one-dimensional lake models require extensive tuning and research. However, three-dimensional models have also been developed to further improve modeling of the Great Lakes.

Three-Dimensional Models:

Three-dimensional models have been developed to capture lake processes that are missing in one-dimensional models. The following list captures some of the 3-D models that have been used in the GLB (see Appendix D for more details on each of these models):

- **POM** (Princeton Ocean Model) (Blumberg and Mellor, 1987)
- **FVCOM** (Finite Volume Community Ocean Model) (Chen et al., 2006)
- **NEMO** (Nucleus for European Modeling of the Ocean) (Dupont et al., 2012)
- **EFDC** (Environmental Fluid Dynamics Code) (Hamrick, 1992; Arifin et al., 2016)
- **GLIM** (Great Lakes Ice-Circulation Model) (Wang et al., 2010)
- **GLARM** (Great Lakes-Atmosphere Regional Model) (Xue et al., 2017)

Studies have shown the advantages of two-way coupling of an RCM with a 3D hydrodynamic model. This is the current direction of next-generation model development and the most likely method for obtaining reliable projections of the future impacts of climatic trends and interannual variability on the Great Lakes system from a regional modeling perspective (Xue et al., 2017).

One of the most common 3-D models is the Princeton Ocean Model (POM), which has been used by NOAA’s Great Lakes Environmental Research Laboratory (GLERL) and by many other researchers (Beletsky et al., 2006, 2013; Fujisaki et al., 2013; Huang et al., 2010). The POM has since been replaced with the 3-D Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2006). The FVCOM has been used to study many different phenomena, such as simulations of Lake Superior (Xue et al., 2015), flows in the Straits of Mackinac which connect Lakes Michigan and Huron together (Anderson and Schwab, 2013), and climate studies for the entire GLB (Bai et al., 2013). FVCOM has also been coupled with the NASA-Unified WRF (NU-WRF) model to simulate lake-effect snowstorms in the GLB (Notaro et al., 2019)

Environment and Climate Change Canada has also developed a 3-D coupled lake-atmosphere-hydrological modeling system, based on the Global Environmental Multiscale model (GEM), a surface and river routing model, MESH (Modelisation Environmentale Surface et Hydrologie), and a 3-D hydrodynamic model from the Nucleus for European Modeling of the Ocean (NEMO) system (Dupont et al., 2012). Further enhancements have also been made to the Environmental Fluid Dynamics Code (EFDC) for Lake

Ontario (Arifin et al., 2016), and Wang et al. (2010) have recently developed a 3-D model to evaluate seasonal cycles of Lake Erie temperatures on lake circulation and thermal structures.

More recently, Xue et al. (2017) have developed a new two-way coupled 3D regional climate modeling system for the Great Lakes (GLARM), to model large-lake hydrodynamics and regional climate dynamics over the Great Lakes region. This model provides future projections on seasonal and interannual variability of regional climate, lake circulation, thermal structure, and ice cover of each of the Great Lakes, as well as estimated of surface heat and moisture fluxes.
There has been a limited amount research conducted to couple these 3-D models with atmospheric models and RCMs to date. Xue et al. (2017) coupled FVCOM with RegCM4 in order to get a better understanding of hydro-climatic interactions, while Long et al. (2016) used the NEMO model with the CanRCM but were not able to directly couple the two together. To fully capture the interactions between the lakes, atmosphere, and land, it is important to advance modeling in this direction (i.e., coupling 3-D hydrodynamic models with atmospheric models).

3.2 Limitations, Gaps and Uncertainties

Many climate modelers emphasized data gaps and limitations within the GLB, as well as gaps in the models themselves. The following section highlights the limitations and gaps that have been gathered through a literature review of the models reviewed in Section 3.1 of this report.

Data Gaps in the Great Lakes Basin:
The following list is a summary of Great Lakes data needs from authors of the scientific journals reviewed for this study (feedback from the workshop was also included in this list). These include refining and/or focusing on:

- Urban and agricultural land use (Sharma et al., 2018)
- Lake surface and profile temperatures (Sharma et al., 2018, Notaro, in person)
- Ice cover (Sharma et al., 2018)
- Ice thickness (e.g., areas of ridging and rafting) (Goyette et al., 2000)
- Energy exchanges at interfaces of land, lakes, ice, atmosphere, and hydrologic system (Laird and Kristovich, 2002; Lofgren, 2004; Sharma et al., 2018)
- Over-lake precipitation (DeMarchi et al., 2009; Sharma et al., 2018)
- Over-lake evaporation (DeMarchi et al., 2009; Sharma et al., 2018; Croley, 1989)
- Evapotranspiration (Lofgren, 2004)
- Lake depth and opacity data (Subin et al., 2012; Martynov et al., 2010)
- Eddy flux evaporation measurements for Lake Ontario (Arifin et al., 2016)
- Lake-effect snow (i.e. through remote sensing) (e.g., gridded products on snowfall and snow depth) (Notaro, in person)

Although many of the items on this list are currently being observed and recorded, authors expressed that there is scarcity in data across the lakes, there is not enough detail in the data, the data exists but is only available for short periods of time (e.g., a few hours or a few days), or the data exists but is not publicly available. For example, researchers have conducted aircraft observations of energy exchanges, thermodynamics, over-lake snowfall for part of the Great Lakes (e.g., Braham and Kelly, 1982); however this data is only taken over a period of a few hours (Sharma et al., 2018).

It was also noted that data does exist for many of the parameters listed above (e.g., ice cover, precipitation, lake sensible and latent heat); however, it is difficult to ground truth to these data points and integrate them into the models. Other parameters were included in the list above as there is a need for more instrumentation and monitoring (e.g., for over-lake precipitation and evaporation), since the data that currently exists is scarce and is often poorly estimated across the Great Lakes (DeMarchi et al., 2009). Laird and Kristovich (2002) and Lofgren (2004) also state that energy exchanges between lakes, air, and ice are observed less frequently (e.g., missing data on air temperatures and humidity gradients near shorelines, ice thickness and cover). Modeling lake ice has therefore been difficult, as there is missing data to validate the models (e.g., heat exchanges, momentum, and mass fluxes of lake ice).

Although there remain many gaps in the collection in data currently, there are many organizations that have started to monitor and collect very useful data within the GLB, that are used to calibrate and validate climate models, and can be used as climate data inputs once the datasets have about 30 years of data (making up a climate normal period). One example of this is the Great Lakes Evaporation Network (GLEN). This is grassroots network of scientists in both the U.S. and Canada that measure year-round evaporation rates on the Great Lakes in a sustained, continuous fashion, that began in 2008. Other such examples include the Global Lake Ecological Observatory Network (GLEON), Great Lakes Observing System (GLOS), and the Global Lake Temperature Collaboration.

Gaps in Global, Regional, and Hydrodynamic Models in the Great Lakes Basin:
The following represents the gaps observed from the literature on all kinds of models within the GLB:

- Teleconnections from large-scale storms are frequently not well captured over the Great Lakes because atmospheric dynamics over the Lakes are poorly represented in the climate models. The models currently do not fully capture the intensity, duration, and timing of convective large-scale storms (Sharma et al., 2018)
- Groundwater, base flow, and rivers are not represented in models (Croley, 1989; Dickinson et al., 1993)
- Snowbelt zones are often underestimated (Goyette et al., 2000)
- Seasonal stratification in lakes is not always well predicted, and the water temperatures near the bottom of the Great Lakes are often misrepresented (Subin et al., 2012; Martynov et al., 2010; Stepaneko et al., 2010)
- Thermal stratification beneath ice cover, radiative warming, and mixing of near-surface water in the spring is not well represented (Keitzl et al., 2016; Mironov et al., 2002)
- Turbulence models tend to over-predict mixing in smaller lakes (Stepaneko et al., 2010)

- LST boundary conditions are usually poorly estimated as many models do not capture hydrodynamic feedbacks and do not explicitly simulate the fluxes of moisture, heat, and momentum across interfaces (Sharma et al., 2018; Zhong et al., 2016)
- Models tend to poorly represent future lake-effect snowfall dynamics (Notaro et al., 2014)
- Models tend to project excess ice cover, poor timing of stratification, insufficient variability in lake surfaces temperatures (Notaro, in person).
- Models lack the resolution required to incorporate realistic lake-effect morphology (Notaro, in person)
- Most models lack the ability to model historical climate patterns over the Great Lakes (Notaro, in person)
- Lack of seasonal predictions of climate; often models predict annual conditions (Notaro, in person)
-

Knowledge Gaps in the Understanding of the Great Lakes in General:

While data and models can be limited, Sharma et al. (2018) have identified various gaps in the understanding of the Great Lakes in general, which require further research and investigation to enhance the models in the future. Some of these gaps include:

- Lack of understanding on the impacts reduced ice cover and warmer LSTs on lake-effect precipitation (produces both increases and decreases)
- Lack of understanding on temporal variations in the occurrences of harmful algal blooms (HABs) and their relationships to climate variability and change
- Lack of understanding of the impacts of teleconnections (e.g., Polar vortex) and their impact on the Great Lakes, and the lack of understanding on how teleconnection patterns will change with climate change
- Lack of understanding on the water quality impacts on rivers and Great Lakes from storm dynamics as well as nutrients and chemicals from urban and agricultural land use changes.

Others have identified additional knowledge gaps, which include the following:

- Lack of understanding of the future of Great Lakes water levels and how these will change with climate change (Notaro et al., 2013).
- Lack of understanding the causes and effects of rapid warming the GLB has experienced in recent years (e.g., theories include the ice-albedo effect, the stratification of the lakes and winter severity, or the atmospheric temperature and cloud changes) (Zhong et al., 2016).
- Lack of understanding of lake-effect morphology on the Great Lakes and inter-lake differences in warming trends and sensitivity (Notaro, in person).

While many gaps in data collection, modeling, and in the general understanding of the Great Lakes for climate modelers exist, gaps also exist in the understanding of climate modeling from a user's perspective. The following section will highlight the uses and needs of users of climate information in the GLB, and how climate modelers can aid practitioners in the understanding of climate information.

4. Applying Climate Model Information across the Great Lakes Basin

Ideally, models that capture the best available science and considerations would be used to assess potential risks and impacts, and plans would be created to respond to the latest information. However, practitioners and decision makers face a number of barriers to access the best available climate data (Environmental Commissioner of Ontario, 2015) including:

- Low awareness of what is considered “best” available climate data and where it is available;
- Inability to understand and incorporate climate data into decision making;
- Large data translation required to access and use the best data; and
- Low capacity or expertise in climate science to understand the limitations or caveats of climate data use.

Notably, a number of these barriers have been improved since the release of the ECO (2015) report, and this section explores the extent to which the latest climate data are accessed for applications and decision making.

4.1 Users of Climate Model Information

There are numerous types of users who typically access or require the provision of climate data. These can range from those interested in basic summaries of trends to those requiring advanced decision support tools for specific sectoral-based studies or applications. It is important to note as well, that these users are affiliated across a range of different types of organizations, such as government agencies, academic institutions, non-profits, private sector consultants, industry and watershed management agencies. A survey conducted in 2015 across the Province of Ontario and across a broader network of climate adaptation practitioners (a total of 114 respondents) provides some insight into the types of these users, where they access climate information in the GLB and what this information is being used for (Morand et al., 2015). A couple conclusions from this survey include:

1. The top three future climate conditions of most interest are extreme rainfall events, long term precipitation changes, and long-term temperature changes;
2. Open source, government-operated datasets, and portals are most preferred when it comes to accessing climate data that can be justified among decision makers; and
3. Respondents prefer web-based accompanying guidance and descriptions of climate data and information products to better understand the approaches used to derive future projections and to improve their level of understanding related to uncertainty;

Figure 3 illustrates the applications for which users are most interested in accessing future climate projections.

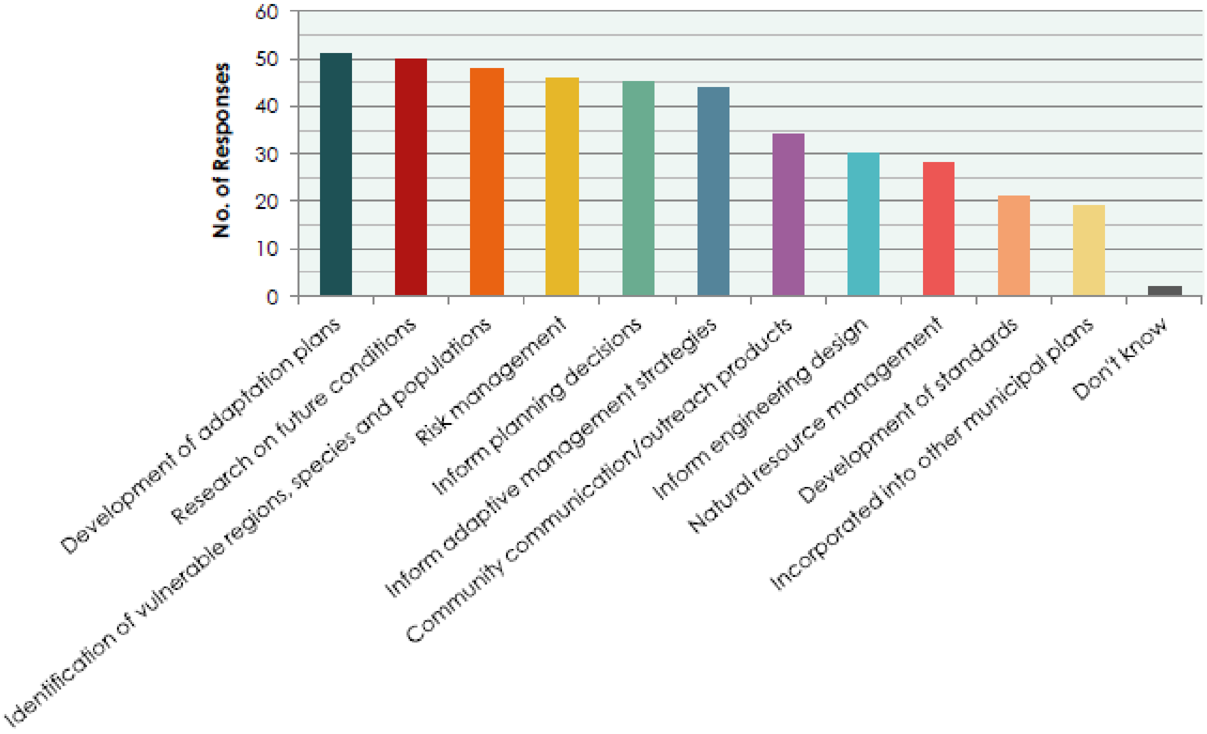


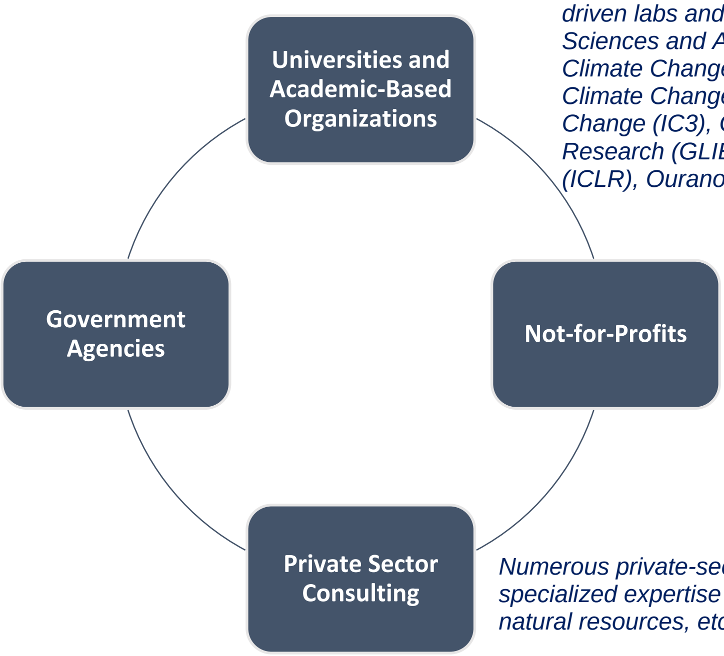
Figure 3: How climate projections are used among users (total of 114 respondents) in Ontario (Morand et al., 2015)

As illustrated above, the practical uses of climate information are diverse. Morand et al. (2015) identifies that the three most common purposes tend to be related to (1) the development of adaptation-related plans, (2) research projects related to future conditions, and (3) identifying vulnerable populations, species and regions. These types of initiatives and projects frequently involve collaboration between those requiring the climate data and those developing and producing the climate data. As a result, an ecosystem of climate service providers has emerged across the GLB to facilitate knowledge transfer, provide clear guidance and plain language communications, and support for employing climate information in practical applications. These climate service providers are often referred to as “translators” or “connectors” and section 4.2 provides a brief summary of these in relation to supporting the uptake of best practices in climate model information.

4.2 Climate Service Providers across the Great Lakes Basin

Today, climate service providers exist at the local, regional, national and international scales, in a broad range of sectors (e.g. water, health, agriculture, disaster reduction management, etc.) and are provided by both private and public sector actors (Vaughan and Dessai, 2014). This network of service organizations have emerged and evolved to meet the increasing need for decision makers to understand limitations of climate information, what constitutes as best practices, and to support the use of climate model information in practical applications in a robust manner.

While this section is not meant to be exhaustive with respect to the number of climate service providers across the GLB, it does provide a brief summary of different types of organizations that can support mobilizing climate information. It is important to note, as well, that numerous climate service providers collaborate closely and share collective objectives to build resilience across systems and sectors in the Great Lakes. In Reeder et al. (2016), authors determined that almost all organizations are interested in increasing the level of formal cooperation, and would value discussions around new mechanisms to share projects and support stakeholders towards increasing the longevity of those involved in the space. Figure 4 illustrates the different types of organizations at a high level.



Sector-specific organizations, climate researchers, data driven labs and institutes (e.g., Great Lakes Integrated Sciences and Assessments (GLISA), Wisconsin Initiative on Climate Change Impacts (WICCI), McMaster Centre for Climate Change (MCCC), Interdisciplinary Centre on Climate Change (IC3), Great Lakes Institute for Environmental Research (GLIER), Institute for Catastrophic Loss Reduction (ICLR), Ouranos)

Federal, Provincial/State and Local governments working to mobilize, connect and fund climate-related work (e.g., Environment and Climate Change Canada (ECCC), National Oceanic and Atmospheric Administration (NOAA), Annexes under the Great Lakes Water Quality Agreement (GLWQA), the International Joint Commission (IJC)

Non-governmental organizations working across all scales and sectors building capacity and co-producing science (e.g., Ontario Climate Consortium (OCC), Local Governments for Sustainability (ICLEI), Clean Air Partnership (CAP), Climate Risk Institute (CRI), formerly known as Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR))

Numerous private-sector consulting companies with specialized expertise in risk, engineering, water, natural resources, etc.

Figure 4: Different Types of Climate Service Providers in the Great Lakes Basin

Each of these organizations play an important role in providing climate services. For example, boundary organizations such as Great Lakes Sciences + Assessments (GLISA), the Ontario Climate Consortium

(OCC), and Ouranos based out of Quebec are vital in connecting various networks of people together, building consistency and capacity, and in establishing and promoting best practices. Government agencies, such as the Annexes under the Great Lakes Water Quality Agreement (GLWQA) hold important convening authority and add legitimacy to approaches, frameworks, datasets and ensuring information being produced is relevant for policy. On the other hand, private consulting firms add value by bringing deep sector or system-specific expertise when working on specific projects (e.g., infrastructure design, hydrologic modeling, etc.).

Figure 5 further classifies climate service providers with respect to the types of work they undertake. Consistent with multi-organizational objectives, (1) education and training and (2) hosting capacity building events and workshops are some of the most common services provided for decision makers and practitioners.

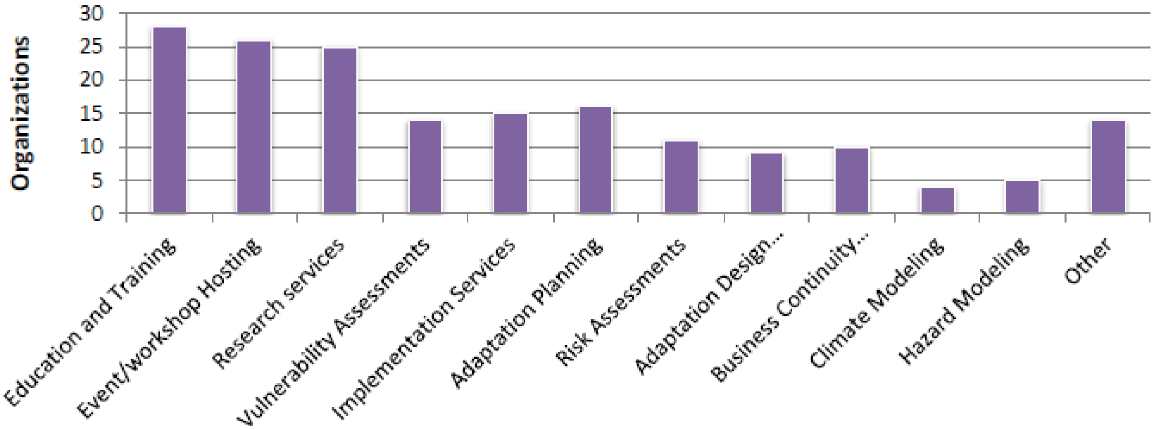


Figure 5: Services offered by Climate Service Providers or “Translators” (Reeder et al., 2016)

4.3 Common Approaches Applied in Great Lakes Basin

This section will present a high-level summary of how climate projections are being used across the GLB, including what types of models are being accessed, limitations noted by study authors and other key take-aways. A total of 41 studies (see Appendix E for a full list of the studies assessed for this section) were assessed to provide insight into this information. Of these 41, this included the following:

- Vulnerability assessments (municipal, regional, system-specific and Great-Lakes Basin wide);
- Select academic papers specific to the GLB where climate projections are presented for use as part of an applied purpose;
- Climate trend reports (e.g., produced by municipalities, universities, and governments)
- Nationally-funded climate change assessments published at the time of this study; and

- Discussion papers related to climate change and particular components of the GLB.

These particular documents were selected due to their relevance to the GLB and because they are explicitly documenting or using climate projections in some manner. Authors included academic experts, government staff and departments (e.g., Parks Canada, NOAA), think-tanks (e.g., the Environmental Law and Policy Centre), municipalities (e.g., City of Chicago, City of Lansing, Region of Peel, City of Toronto, Durham Region), and watershed-based organizations (e.g., Conservation Authorities in Ontario, watershed management councils). If a particular document did not clearly outline or describe the use of projections, was focused on theoretical model development but not its application, and/or focused largely on historical observational datasets, these were excluded.

Figure 6 illustrates the different approaches these studies have taken to incorporate future climate information. The vast majority (88%, or 36 out of the 41 studies) explicitly emphasized the need to employ an ensemble of climate model runs to capture the range in future conditions, and only 12% (or 5 studies) took an alternative approach (e.g., running one single GCM, RCM and/or using statistically weather generation techniques.

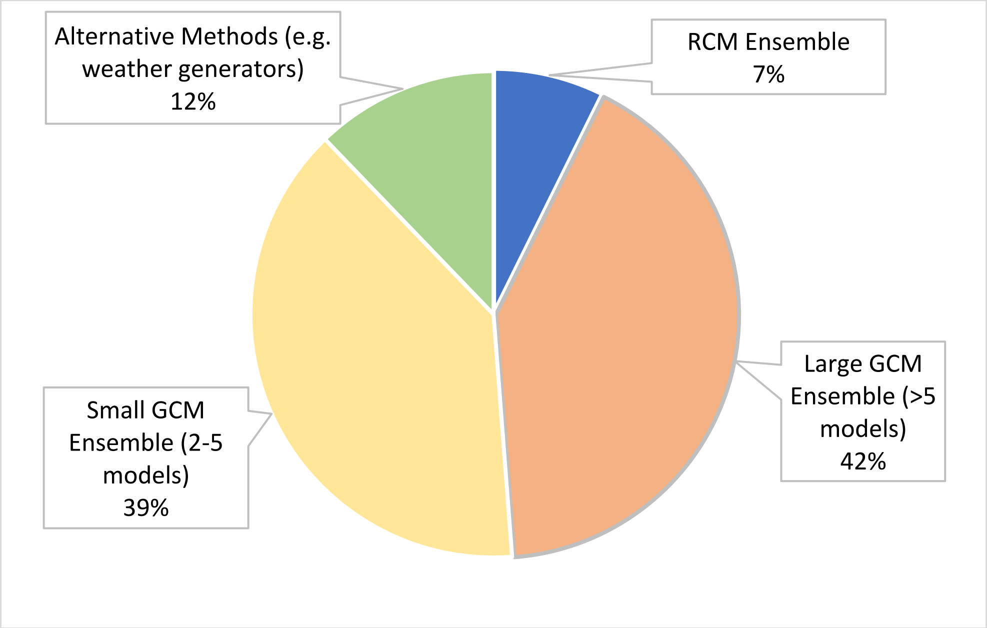


Figure 6: Climate projections used in the 41 Studies across the Great Lakes Basin (studies range from 2003 to 2019).

It appears that using an ensemble of GCMs (i.e., statistically downscaling and bias-correcting these), remains the most common approach when assessing climate change impacts and adaptation options in the GLB. This is particularly true for non-academic related studies and publications. Approximately 80% of the studies analyzed used an ensemble of GCMs (42% using greater than 5 models, and 39% using less than 5 to comprise a smaller ensemble). The use of RCMs or an RCM ensemble appears to be less commonly applied (only 7% of studies examined involved the use of dynamical downscaling specific to the GLB when applying data for a particular purpose).

This result may be for a number of reasons:

1. Practitioners and decision-makers tend to adopt similar approaches they have observed in previous years (e.g. coming "second" and learning lessons from the leading study is often easier to justify) and based on similar contexts (e.g., neighbouring jurisdictions or in other levels of government);
2. Decision makers frequently cite the challenge of accessing academic literature to adopt and learn from as a barrier to employing the latest best practice or information; and
3. The increasing availability and emphasis on RCMs may be more challenging to navigate as a non-climate expert (e.g., numerous GCMs have been incorporated into open source data portals since the release of the IPCC (2013) report, whereas RCM ensembles are being incorporated more recently.

Interestingly, almost 50% of the studies that were examined involved the derivation of climate projections specifically to run subsequent impact models (e.g., hydrologic models, species-response models, etc.) and develop adaptation actions or ideas to reduce vulnerability (e.g., Stewart et al., 2016). A number of limitations, or lessons learned, were flagged by the authors across these studies, and a subset is included below:

- Current information availability and modeling efforts are in some cases being restricted by jurisdictional boundaries, which impedes vulnerability assessments (Rempel & Hornseth, 2017).
- Water levels highly influence the community, and future water levels and swings in net basin supply remain challenging to adapt to. Better projections would be valuable for these complex variables (Wisconsin Initiative on Change Impacts, 2017).
- Clear and practical guidance could add value to decision makers to interpret how to make decisions based on the range in modeled conditions (Fausto et al., 2016)
- The complexities of ecosystem response and system-specific changes as a result of climate projections is much more heterogeneous than applying climate information allowed for (Chu, 2015).
- There is a lack of understanding of different modeling uses by practitioners, and there is a need for more collaboration and dialogue between modelers and practitioners (Notaro, in person).

In summary, while the availability of climate models and information improves across the GLB and priorities are discussed to fill gaps for future understanding (i.e., see Section 3.2 and Section 5 below), it is important to remember that disseminating, and co-producing "plain language" scientific support tools is equally as important among practitioners to ensure the latest science and information is being incorporated into applied studies and assessments. Previous surveys indicate that practitioners and decision makers value government-endorsed information sources or approaches (Morand et al., 2015). Across the Ontario Climate Consortium network for example, a number of decision makers and practitioners are broadly aware of some of the recent scientific efforts (e.g., that regional climate modeling is underway, that 3D numerical models are in existence); however, it is the access and understanding of how to apply this information that is a barrier for the uptake of best practices.

5. Recommendations for Climate Modelers, Translators, and Users

The outputs of climate models in the GLB have great applicability across a wide range of stakeholders and sectors, as seen in the previous section of the report. More specifically, the more climate models in the GLB are enhanced, the more residents and governments can plan and adapt to the changing climate in the future. The following section provides a preliminary list of recommendations for climate modelers, translators, and users, which have been validated and updated based on the feedback from the workshop on June 27th, 2019.

Recommendations for Climate Modelers

As Section 3 demonstrated, there are many gaps in climate modeling that still exist today, including gaps in data collection, model development, and in the understanding of the Great Lakes themselves. The following recommendations are for climate modelers and potential funding sources and agencies of climate modeling, to enhance the robustness of the models used in the GLB. The following are some examples of parameters that can be enhanced from models to inform adaptation planning in the future:

Recommendation #1: Increase two-way coupling of models that incorporate the atmosphere, land, and lakes and increase research and funds to 3D modeling.
As Section 3 highlighted, many of the models that currently exist examine components of the atmosphere, lakes, or lands independently of one another. However, isolating these parameters produces gaps in modeling such as not capturing atmospheric patterns (e.g., influences from lake-effect precipitation, energy exchanges between lakes and the lower atmospheric boundaries, evaporation, teleconnection patterns, convective storms, etc.), hydrodynamics (e.g., interlake and river flows, heat and sediment exchanges between lakes and rivers), and many more. Therefore, more efforts need to be made to dynamically couple land, lake, and atmospheric numeric models with RCMs to further enhance and integrate the models that already exist today, to produce more 3D models.

Recommendation #2: Enhance data collection and conduct targeted field studies on lake climatology to feed into and validate climate models, and enhance spatial-temporal data coverage.

Many of the gaps in climate modeling of the Great Lakes occur because of the lack of data to feed into the models, or the lack of data to validate projections of specific parameters. Therefore, it is recommended that more data be collected on the following parameters to enhance climate modeling in the future:

- Over-lake precipitation
- Over-lake evaporation
- Land and lake breezes
- Inter-river and lake flows
- Groundwater base flows
- Land use changes
- LSTs and lake temperatures by depth
- Ice thickness and dynamics
- Evapotranspiration
- Lake depth and opacity
- Eddy flux evaporation
- Lake circulation
- Lake-effect snow

One of the most common needs from climate modelers is to have more robust projections of LSTs, ice cover, and winds as these parameters have a great influence on energy fluxes and exchanges between the lakes and the atmosphere. Currently, there are questions in the robustness of projections of these three climate parameters. Therefore, more dynamical coupling of these parameters with RCMs should be undertaken to further refine and enhance these projections, to better understand the impacts of lake-land-atmosphere interconnections, climate change, and their influences on the climate (e.g., lake-effect snow).

In addition, it is recommended that ground-truthing of data that already exists should be enhanced, to better predict location-specific climate changes in the GLB. For example, Sharma et al. (2018) recommend that ground truthing of lake temperatures, ice cover, precipitation, and lake sensible and latent heat should be undertaken. This could be done through various different agencies, and through citizen science data collection (e.g., NASA’s GLOBE program).

Recommendation #3: Develop a shared set of data collection tools for operational users, climate modelers, and weather forecasters to project socio-economic impacts to residents of the GLB

Develop an integrated set of data collection tools that will aid in the collection of real-time data, that can be shared amongst operational users (e.g., shipping and navigation, farmers, storm water management, infrastructure planning), climate modelers, and weather forecasters, as well as a place to go to for consistent, long-term data. This will increase the amount of data accessible to climate modelers to feed into models and can help operational workers to further understand climate influences. This will aid climate modelers to develop long-term climate projections of the impacts on ecosystem sustainability, hydrometeorological extremes, engineering design, human health, and socioeconomic systems. Other regions across the globe could benefit from such an approach and could be used as a template for other regions with cities, large lakes, inland seas, and coastlines facing similar kinds of climate change impacts.

Recommendations for Climate Modelers and Climate Information Users and Translators

Recommendation #4: Conduct continuous diverse stakeholder engagement between climate modelers, users, translators, and funding agencies
It is recommended that climate modelers engage with each other, as well as with practitioners that will be using their climate projections for various types of planning (e.g., infrastructure design, land use development, municipal climate change planning). Climate change modelers can learn from one another, by exchanging key lessons learned from previous experiences, their gaps and data needs, and their modeling strengths – this will aid in the development of a more robust and integrated modeling system within the GLB. Further, collaboration between climate modelers and practitioners can help in identifying key climate projection needs for climate adaptation planning in local communities within the GLB. Continuous engagement with a diverse group of stakeholders will aid in the evolution of climate modeling and will ensure that climate projections are being used for adaptation planning in the GLB. Furthermore, this can help users and translators identify needs for future climate modeling or updates to current climate models for their uses. Collaboration amongst users and translators can enhance practitioners' understanding of climate information and how it can be used for planning practices and can help build a community of practitioners that can help one another in their climate adaptation work.

Recommendations for Climate Information Users and Translators

The following recommendations are specific for climate information users and translators in the GLB moving forward.

Recommendation #5: Continue to emphasize the connections between climate projections and local impacts
Numerous innovative and important work has been conducted and/or is underway across the GLB to adapt to the impacts of climate change. However, some uncertainty still exists in terms of what future climate projections and scenarios actually mean "on the ground". Thus, translators of climate information should continue to focus on training for applying this data and allow decision makers to better understand not just the impacts, but critical thresholds, beyond which risk levels increase.

Recommendation #6: Increase communication on the comparison of various climate model ensembles to practitioners
It would be beneficial for future studies to highlight projections of various climate models for practitioners and scientists to compare the results of different models across the GLB. This way, practitioners would be able to choose an ensemble, based on the ensemble's projections in comparison to others. For example, if the ensemble over projects all climate variables, a practitioner may not choose to use this one. There does not exist a study that compares all ensembles used in the GLB.

Recommendation #7: Promote the importance of consistent approaches, where possible, being applied across similar regions in the GLB

While it is unlikely that all practitioners will use the same source of information, models or data while undertaking research and adaptation projects, inconsistencies have historically arisen even within neighbouring jurisdictions with respect to best practices. In other words, practitioners within the same region may be planning for, or designing to, differing futures while focusing less on low regret adaptation actions. This confusion may arise for a number of reasons, but may include lack of understanding for data sources or best practices, confusion as to which data sources or portals are ideal for specific applications, and political decisions. Therefore, there is a need for climate modelers and translators of this information to clearly identify best practices as they emerge and to promote consistency, where appropriate and where possible.

Recommendation #8: Build emerging climate information into existing portals and tailor its output, where possible, for different user groups

Increasingly, users of climate information across the GLB need general and specific climate data to support adaptation decisions at the community, watershed, regional and site levels. However, an over-abundance of climate data options can make it challenging for practitioners to select, justify and make decisions using the most appropriate information (Clean Air Partnership, 2018). Therefore, it is recommended that as the latest scientific information is released from climate models, this should be built into existing platforms or portals (e.g., not creating an additional source) and be categorized for different user groups in a transparent manner (e.g., information for basic, intermediate and advanced users and/or specific sectors).

Recommendations for Funding Agencies

Recommendation #9: Bolster available resources and opportunities to focus funding, specifically for Great Lakes scale climate modeling initiatives

It is recommended that funding agencies across the GLB (e.g., federal, state, provincial, municipal and local governments, private agencies, universities, etc.) focus on binational funding of Great Lakes modeling, to decrease the gaps of having inconsistent data gaps across country barriers, and to have more consistent and robust climate projections.

6. Conclusions and Next Steps

The Great Lakes have a significant impact on the regional climate of the eight states and two provinces that surround them, which impacts over 30 million residents in the area. As climate continues to change, it is important to understand the Great Lakes' influence on the regional climate as well as the climate's influence on the physical, chemical, and biological components of the lakes. Climate change may pose significant threats to residents of the GLB, such as erosion, flooding, degraded water quality, warmer summers and winters, more intense and frequent storms, and many more. In order to prepare and plan for these predicted impacts of climate change, it is important to have an idea of when these impacts might occur, and which areas might be impacted the most by certain phenomena. Therefore, climate modeling is an essential first step in climate adaptation planning.

The state of climate modeling in the Great Lakes has enhanced significantly in the past few decades as climate change has gained momentum. Many efforts have been made in creating one- and three-dimensional hydrodynamic models on specific phenomena of the Great Lakes, and many modelers have started to couple these models with regional or global climate models to better predict climate impacts across the GLB. While there have been significant strides in climate change projections for the GLB, there exist numerous gaps in data collection, gaps in the model development, and gaps in the general understanding of the Great Lakes and their interactions with outside influences, such as large teleconnection patterns from the Gulf of Mexico and the Atlantic Ocean.

This report highlights these gaps in detail, and provides recommendations for climate modelers, users, translators, and funding agencies moving forward. One potential "ideal" goal for climate modelers is to create an integrated lake-land-atmospheric modeling system that can incorporate the latest three-dimensional numeric models that have been validated through historical analyses, and could include more outside influences on climate to regional and global climate models. This will help improve the lake model simulations, generate more collaboration amongst climate modelers, users, and translators, and will improve and enhance adaptation planning across the GLB.

The first step towards creating integrated lake-land-atmospheric modeling systems and to address the gaps identified in this report is to engage a broad range of climate modelers across the GLB to identify data and model needs to improve current models. On June 27th, 2019, over 20 climate modelers, practitioners, funding agencies, scientists, policy makers, etc. gathered in Ann Arbor, Michigan to discuss the state of climate modeling in the GLB, and to provide further recommendations for future work in the basin, and it was indicated that this type of collaboration is needed among practitioners and modelers.

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Appendix A: Stakeholder Workshop Agenda

Workshop Agenda

9:00 – 9:10	**Welcome and Introductions;** Glenn Milner, OCC • Roundtable and Webinar Introductions
9:10 – 9:30	**Assessment of Climate Studies and Identifying Gaps and Areas of Greatest Uncertainty;** Glenn Milner and Frances Delaney, OCC • Present findings of pre-workshop report
9:30 – 9:45	**An overview of GLISA's Climate Modeling Research Findings;** Laura Briley, GLISA
9:45 – 10:00	**Climate Change Impacts on Coastal Storms and Ice Cover for Lakes Erie and Ontario;** Pete Zuzek, Linda Mortsch
10:00 – 11:00	**Activity 1: Identifying Preferred Climate Models for Use in the Great Lakes Basin: Strengths, Limitations and Prioritizing Gaps** • Activity run both in-person and via Mentimeter for those on webinar (OCC to facilitate)
11:00 - 11:15	*Break* **coffee and light snacks provided*
11:15 – 11:20	**Assessing and Enhancing the Resilience of Great Lakes Coastal Wetlands: Program Overview;** Greg Mayne, Environment and Climate Change Canada
11:20 – 11:35	**Projections of Key Climate Variables for use in Wetlands Vulnerability Assessment;** Armin Dehghan, Environment and Climate Change

11:35 - 11:50	**Projections of Great Lakes Water Levels under a Range of Climate Change Scenarios;** Frank Seglenieks, Environment and Climate Change Canada
11:50 – 12:25	**Activity 2: Facilitated Discussion – Strengths and Opportunities for Improvement on Climate Modeling used in the Coastal Wetlands Assessment** • Activity to be run both in-person and via Mentimeter for those on webinar
12:25 - 12:30	**Closing Remarks**, Glenn Milner, OCC

Appendix B: Overview of Climate Change Modeling Experts Workshop, June 27, 2019

1. Assessment of Climate Studies and Identifying Gaps and Areas of Greatest Uncertainty; Glenn Milner and Frances Delaney, OCC

Glenn Milner and Frances Delaney from the Ontario Climate Consortium provided an overview for the workshop, and described the objectives of the day, which included the following:

- Review the existing Great Lakes regional climate modeling efforts, including the strengths, limitations and credibility of climate change projections and their applicability to the Great Lakes Basin
- Share preliminary results from relevant studies in Canada and the U.S.
- Identify gaps and areas of greatest uncertainty and develop recommendations for future work.

Glenn and Frances then walked the audience through the findings of the report, demonstrating the state of climate modeling in the GLB. They explained the main concepts of climate modeling (e.g., global climate models, regional climate models, coupling 1D or 3D models to other climate models, downscaling methods, etc.), the main climate models that are used in the GLB, the ensembles of models available for users in the GLB, and which models users and practitioners are using across the GLB and for what purposes. From this overview, Glenn and Frances also highlighted the various gaps that currently exist in climate modeling. These gaps included data gaps, gaps in the models themselves, and knowledge gaps that still exist on phenomena in the GLB.
After the presentation, a few comments and questions were asked, these included the following:

Comment #1: There is a large knowledge gap that exists as there is a lack of historical climate analyses (e.g., extreme precipitation, warming trends) to validate the models we are currently using. Current climate models that are being used in the GLB also cannot adequately reproduce the historical climate changes that have been observed overtime in the GLB. There is also a lack of lake circulation, lake temperature by depth, and ice movement data, which would be extremely useful for the inputs of these models.

Answer #1: Glenn and Frances indicated that they would add these knowledge and data gaps in the report.

Comment #2: It would be good to see the difference in the range in projections of each of the climate models highlighted in the report and presentation (e.g., what models overestimate, which ones under estimate different climate parameters).

Answer #2: Glenn and Frances indicated that although this would be very helpful for users and modelers, this would take a significant amount of time, and is out of scope for this project.

Comment #3: A lot of these gaps are not consistent across the entire GLB, however there is a gap in the communication around these – a lot of modelers are unaware of other models/data out there that are filling these gaps.

Answer #3: Glenn and Frances noted that this was a great point, and that they would add this to the report, both in the gaps section, and in the recommendations.

2. An overview of GLISA's Climate Modeling Research Findings; Laura Briley, GLISA

Laura Briley, a climatologist from the Great Lakes Integrated Sciences and Assessments (GLISA) from the University of Michigan spoke about GLISA's various products and their newest research findings from these new reports and products. She first explained GLISA and their objective of making climate science usable for practitioners across the GLB, and highlighted all of the organizations that GLISA collaborates with on a regular basis (e.g., federal governments, cities and municipalities, tribal governments, boundary organizations, and state and provincial governments). She then explained the concepts of a climate model ensemble, and walked the audience through GLISA's various projects and products, these included:

- Climate Model Ensemble Overview Project, where GLISA produced criteria for users and practitioners using ensembles in the GLB
- Climate Model Buyer's Guide, which provides basic model requirements and model evaluation criteria
- Climate Model Report Cards, which demonstrates components of specific models and evaluates them
- CMIP 5 Lake Evaluation, which evaluates how each of the IPCC's [available] CMIP5 GCMs incorporate the Great Lakes
- Scenario Guide, to explain what scenarios are and the different types used for different types of adaptation planning
- Downscaled Data Guide, to aid practitioners in choosing/using downscaled data

After the presentation, a few comments were made, these included the following:

Comment #1: Some of the 18 GCMs in the CMIP5 Lake Evaluation that model the lakes as "dynamic lakes" actually have really low resolution (e.g., 2 degrees) so they're limited in that sense as well. Some of these also may be modeling these lakes as shallow lakes, so be careful with these.

Answer #1: Laura acknowledge that this was a great point and that she would take this back to her team.

Comment #2: Model accessibility is a huge gap, and it's impressive that they were able to determine lake interpretation for all of the CMIP5 models.

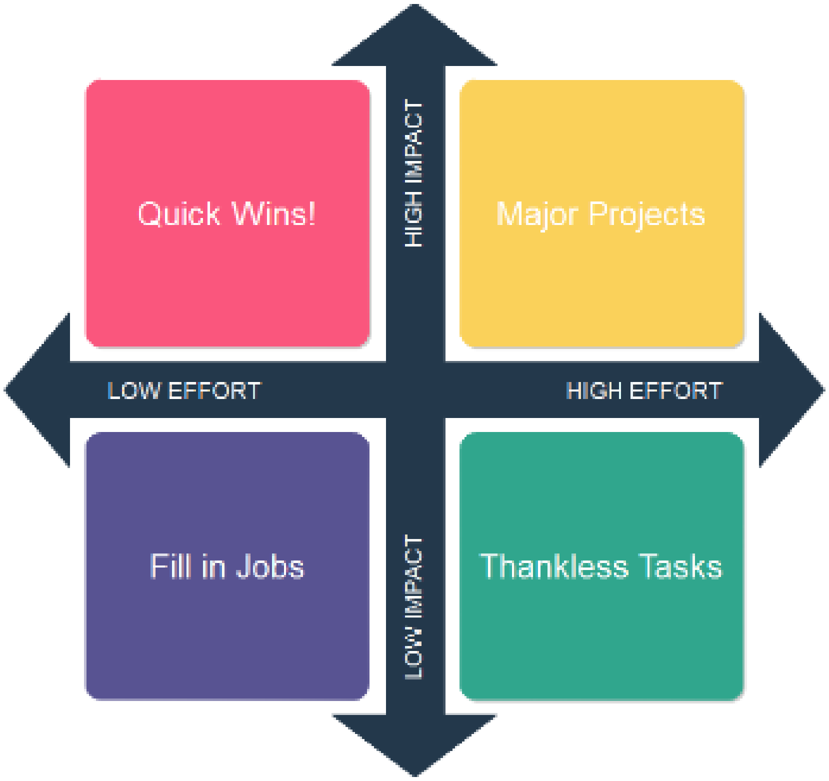
3. **Climate Change Impacts on Coastal Storms and Ice Cover for Lakes Erie and Ontario;** *Pete Zuzek, Zuzek Inc. and Linda Mortsch, University of Waterloo*

Pete Zuzek from Zuzek Inc. presented on his preliminary findings of a climate change study on coastal storms and ice cover for Lakes Erie and Ontario. He explained the methods used for his study, including which models were used (e.g., using the Weather Research and Forecasting Model, the MIKE21 Model, and the Spectral Wave Model, WAVAD Model), which data were used (e.g., buoy data, storm data), and how these were all bias corrected. He then went through projections for Lakes Erie and Ontario, for water surface temperature, wave heights and ice cover for the late century at the highest emissions scenario of RCP 8.5. He then summarized the key findings of his study, including where the points of highest concern might be, and showed the audience where wave data will be made available in the near future.
After his presentation, there were a few comments and questions, which included the following:

Question #1: Will you be looking at more scenarios other than RCP 8.5?
Answer #1: Pete said that this would be ideal, however there is a lack in funding currently, so this will probably not occur in the near future.

Activity 1: Identifying Preferred Climate Models for Use in the Great Lakes Basin: Strengths, Limitations and Prioritizing Gaps

This activity was an open discussion with all the participants, and was aimed at getting the participants of the workshop to identify the current approaches in climate modeling that may have been missed in the report and presentation given by OCC, and the strengths of these models, the potential improvements to be made to current models and data collection, and how to fill these gaps. Glenn Milner presented the following matrix to guide the discussions of the participants:



As the matrix above indicates, actions or initiatives that would take low effort and would create high impact are called “Quick Wins”, actions with high effort and high impact would be considered “Major Projects”, whereas other actions that would have low impact and low effort would be called “Fill in Jobs”, and those low impact projects that would require effort would be called “Thankless Tasks”. Therefore, the participants were asked to think about the Quick Wins and Major Projects that could be undertaken to improve the state of climate modeling in the GLB.

Specifically, the questions that were asked to the participants included the following:

- **Current Approaches and Strengths:**
    - If you had to identify strengths of your approach in developing or using climate projections, what would they be?”
- **Identifying Gaps and Future Needs:**
    - What are some of the gaps or barriers you are facing?
    - Are there any additional gaps you can think of that we should consider?
- **Filling Gaps and Building on Strengths:**
    - How can we actually begin to achieve quick wins?
    - To what extent is increased coordination needed between modeling centres that have data across the Great Lakes Basin? Would this help you?
    - Who should be involved in this process? Consider modelers, translators and users.

The following summarizes the discussions at the workshop:

Current Approaches and Strengths:

Participants provided their input on what initiatives and programs they thought are currently working well and highlighted the strengths in some of the climate modeling that is currently taking place. The participants noted the following strengths in climate modeling in the GLB:

- Sharing data amongst and engaging with diverse stakeholders (e.g., the workshop, the various Great Lakes Water Quality Agreement (GLWQA) Annexes, etc.) is a great strength we currently have. For example, Annex 9 of the GLWQA is a group that brings a diverse group of people together to work on climate change impacts in the Great Lakes, and acts as a good coordination umbrella.
- Dynamic downscaling of lake-atmospheric conditions has been modeled well in the GLB
- Conducting in-depth assessments of historical climates over the Great Lakes has been done well
- Evaluating lake representation in Regional Climate Models (and Global Climate Models – e.g., the CMIP5 model evaluation conducted by GLISA)
- Using climate scenarios rather than many different projections is a strength within the modeling in the GLB
- Translating complex scientific information into practical and useful information for practitioners (e.g., GLISA’s Buyer’s Guide and Model Report Cards)

Identifying Gaps and Future Needs and Filling Gaps and Building on Strengths:
Participants then identified gaps in research and in communication on climate modeling in the GLB, the current research that is being done to fill these gaps, organizations and people working on these gaps, and whether there were quick wins identified. For simplicity, the results from the workshop were divided into technical gaps on modeling, data, and other phenomena in the GLB (Table A1), and into the communication-oriented gaps (Table A2).

Table A1: Gaps and challenges faced by climate modelers in the Great Lakes Basin.

Gap	Current Research Being Done?	Who is working on gap?	Quick Win?
Gaps in Modeling, Data, and Other Phenomena in the Great Lakes			
Reason for the rapid warming of Great Lakes in recent years	There are many theories that scientists and researchers have proposed to be the cause for the rapid warming (e.g., ice-albedo effect or by changes in cloud cover).	Michael Notaro and others	Continue research in this area
Lake effect morphology in modeling	Michael Notaro noted that his research team is currently working on this, however, they are using remote sensing technologies, which treats lakes as shallow lakes	Michael Notaro and team	Continue research in this area
Groundwater and base flow simulations and modeling	Participants noted that the International Joint Commission (IJC) is currently working on this however, it still needs a lot of work	International Joint Commission	Continue research in this area
Convective storm modeling (intensity, duration, and frequency)	Participants noted that OURANOS is trying to improve parametrization of indicators to capture convection more, however there are still gaps in this research	OURANOS	Continue research in this area
Algal bloom projections	National Oceanic Atmospheric Administration (NOAA) works on detailed forecasts of algal blooms (short-term forecasts).	NOAA	Continue to fund this research, and increase forecast period to climate normal period

Distinction between “natural variability” vs. “climate change” (e.g., teleconnection patterns bringing in colder winters).	Many theories, researchers have been researching this for a long time, however there are still gaps.	Not specified	Continue research in this area
Jet streams (e.g., polar vortex)	Participants noted that jet streams allow for rapid ice cover to form over lakes (e.g., especially Lake Erie) but models do not capture this rapid ice formation (models only have zonal variability, but not jet streams). Therefore, there is research being conducted on this.	Not specified	Continue research in this area
Lake effect snow in remote sensing technologies	N/A	N/A	N/A

Table A2: Gaps and challenges faced by practitioners in the Great Lakes Basin on communication, engagement, and funding.

Gap/Challenge	Current Research Being Done?	Who is working on gap?	Quick Win?
Gaps and Challenges in Communication, Engagement, and Funding:			
Translation of climate models and portals (metadata, guidance, translation)	OCC and GLISA have started to facilitate this and are translating models and developing guidance for practitioners specifically.	OCC and GLISA (and many more)	Continue to support OCC and GLISA in future work
Communication on which models represent the Great Lakes adequately, and which ones to use	OCC and GLISA have started to facilitate this (e.g., OCC has summarized the state of climate models in this report, and GLISA has produced many products such as the CMIP5 Lake Evaluation, Model Report Cards, etc.)	OCC and GLISA (and many more)	Continue to support OCC and GLISA in future work
Translation of models into practical tools for practitioners and engineers	GLISA and OCC have begun to translate models for practitioners into guidance documents, report cards, etc.	GLISA and OCC	Continue to support GLISA and OCC in translating

			models and science
Binational coordination and engagement on climate change science and modeling for the Great Lakes (e.g., need for more meetings and working groups)	Currently there is a Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD) (a group that has both external and academic), however, the group does not focus too much on climate change Annex 9 of the GLWQA also helps with coordination	Various stakeholders	Expand both CCGLBHHD and Annex 9, and increase climate change awareness to practitioners across the GLB
Comparison of model projections and data for practitioners to choose a model for their use (no study analyzes and combines data sets and projections for comparison, as each model has different resolutions, different data formats and domains, etc.)	N/A	N/A	
Communication on climate change modeling to ensure longevity and funding (e.g., across political barriers)	N/A	N/A	
Documentation and accessibility of models (e.g. metadata is not available on all CMIP5 models)	N/A	N/A	

Assessing and Enhancing the Resilience of Great Lakes Coastal Wetlands: *Program Overview; Greg Mayne, Environment and Climate Change Canada*

Greg Mayne from Environment and Climate Change Canada introduced the Vulnerability Assessment program currently underway to enhance the resilience of 22 wetlands across the

GLB. Greg discussed the methods and models that have been used thus far into the process, and described how the overall vulnerability will be calculated for each of the wetlands under study (e.g., how exposure, sensitivity, and adaptive capacity will be calculated). He then introduced Armin Dehghan and Frank Seglenieks who have been conducting the modeling for the vulnerability assessments.

Projections of Key Climate Variables for use in Wetlands Vulnerability Assessment; *Armin Dehghan, Environment and Climate Change Canada*

Armin presented her findings climate projections for temperature, precipitation, ice cover, and lake surface temperature, using the Canadian Regional Climate Model (CRCM5), driven by CNRM-CM5 and CanESM2 global climate models. She demonstrated the historical observations with the model's projections, which showed the robustness of the CRCM5 model. She then walked the audience through each climate variables' projections for mid-century (2040-2059) and late century (2080-2099), for both climate scenarios of RCP 4.5 and 8.5, for both global climate model runs. She found that temperature increased mostly in the winters, especially on the Canadian side of the Great Lakes; precipitation increased in winters and springs, but decreased in summers; Lakes Erie and Superior are warming faster than all other Great Lakes in the winters; and that the Great Lakes will experience up to an 80% reduction in ice in the winters, and up to 100% ice loss in the springs.

Projections of Great Lakes Water Levels under a Range of Climate Change Scenarios; *Frank Seglenieks, Environment and Climate Change Canada*

Frank presented his preliminary findings of Great Lakes water level projections (a function of precipitation, evaporation, runoff, and total net basin supply), using the Canadian Regional Climate Model (CRCM5) for three time slices (2011-2040; 2041-2070; and 2071-2100). He walked the audience through all climate variables' projections for all time slices and for both climate scenarios, RCP 4.5 and 8.5. He then demonstrated how water levels were calculated, using the Coordinated Great Lakes Routing and Regulation Model (CGLRRM) (see Figure A1 below). He mentioned that his projections are not final, as he still needs to perform bias correction on his findings, and may also run his runoff data through a hydrological model. He then asked the audience a series of questions:

- Are there other sources of data you would recommend? (RCMs/GCMs)
- Should we only use RCMs that have a good/any lake model representation?
- Should we run a hydrological model or use the raw/routed runoff from the RCMs?
- What time period should we use for current climate (i.e. 1961-1991, 1971-2000, 1950-2005)?
- Should we use other bias correction methods?

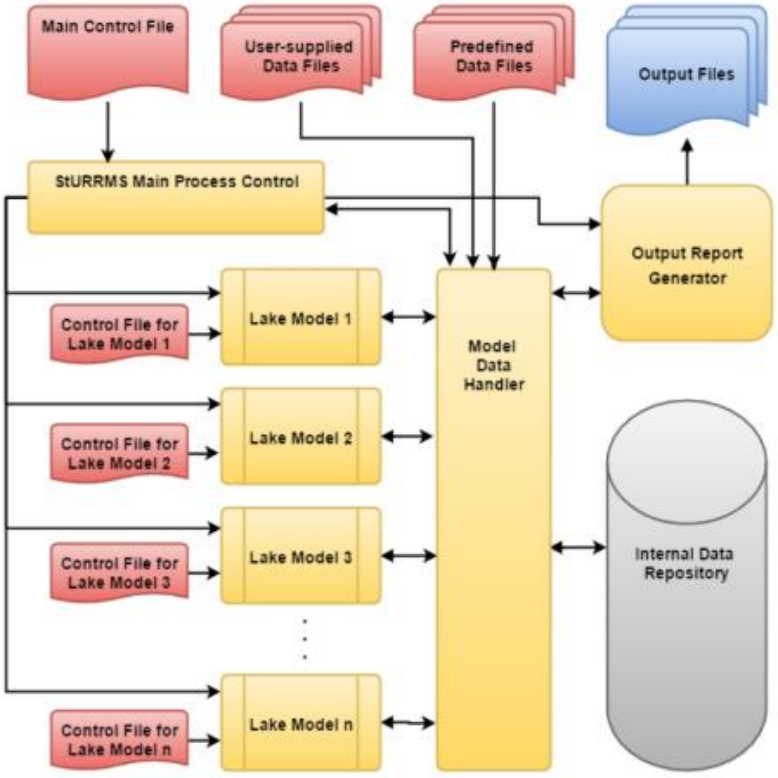


Figure A1: The Coordinated Great Lakes Routing and Regulation Model.

Activity 2: Facilitated Discussion – Strengths and Opportunities for Improvement on Climate Modeling used in the Coastal Wetlands Assessment

Glenn and Frances then introduced the next activity, which was to get participants' opinions and inputs on the coastal wetland vulnerability assessment modeling and methodologies presented by Greg, Frank, and Armin. The following activity was another group-wide facilitated discussion. The participants were asked the following questions:

1. What are some of the strengths of the approach taken in the coastal wetlands assessment? Do these strengths reflect those identified in Activity 1?
2. What are potential improvements in the climate modeling efforts? Are these consistent based on the gaps identified in Activity 1?
3. Based on the top 5 priority gaps identified in Activity 1, are there opportunities to begin to address one or more of them as part of this work? If so, what would that actually look like?

The following summarizes the questions and comments given to Frank and Armin in regards to their presentations and the questions posed by OCC.

Discussion on Great Lakes Water Levels:

- Comments:
    - Andre Erler spoke about baseflow and groundwater and how some of his models have accounted for this.
    - Michael Notaro spoke about how the different timing of the projections of the climate variables in the lakes are most likely attributable to the depths of the lakes (e.g., Lake Erie's ice cover will diminish first because it is the most shallow of the Great Lakes).
    - Frank asked Scott Steinschneider if there are models that adequately capture the waviness of jet streams. To which Scott mentioned that he is not fully aware of the bias in this feature, but aspects of what is unresolved can influence large-scale dynamics. He added that there have been studies on this, and it continues to be an important research question. Michael Notaro also noted that the University of Michigan is also trying to capture jet stream waviness into their models.
        - On the same subject, Andre Erler mentioned that there is no solid evidence to link climate change with cold winters we've experienced in the GLB (e.g., many studies have shown that teleconnection patterns are actually linked to natural variability, which have been the main cause of these colder winters recently), and that this should not be of concern to Frank to include in his models.
        - Lauren Fry asked if these teleconnection patterns are currently being incorporated into the models, as these will influence future climates, regardless of their link to climate change.

- Andre Erler noted that the teleconnections are incorporated into current models, however, they do not have direct interactions with ice cover (e.g., large scale circulation patterns are captured in RCMs, and not in GCMs).
- Scott Steinschneider mentioned that is would be beneficial to know which GCMs incorporate teleconnection patterns in them. He also noted that variability in teleconnection patterns needs to be documented, in order to represent these features in the models.

Other questions and comments on Armin and Frank's presentations were sent to them offline, after the workshop.

Appendix C: Detailed Inventory of 1-Dimensional Climate Models in the Great Lakes

Available in separate document.

Appendix D: Detailed Inventory of 3-Dimensional Climate Models in the Great Lakes

Available in separate document.

Appendix E: List of 41 Studies Reviewed for Analysis of Climate Models Uses by Practitioners in the Great Lakes Basin

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Appendix F: Comparison of Projected Changes in the Great Lakes Basin for RCP8.5 - representative of Southwestern, ON, Canada*

Ensemble	Variable	Short-Term (2020s)	Mid-Century (2050s)	Late Century (2080s)	Citation
York University Super-Ensemble *(209 members, 22% by dynamical downscaling, 78% by statistical downscaling)*	Average Annual Air Temperature	N/A	**+2.9°C** (50th perc.)	**+4.8°C** (50th perc.)	Deng, Z., Liu, J., Qiu, X., Zhou, X., & Zhu, H. (2018). Downscaling RCP8. 5 daily temperatures and precipitation in Ontario using localized ensemble optimal interpolation (EnOI) and bias correction. Climate Dynamics, 51(1-2), 411-431.
	Total Annual Precipitation (mm)	N/A	**+60.2mm** (50th perc.)	**+79mm** (50th perc.)	
Climate Data for a Resilient Canada (ClimateData.ca) *(24 GCMs, statistical downscaling)*	Average Annual Air Temperature	**+1.8°C** (50th perc.)	**+3.8°C** (50th perc.)	**+5.2°C** (50th perc.)	Cannon, A.J., S.R. Sobie, and T.Q. Murdock, 2015: Bias Correction of GCM Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and Extremes? Journal of Climate, 28(17), 6938-6959, doi:10.1175/JCLI-D-14-00754.1.
	Total Annual Precipitation (mm)	**+69.4mm** (50th perc.)	**+86.7mm** (50th perc.)	**+121.4mm** (50th perc.)	
Climate Atlas of Canada (ClimateAtlas.ca) *(24 GCMs, statistical downscaling)*	Average Annual Air Temperature	**+1.9°C** (50th perc.)	**+3.9°C** (50th perc.)	**+5.5°C** (50th perc.)	Prairie Climate Centre (2019). Climate Atlas of Canada, version 2 (July 10, 2019). https://climateatlas.ca
	Total Annual Precipitation (mm)	**+74mm** (50th perc.)	**+80.3mm** (50th perc.)	**+100mm** (50th perc.)	

Ensemble	Variable	Short-Term (2020s)	Mid-Century (2050s)	Late Century (2080s)	Citation
Windsor Climate Trends Report *(CRCM5, Dynamically downscaled)*	Average Annual Air Temperature	**+1.2°C** (50th perc.)	**+2.6°C** (50th perc.)	**+4.4°C** (50th perc.)	City of Windsor, 2018 (https://www.citywindsor.ca/residents/environment/Environmental-Master-Plan/Documents/Windsor%20Climate%20Change%20Adaptation%20Plan.pdf)
	Total Annual Precipitation (mm)	**+18.6mm** (50th perc.)	**+47.3mm** (50th perc.)	**+70.1mm** (50th perc.)	
NA-CORDEX *(5 RCMs driven by 6 GCMs comprising a 16-member dynamically downscaled ensemble)*	Average Annual Air Temperature	**+2°C** (ensemble average)	**+3.5°C** (ensemble average)	**+5.5°C** (ensemble average)	Ontario Climate Consortium. (2019). Deriving Consistent Climate Projections across Greenbelt Municipalities in Southern Ontario. DRAFT.
	Total Annual Precipitation (mm)	**+46.5mm** (ensemble average)	**+78.3mm** (ensemble average)	**+182.9mm** (ensemble average)	
University of Regina Ontario CCDP *(1 RCM driven by 5 GCMs comprising a 5-member dynamically downscaled ensemble)*	Average Annual Air Temperature	**+1.3°C** (50th perc.)	**+1.5°C** (50th perc.)	**+2.1°C** (50th perc.)	Wang, Xiuquan, Gordon Huang (2015). "Technical Report: Development of High-Resolution Climate Change Projections under RCP 8.5 Emissions Scenario for the Province of Ontario". IEESC, University of Regina, Canada.
	Total Annual Precipitation (mm)	**+67.9mm** (50th perc.)	**-27.7mm** (50th perc.)	**+79.6mm** (50th perc.)	
University of Wisconsin-Notaro Ensemble *(1 RCM driven by 6 GCMs comprising a 6-member dynamically downscaled ensemble)*	Average Annual Air Temperature	N/A	**+2.3°C** (50th perc.)	**+4.5°C** (50th perc.)	Notaro, Michael, Val Bennington, and Brent Lofgren. 2015. Dynamical Downscaling Based Projections of Great Lakes Water Levels. Journal of Climate. 28.24 (2015): 9721-9745.
	Total Annual Precipitation (mm)	N/A	**+66mm** (50th perc.)	**+122mm** (50th perc.)	

*Note: The authors advise significant caution in basing conclusions using the above information. Each dataset and ensemble was derived differently, with significant methodological variations. This is for high level illustration and reference only.