2021 Great Lakes Climate Modeling Workshop

Great Lakes Integrated Sciences and Assessments (GLISA)
September 2021

Annex 9 of the GLWQA
Climate Change Impacts

Acknowledgements

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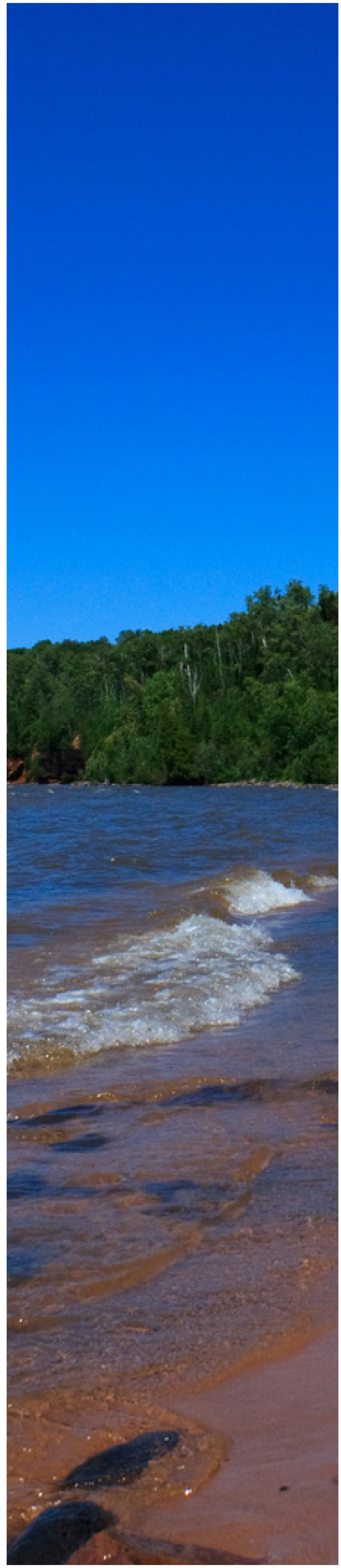

Table of Acronyms

Acronym	Meaning
CCS	Climate Change Signal
CMIP	Coupled Model Intercomparison Project
CRCM5	Canadian Regional Climate Model
C-3D-GLARM	Coupled 3D Great Lakes Atmosphere Regional Model
DQM	Detrended Quantile Mapping
ECCC	Environment and Climate Change Canada
FVCOM	Finite Volume Community Ocean Model
FVCOM-CICE	One-way Coupled Hydrodynamic-ice Model
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
GLB	Great Lakes Basin
GLISA	Great Lakes Integrated Sciences and Assessments
GLWQA	Great Lakes Water Quality Agreement
GRIP	Great Lakes Runoff Intercomparison Program
GRIP-M	Lake Michigan GRIP
GRIP-O	Lake Ontario GRIP
IDF	Intensity-Duration-Frequency
LBRM	Large Basin Runoff Model
MBC	Multivariate Bias Correction
NA-CORDEX	North-American Coordinated Regional Climate Model Downscaling Experiment
NBS	Net Basin Supply
NOAA	U.S. National Oceanic and Atmospheric Administration
NWM	U. S. National Water Model
OCC	Ontario Climate Consortium
QDM	Quantile Delta Mapping
QM	Quantile Mapping
RCM	Regional Climate Model
STAR	Seasonal Trends and Analysis of Residuals
U.S.	United States
UW-RegCM4	University of Wisconsin Regional Climate Model Version 4 RegCM4
WCPS	Water Cycle Prediction System
WRF	Weather Research Forecast Model

Introduction

In 2019, the Ontario Climate Consortium (OCC) co-hosted the first Great Lakes Climate Modeling Workshop with the Great Lakes Integrated Sciences and Assessments (GLISA) in Ann Arbor (MI). This workshop reviewed existing Great Lakes regional climate modeling efforts, shared preliminary results from relevant studies in Canada and the United States (U.S.), worked to identify current gaps and uncertainties, and developed recommendations for future work. A report detailing the findings of this workshop and the state of climate modeling in the Great Lakes Basin was produced by OCC (Delaney and Milner 2019). The 2019 report outlines the importance of regional modeling efforts for the Great Lakes Basin (GLB), current modeling methodologies, and provides an overview of existing climate models that incorporate simulations of the Great Lakes themselves. The 2019 workshop resulted in the development of nine recommendations for advancing the state of climate modeling in the region (See Table 1). These recommendations guided the development of the 2021 workshop, and progress made since 2019

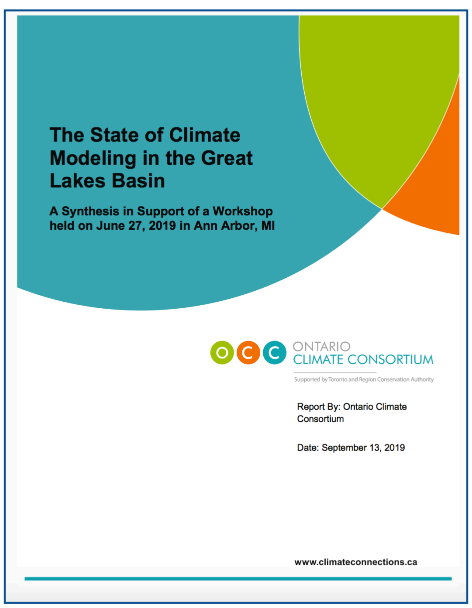

Figure 1. *Front cover of the 2019 Great Lakes Climate Modeling Workshop report.*

for each is described in Table 1. The progress update represents recent work by anyone in the fields that our literature review uncovered or participants brought to the discussions. New recommendations for researchers and practitioners coming out of the 2021 workshop are listed in each workshop session summary as well as in Table 2.

Under the auspices of the Great Lakes Water Quality Agreement (GLWQA) Annex 9 on Climate Changes Impacts with support from the U.S. National Oceanic and Atmospheric Administration (NOAA) Great Lakes Regional Collaboration Team and Environment and Climate Change Canada, GLISA co-hosted a second Great Lakes Climate Modeling Workshop during the week of March 21, 2021 to: 1) review the existing Great Lakes regional climate modeling efforts, including the strengths, limitations, and credibility of climate change projections; 2) share preliminary results from recent work and models in Canada and the United States; 3) identify gaps and areas of greatest uncertainty; and, 4) develop recommendations for future work. This workshop is an example of the ways in which Annex 9 facilitates the exchange of information between the U.S. and Canada and fosters the development and improvement of regional scale climate models. The workshop offered a platform to sustain regional discussions around the topics of physical climate modeling and translating climate information and expanded its scope to include model bias and lake levels. Four virtual sessions were held on the Zoom platform across four days in a single week focusing on: 1) physical climate modeling, 2) bias and bias correction, 3) lake level impact modeling, and, 4) translating climate information. This report provides a summary of the 2021 workshop, including updates on the state of climate modeling in the basin and highlights from each session.

Each workshop session was approximately two hours in length and consisted of a feature presentation that set the context for the session topic followed by two or three shorter (i.e., 10 minute) presentations highlighting relevant current work. The remainder of each session was dedicated to speaker questions and answers and group discussion, which was framed and facilitated by dedicated session co-chairs, one each from Canada and the United States. This format allowed participants to be informed of the latest research and work in the region, provided the opportunity to converse with other experts in the field, and offered the opportunity to share their knowledge and expertise during the discussion. Please see Appendix A for the detailed workshop agenda and Appendix B for the list of workshop participants.

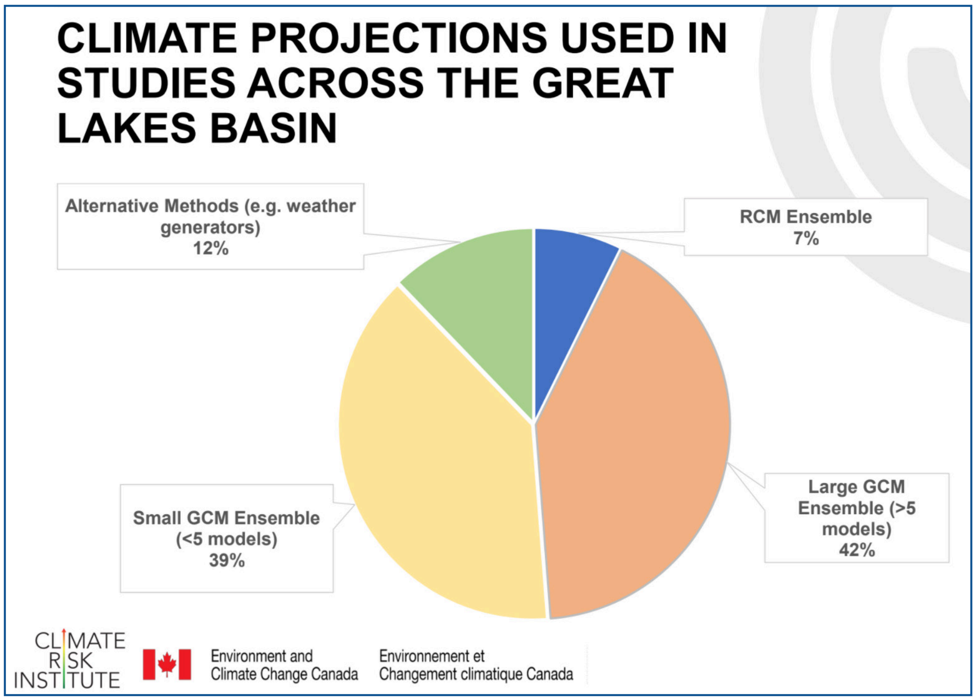

Figure 2. *Breakdown of how different types of climate projections are being used across the region between 2003 and 2019. Source: Ontario Climate Consortium*

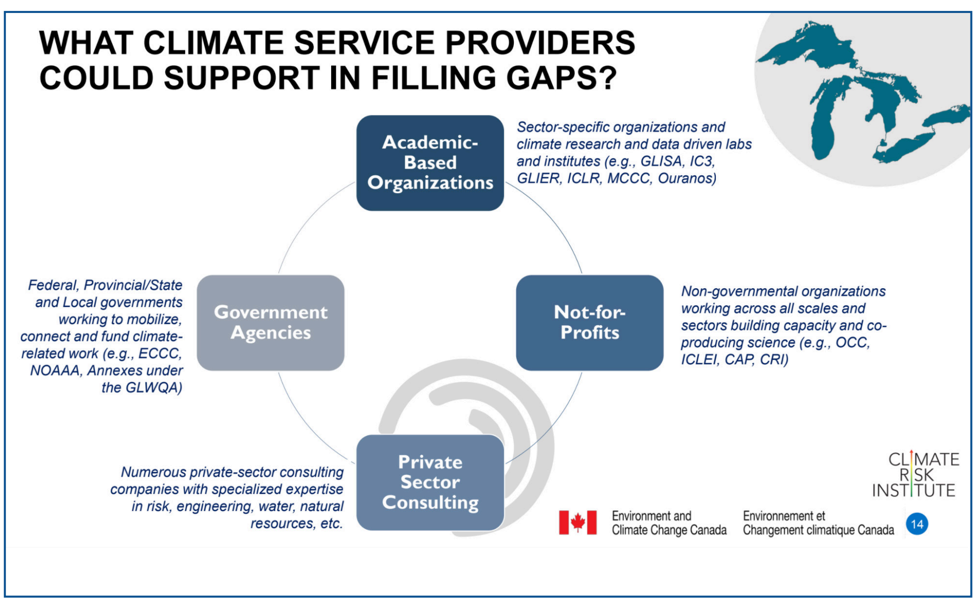

Figure 3. *Different entities and their climate service roles and expertise. Source: Ontario Climate Consortium*

Table 1

Recommendations and Progress Updates

A. Recommendations for Climate Modelers

A1. (2019) Increase two-way coupling of models that incorporate the atmosphere, land, and lakes and increase research and funds to 3D modeling.

Update:
Two new 3D coupled lake-atmosphere modeling efforts are underway in the region. Both products show improvements over previous 1D coupled lake simulations.

- High-Resolution 3D Lake Coupled Simulations for the Region (NU-WRF/FVCOM) (see details in Notaro presentation summary in session 1, Notaro et al. 2021)
- A new 2-way Coupled 3D Great Lakes-Atmosphere Regional Model (C-3D-GLARM) was configured using Regional Climate Model (RegCM4) and a hydrodynamic model based on the Finite Volume Community Ocean Model (FVCOM) (additional details available in Xue et al., 2017)

A2. (2019) Enhance data collection and conduct targeted field studies on lake climatology to feed into and validate climate models, and enhance spatial-temporal data coverage.

Update:
Observations and physical laws work together to validate models over long periods of time.

- A new data assimilation scheme has been developed for Lake Erie using a 3D hydrodynamic model to improve lake thermal structure and create hydrodynamic reanalysis products (Ye et al., 2020).
- The new estimates of monthly water balance components from 1950 to 2019 for the Great Lakes published by Do et al. (2020) can be used for examining changes in water availability or benchmarking new hydrological models.

**see page 42 of the 2019 workshop report for more detail on gaps in lake climatologies.*

A3. (2019) 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.

Update:
Observations and physical laws work together to validate models over long periods of time.

- A new data assimilation scheme has been developed for Lake Erie using a 3D hydrodynamic model to improve lake thermal structure and create hydrodynamic reanalysis products (Ye et al., 2020).
- The new estimates of monthly water balance components from 1950 to 2019 for the Great Lakes published by Do et al. (2020) can be used for examining changes in water availability or benchmarking new hydrological models.

**see page 42 of the 2019 workshop report for more detail on gaps in lake climatologies.*

A4. (2021) Utilize large (50+ member) ensembles when available to evaluate regional climate change, variability, and extremes.

A5. (2021) Coordinate regional modeling efforts to include standardized outputs, metrics, etc. to address uncertainty in a consistent manner.

A6. (2021) Climate models used in the Great Lakes region should include lake simulations, especially 3D lake simulations when available, which are needed to accurately represent the role of lake ice cover and the annual lake ice cycle in climate models.

A7. (2021) Develop guidance for which physical climate processes (e.g., convective precipitation, lake-effects, lake ice climatology, etc.) should be evaluated in climate models prior to bias adjustment procedures or other uses.

A8. (2021) Develop multiple tiers of model diagnostics based on the sophistication of the models being assessed (e.g., GCMs versus RCMs with lake simulations) to help modelers know where improvements need to be made and to help translators and end users know which models offer the most credible information. See examples in Session 3 "New Recommendations for Researchers".

A9. (2021) Evaluate model biases to determine if bias adjustment adds value or conceals major model uncertainties.

A10. (2021) Create an active inventory of who is conducting climate and lake modeling in the region to stay informed of the latest available data sets and state-of-the-art research and foster new collaborations/partnerships.

B. Recommendations for Climate Modelers and Climate Information Users and Translators

B1. (2019) Conduct continuous diverse stakeholder engagement between climate modelers, users, translators, and funding agencies.

Update:
Activities across the region are advancing this goal, but there remains opportunity for improvement.

- This 2021 modeling workshop expanded on the 2019 workshop audience to include researchers, translators, users, and funding agencies in addition to climate modelers.
- The GLWQA Annex 9 Extended Subcommittee instituted a new quarterly webinar series to increase the sharing of new research and improve engagement.
- In 2018 the International Joint Commission facilitated a bi-national poll about the Great Lakes basin (Great Lakes Water Quality Board, 2018). The results of this poll were analyzed to inform public engagement strategies.
- The Wisconsin Initiative on Climate Change Impacts established a Great Lakes Working Group (University of Wisconsin)

B2. (2021) Communicate information about model biases to end users of the data or information.

B3. (2021) Additional research into future lake level variability is needed to understand future risks and communicate those risks to practitioners.

B4. (2021) Collaborations between researchers, translators, and end users should expand their networks to bring in underserved stakeholders to inform adaptation work.

B5. (2021) Avoid using bias-adjusted projections from models where important physical climate processes are poorly represented.

C. Recommendations for Climate Information Users and Translators

C1. (2019) Continue to emphasize the connections between climate projections and local impacts.

Update:
Several new studies (not limited to those mentioned here) are available that investigate:
- Regional impacts in the Durham Region of Canada (Delaney et al. 2020)
- Future climate impacts on net basin supply (NBS) and water levels, two focus areas for this workshop: Erler et al. 2019 (climate change impacts on surface water resources); Gronewold and Rood 2019 (water level changes implications for future variability); Mailhot et al., 2019 (Great Lakes' hydrological conditions in a changing climate)

C2. (2019) Increase communication on the comparison of various climate model ensembles to practitioners.

Update:
Physical climate information relevant to impacts can be derived from global and continental-scale simulations in addition to those specifically focused on the Great Lakes basin.
- GLISA published a climate model consumer reports framework to communicate similarities and differences between models, model biases, and model projections for the region (Briley et al., 2020, Consumer Reports).
- The Coordinated Regional Climate Downscaling Experiment for North America (NA-CORDEX) is being used to assess future Great Lakes hydrological conditions (Mailhot et al., 2019) and as the foundation for a new North American climate service (McGinnis and Mearns 2021).
- The ClimEx project is a 50-member initial-conditions ensemble based on the Canadian Regional Climate Model (CRCM5) Large Ensemble (Leduc et al., 2019)

C3. (2019) Promote the importance of consistent approaches, where possible, being applied across similar regions in the GLB.

Update:
Recent publications suggest a convergence on the idea that better physical representations of the hydroclimate system offer improvements over simpler methods (Deacu et al., 2012; Erler et al., 2018; Lofgren & Rouhana, 2016; Xue et al., 2017) and these studies are informing the research community on which models and methods are the most credible.

C4. (2019) Build emerging climate information into existing portals and tailor its output, where possible, for different user groups.

Update:
There is a need to identify which portals are most used by stakeholders to know where to focus communication efforts, but some known information sources are already tailoring output for different user groups.
- GLISA is in the process of developing future climate scenarios for different stakeholder groups (e.g., municipalities, natural resource managers, etc.) and will publish those scenarios to their website in late 2021.
- The Climate Resilience Toolkit's Great Lakes portal offers tailored information and regional case studies.
- The Climate Explorer offers users county-level maps and graphs to assist users in making decisions for building resilience to extreme events.

C5. (2021) Translators should only recommend climate projections to end users where important lake-land-atmosphere interactions and feedbacks (i.e., minimally 1D lake representations and preferably 3D lake representations) are simulated.

C6.	(2021) Increase transparency of model biases in climate and hydrologic models to end users.
C7.	(2021) Explore alternatives to quantitative projection information (e.g., scenario planning) when model biases are large.
C8.	(2021) Inquire about model biases to assess the fit of projection information.
C9.	(2021) Incorporate an increased chance for more variable future lake levels (highs and lows) into coastal planning activities.
C10.	(2021) Showcase case studies utilizing climate projection information to help with uptake.
C11.	(2021) Advance research on developing future IDF curves with special attention to communicating uncertainties.
C12.	(2021) Explore approaches such as arbitrary precipitation increases as an alternative to translating specific climate projections into IDF information.
C13.	(2021) Practitioners can help translators develop new mediums for communicating climate information to stakeholders who may not access information using conventional means.

D. Recommendations for Funding Agencies

D1. (2019) Bolster available resources and opportunities to focus funding, specifically for Great Lakes climate modeling initiatives.

Update:
This topic was not covered during the 2021 workshop, but will be considered for future agendas.

* It should be noted that the new recommendations for 2021 were developed after the workshop by the planning committee, based on the feedback and discussion during the workshop itself. While the new recommendations have been reviewed by session chairs, they have not been reviewed by workshop presenters or attendees and are not meant to be exhaustive .

Workshop Session 1:

Physical Climate Modeling

Monday, March 21 2021: 11-1:30 EST
Session Co-Chairs:

- *Canada: Dr. Biljana Music, Ouranos*
- *United States: Dr. Brent Lofgren, NOAA Great Lakes Environmental Research Laboratory*

The physical climate of the Great Lakes region is in part related to the presence of the lakes as regional climate features. The Great Lakes themselves play an important role in the weather patterns and climate processes of the surrounding region due to their sizes, depths, and degrees of thermal inertia. Climate models include various representations of the lakes, and some models omit the lakes altogether. Important background information about climate models, challenges that are faced in simulating the regional climate, and a list of regional model products is available in the 2019 Great Lakes Climate Modeling Workshop report (Delaney and Milner 2019).

The first hour of session 1 was dedicated to a recap of the 2019 workshop report, 2021 workshop objectives, and participant introductions via breakout rooms. The remainder of the session included a feature presentation, two lightning round presentations, and a facilitated discussion on physical climate topics. The objectives of session 1 of the 2020 workshop were to update the modeling community on progress made since 2019, identify remaining gaps in knowledge, and to provide a forum for discussion on emerging questions.

Recent Research

Recent physical climate science research in the Great Lakes region emphasizes the areas of better understanding physical climate processes, improving observational data sets for model evaluation, and working towards improved model simulations for the region. The following summary of recent studies may not be exhaustive, but is intended to cover a range of scientific topics relevant to this session and share new resources.

Precipitation processes are of paramount importance to understanding current hydrologic conditions and extremes in the Great Lakes, but gridded precipitation data products can have large discrepancies due to the use of different precipitation estimation procedures. Wong et al. (2017) compared daily precipitation products for large-scale hydro-climate applications over Canada to inform users of which products performed best for which regions and seasons. The work of Minallah and Steiner (2020) in investigating the components of the regional moisture budget using reanalysis data sets is improving our understanding of precipitation processes and informing the evaluation of new climate model simulations (see Minallah's presentation summary, below, for more detail). Another new study is improving our understanding of primary atmospheric controls on winter precipitation in the GLB (Fu and Steinschneider, 2019). Several studies have also explored how future precipitation patterns, including extremes, are anticipated to change with a changing climate (Byun and Hamlet, 2018, Peltier et al., 2018, Leduc et al., 2019, and Zhang et al. 2020).

Climate modeling is also a rapidly changing field at the global scale. One of the most widely used ensembles is the Coupled Model Intercomparison Project (CMIP), but CMIP5 and earlier versions have limited use for Great Lakes practitioners due to their poor or missing representation of important lake-land-atmosphere interactions (Briley, Rood, and Notaro, 2021). Some CMIP6 simulations are now available for use, and there is a subset of high-resolution models GLISA and others

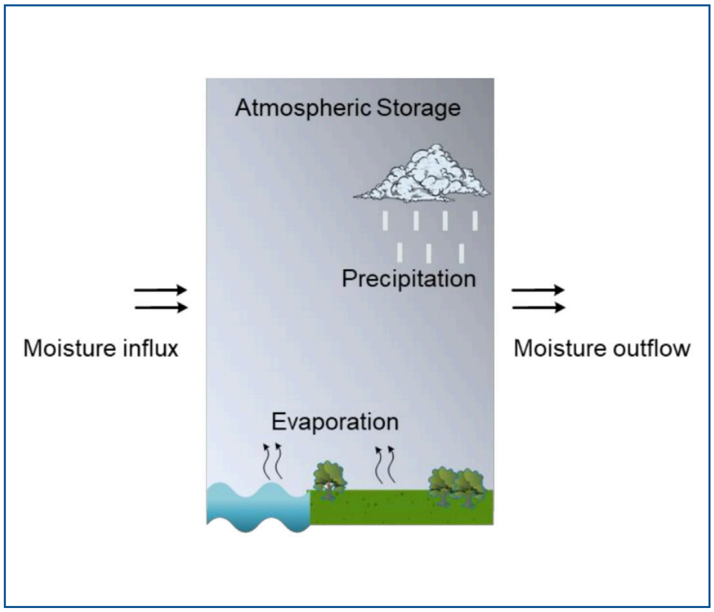

Figure 4. *Depiction of the moisture budget equation, dependent upon the moisture flux into and out of a model grid cell and the amount of evaporation and precipitation within the cell. Source: Samar Minallah (University of Michigan, Climate & Space Science and Engineering)*

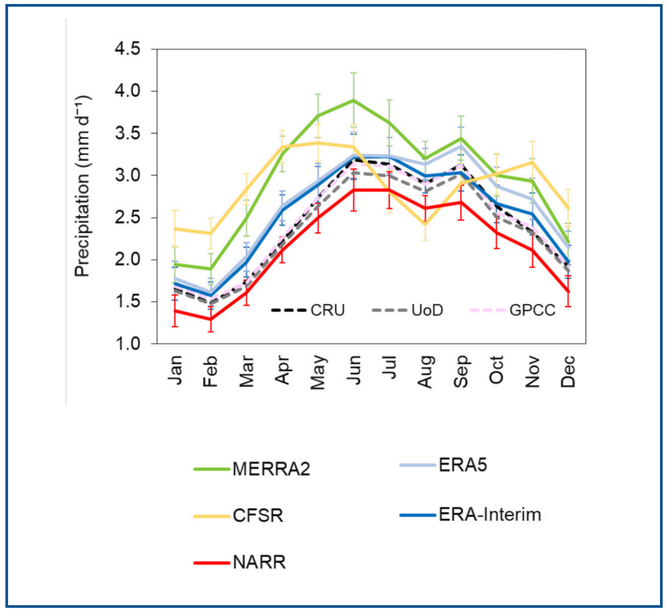

Figure 5. *Example monthly time series of precipitation totals over the Great Lakes region for five reanalysis products (colored solid lines) and three observation-based products (dashed lines). Source: Samar Minallah (University of Michigan, Climate & Space Science and Engineering)*

will be evaluating for the Great Lakes region. In the meantime, regional climate modeling efforts aim to better represent the Great Lakes and important regional climate processes (Sharma et al., 2018). Two new modeling efforts are underway that incorporate the more sophisticated 3D coupled lake models into regional climate model simulations (Xue et al., 2017, Notaro et al., in review). Other new modeling efforts in the region include climate change projections generated using the PRECIS regional climate model (Zhang et al. 2020), new high-resolution RCM projections over North America (see Wuebbles' presentation summary, below), and the one-way coupled hydrodynamic-ice model (FVCOM-CICE) and WRF (Fujisaki-Manome et al., 2021).

Large ensembles of regional climate models to assess climate change and variability is also a growing area of research in the GLB. Deser et al., (2020) point out the need for initial-condition large ensembles to distinguish between uncertainties related to internal climate variability versus model differences. The ClimEx Project (Leduc et al., 2019) offers a 50-member ensemble of climate change projections over northeastern North America using the Canadian Regional Climate Model (CRCM5). Ensembles like ClimEx will provide valuable information about future climate variability and sensitivity and offer a benchmark comparison for future single-RCM ensembles.

RCM ENSEMBLES AVAILABLE IN GREAT LAKES REGION

Ensemble	# of RCMs Used	Scenarios Available	Spatial Resolution	Data Available via Public Portal
NARCCAP	6	A2	50 km	✓
NA-CORDEX	7	RCP 4.5 RCP 8.5	25 km and 50 km	✓
Peltier Ensemble	1 (WRF)	RCP 8.5	10 km	By Request
Notaro Ensemble	1 (RegCM)	RCP 8.5	25 km	✓
USGS CC Viewer	1 (RegCM)	RCP 4.5 RCP 8.5	15 to 50 km	✓
URegina Ensemble	1 (RegCM)	RCP 4.5 RCP 8.5	25 km	✓
York U Super-Ensemble	8	RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5	10 km	✓

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Figure 6. *Summary of the regional climate model ensembles that are available in the Great Lakes region. Note that not all of these ensembles include models that adequately represent important lake-land-atmosphere interactions, so careful evaluation is required before use. Source: Glenn Milner (Climate Risk Institute)*

Presentation Summaries

As stated earlier, the purpose of the physical climate modeling session was to update participants on the progress made in physical climate modeling since 2019, discuss current knowledge gaps, and collect input to guide the future of physical climate modeling in the region. In session 1, the featured presentation was on GLISA's Great Lakes Ensemble project and new 3D-lake coupled climate simulations for the region. Other presentations focused on recent work assessing the simulated moisture budget of the Great Lakes region, a new statistical downscaling method (STAR approach), and new high-resolution dynamic downscaling for North America. Next, we provide a brief summary of each presentation.

Featured Presentation: New High-Resolution 3D Lake Coupled Simulations for the Region (NU-WRF/FVCOM)

Michael Notaro, University of Wisconsin-Madi

GLISA's Great Lakes Ensemble Project aims to provide high quality climate data and information in a way that is valuable to end users in the Great Lakes region. As part of the Ensemble project, GLISA evaluates how well the Great Lakes are simulated in global and regional climate models, assesses model biases, summarizes model performance, and provides guidance to end users (learn more about this work here). All of this work is guided by and co-produced with GLISA's Scientific Advisory Committee and Practitioner Working Group. Notaro presented slides on GLISA's behalf (from Laura Briley) on the project.

Delaney and Milner 2019 provided an overview of the UW-RegCM4 (Notaro) Ensemble. Since then, Notaro and the Nelson Institute Center for Climatic Research at the University of Wisconsin-Madison have continued their research and updated their approaches in collaboration with GLISA to include new 3km simulations using the NASA-Unified Weather Research and Forecasting model coupled two-way to the Finite Volume Community Ocean Model (FVCOM) using the OASIS Model Coupling Toolkit. This work focuses on exploring added benefits of 3D versus 1D lake model coupling for the Great Lakes region and includes nudging, spatially-varying bathymetry, and seasonally-varying lake surface temperatures. These updates have led to new knowledge about representing the Great Lakes in climate models and how to produce more reliable climate projections. Early evaluations show:

- The new 3D lake model captures the seasonal evolution of lake surface temperatures across each lake while the 1D lake model generates excessively cold water temperatures.
- The representation of ice cover is improved with the 3D lake model, as the 1D lake model produced excessively long ice seasons with too much ice cover.

The next steps for Notaro's work include examining the model's year-round performance and capacity to capture the abrupt warming of the Great Lakes as well as examining the representation of lake-effect snow, polar vortices, summertime heavy rain events, and other extremes. Future work includes generating 3km future simulations for the Great Lakes region focused on future hydrologic extremes (lake-effect snow and heavy rain events) and changes to 3D lake temperatures, circulation, ice cover, and net basin supply of the Great Lakes.

Atmospheric Moisture Budget of the Great Lakes Region

Samar Minallah, University of Michigan

Minallah presented work related to the moisture budget of the Great Lakes region (Minallah and Steiner, 2021) and shared results including the partitioning of moisture contribution from local (i.e., regional evapotranspiration) and remote (i.e., net moisture influx) sources using reanalysis data sets. Reanalysis data are helpful to provide a consistent process-based assessment of the atmospheric moisture cycle and can be used as a baseline to assess model simulations and drivers of future climate change. Minallah's moisture budget results are being used to evaluate CMIP6 simulations for the Great Lakes region. The research assessed historical precipitation biases in 15 CMIP6 models using ERA-Interim as a baseline and found some models show a reasonable annual precipitation magnitude but can have significant biases in different months. However, common patterns in future precipitation projections emerged and suggest an increase in wetness in the winter months, a decrease in moisture flux convergence in the summer months, and an increase in the magnitude of evaporation throughout the year in all models. However, the representation of lakes in these models can affect the monthly magnitudes and spatial distribution of precipitation. The absence of simulated lakes alters the localized convergence/divergence patterns. Minallah concluded that CMIP6 models without lake representations are not adequate to assess climatic changes in the region.

New Statistical Downscaling Approach: STAR (Seasonal Trends and Analysis of Residuals) and New High-Resolution (12km) Dynamic Downscaling for North America

Don Wuebbles, University of Illinois

Wuebbles presented a new software package, Seasonal Trends and Analysis of Residuals (STAR), that can run many global climate models (GCMs) and scenarios efficiently, automatically bias-correct the GCM output, and produce downscaled results for weather stations or a high-resolution (~6.25km) grid. STAR is based on signal decomposition algorithms that decompose temporal changes in data into long-term trends, seasonal climatologies, and daily anomalies and can determine which aspects are changing in a time series. Currently, CMIP6 results are being downscaled using STAR for two scenarios (ssp585 and ssp245) for temperature and precipitation to the CONUS weather stations and grid. Southern Canada will be added in along with additional variables and scenarios in the future. The goal is to calculate several dozen impact-relevant indicators for use in adaptation studies.

A new regional climate modeling effort using the Weather Research Forecast (WRF) Model is available for the RCP4.5 and RCP8.5 scenarios at mid- and late-century driven by four different CMIP5 GCMs. Simulations cover all of North America, but the RCM is not coupled to a lake model to improve the representation of the Great Lakes. The goal is to eventually produce a 1km product over the GLB coupled to a Great Lakes hydrological model to analyze regional climate change impacts, including water level changes.

Facilitated Discussion

After the presentations, session co-chairs led workshop participants through a facilitated discussion in two breakout groups. The following guiding questions were used to steer the discussion, and key themes from the conversation are noted under each.

<u>What can climate models tell us about climate variability versus climate change over the region?</u>

- We need large ensembles to evaluate regional climate change and variability.
- We need coordinated modeling (e.g., standardized outputs, metrics, etc.) to address uncertainty.
- Temperature and precipitation biases in some models can be as large as the climate change signal, so uncertainty is large in some cases.

<u>What areas of improvement are necessary in physical modeling of climate?</u>

- Convective resolving capabilities are needed to get accurate precipitation representation.
- Simulated lake dynamics and coupling to the land/atmosphere must be incorporated into climate models for them to provide meaningful information in our region.
- 3D lake representations show significant improvement over coupled 1D lake simulations.

<u>What are the models telling us about the source of moisture, underlying processes/drivers of the atmospheric moisture flux over the Great Lakes region, and whether the climate models capture it?</u>

- Reanalysis data sets are helpful to provide a consistent process-based assessment of the atmospheric moisture cycle, but some products (particularly MERRA-2 and CFSR) produce too much moisture and violate the mass balance equation.
- GCMs can tell us where atmospheric moisture is coming from outside of the region, but we need lake evaporation simulated to understand local evaporation sources.
- Whether or not the Great Lakes are simulated in CMIP6 models results in markedly different evaporation and moisture flux convergence magnitudes and patterns, and consequently can influence the simulation of micro-scale climatic patterns.

<u>The following discussion questions were posed, but not discussed, due to time constraints:</u>

- What climate impacts applications (e.g. ecosystems, water quantity, floods/droughts, shipping, recreation) would best benefit from examining secular change in climate variables (changes that go in a consistent direction over multiple decades to centuries) vs. changes in variability?
- What approaches can be used to analyze changes in temporal variability of climate? Concentrate mainly on annual to decadal variability that can affect lake levels.

New Recommendations for Climate Modelers

- Utilize large (50+ member) ensembles when available to evaluate regional climate change, variability, and extremes.
- Coordinate regional modeling efforts to include standardized outputs, metrics, etc. to address uncertainty in a consistent manner.
- Climate models used in the Great Lakes region should include lake simulations, especially 3D lake simulations when available, which are needed to accurately represent the role of lake ice cover and the annual lake ice cycle in climate models.

New Recommendations for Climate Information Users and Translators

- Translators should only recommend climate projections to end users where important lake-land-atmosphere interactions and feedbacks (i.e., minimally 1D lake representations and preferably 3D lake representations) are simulated.

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Workshop Session 2:

Bias & Bias Correction

Tuesday, March 22, 2021 11-1 EST
Session Co-Chairs:

- *Canada: Alex Cannon (Environment and Climate Change Canada)*
- *United States: Laura Briley (Great Lakes Integrated Sciences and Assessments)*

Bias and bias correction, or, as explained below, more appropriately termed bias "adjustment," was a new topic included in the 2021 workshop. The objectives of session 2 of the 2021 workshop were to discuss bias adjustment methods and best practices and provide an overview of model biases in the Great Lakes region.
There are no perfect models; random and/or systematic errors, or biases, exist in all models. Bias can vary by climate variable, location, and time, and bias generally increases at finer spatial resolutions. In some models, the errors can be quite large and bring into question the scientific credibility of the information. Bias "correction" is a procedure to adjust the model outputs to fit historical observations and make the outputs statistically more realistic. One must make the assumption that the historical adjustment factor is the same in the future in order to adjust future model outputs. In the Great Lakes region, there are several reasons why this assumption is not valid (Briley et al., 2017). It is important to point out that bias correction does not improve the physical climate representation in the models, so that is why we will refer to it as bias "adjustment" going forward. If bias adjustments are small, then perhaps the underlying model error is small. If bias adjustment is large, then the underlying error is almost certainly large. Bias adjustment obscures model errors, so oftentimes information about a model's bias is left out of the conversation about data quality with end users.

Some users require climate model output to be adjusted before the data can be used in their application. For

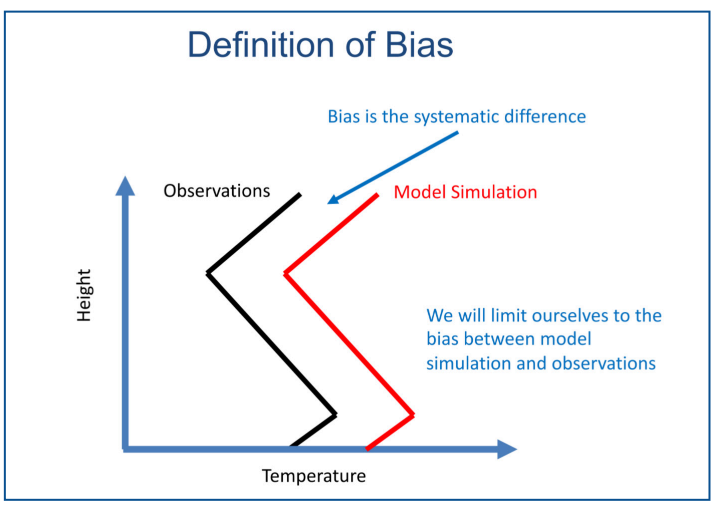

Figure 7. *Depiction of model bias defined here as the difference between a hypothetical observed and simulated temperature profile. Source: Ricky Rood (University of Michigan, GLISA)*

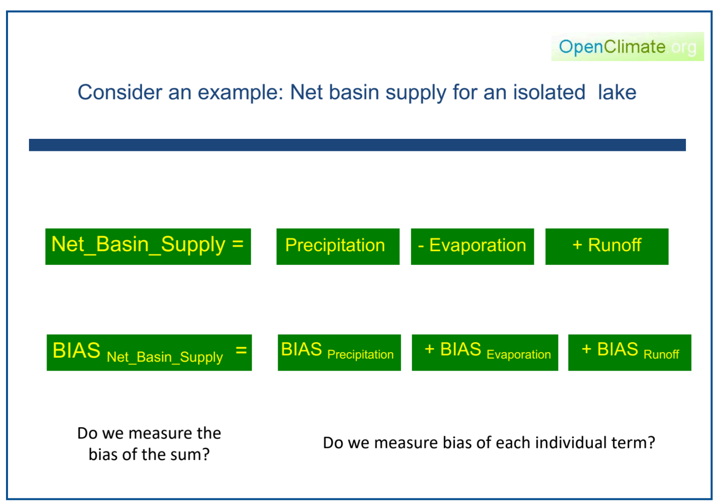

Figure 8. *Bias in net basin supply calculations is a result of biases in its individual components: precipitation, evaporation, and runoff. When the bias of any given component is large (e.g., >100%) then it is difficult to maintain that the information is credible. Source: Ricky Rood (University of Michigan, GLISA)*

example, hydrological modeling requires a realistic time series of precipitation inputs to accurately simulate surface and groundwater flows. If a climate model has a very wet bias to start with, those biases will propagate forward in the hydrologic model if they are not adjusted. There are many approaches to performing bias adjustment, but there are limitations and pitfalls for each approach. Sometimes the fundamental assumptions of bias adjustment, such as climate stationarity (i.e., patterns of the past are assumed the same in the future) are not valid. There are several non-stationary examples of climate processes in the Great Lakes region that require caution on behalf of the user (Briley, Ashley, & Rood, 2017). Ultimately, if and how bias adjustment occurs needs to be determined through a conversation between the end user and experts fluent in regional climate processes and the strengths and weaknesses of different bias adjustment approaches.

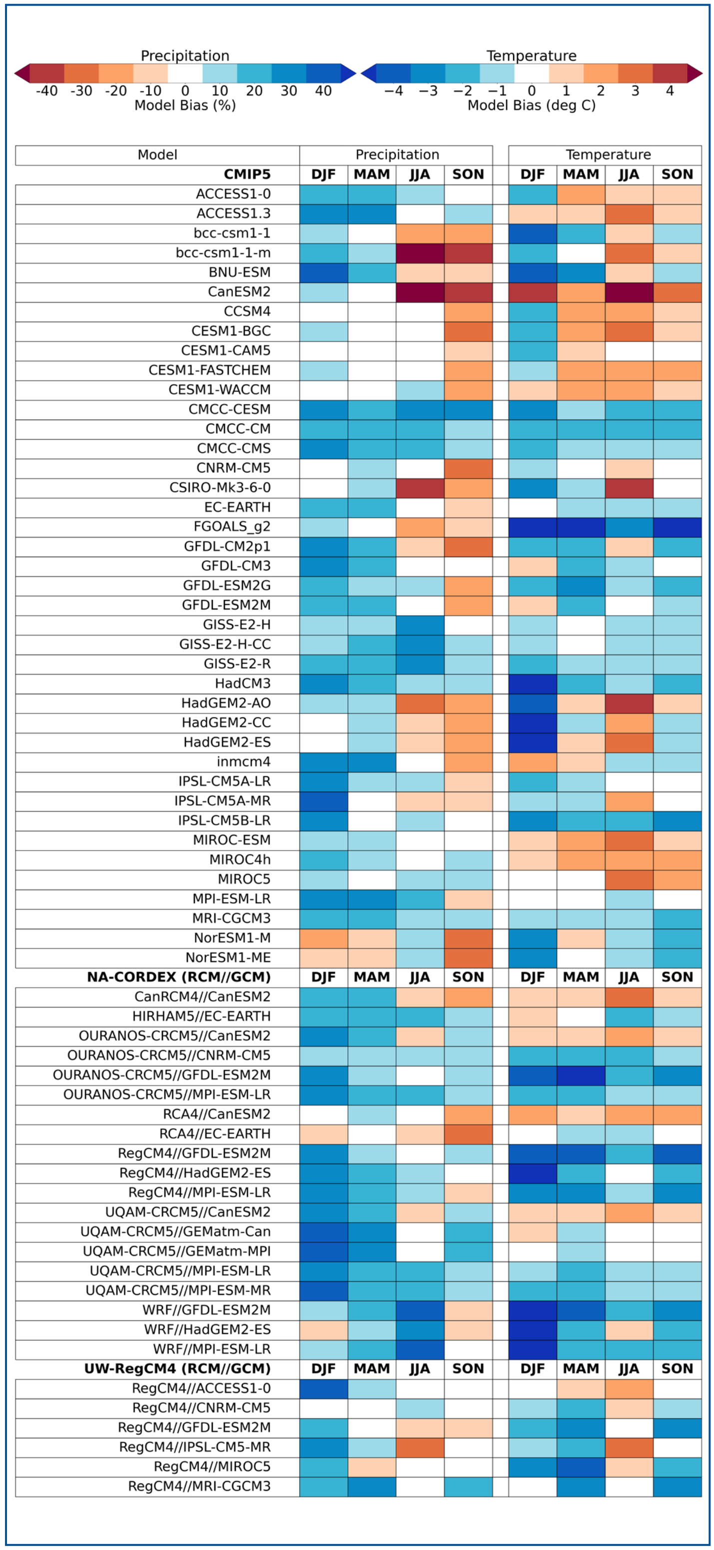

Figure 9. *Seasonal precipitation and temperature bias for CMIP5, NA-CORDEX, and UW-RegCM4 projection datasets. All model biases are evaluated against NOAA's National Centers for Environmental Information (NCEI) Climate Divisions Dataset from 1980-1999. More on GLISA's methodology is available here.*

Recent Research

Recent bias adjustment research emphasizes work in the areas of adjustment methods, limitations, interpretation, and recommendations. Cannon, Piani, and Sippel (2020) provide a helpful overview of the simplest, single-variable (i.e., univariate) methods for bias adjustment along with their underlying assumptions, limitations, and a brief historical background. White and Toumi (2013) discuss limitations of bias adjusting RCM inputs, which is important for the Great Lakes region because the best climate simulations are coming out of regional climate modeling efforts.

There has been a recent proliferation of the number of bias adjustment methods available, ranging from simple to complex, and evaluation of them is necessary to understand limitations and appropriate uses of them. Lanzante et al. (2020) use the Perfect Model design to examine the skill of several distributional methods, including the representation of climate extremes. They found "little meaningful difference in performance between most of the downscaling methods and across several fundamentally different evaluation metrics," but there was overall better performance when the method employed the change-factor and bias-correction (Lanzante et al, 2020). Cannon, Sobie, and Murdock (2015) examined Quantile Delta Mapping (QDM) and found that "[quantile mapping] QM can inflate the magnitude of relative trends in precipitation extremes with respect to the raw GCM, often substantially, as compared to [detrended quantile mapping] DQM and especially QDM." These results can help guide the choice of method to use depending on what matters most for the application, especially when climate extremes are of interest.

In addition to the bias adjustment methods developed for individual climate variables, new Multivariate Bias Correction (MBC) algorithms have been recently developed (Cannon 2016 and 2018) to correct for failures in recreating inter-variable, spatial, or temporal dependencies (François et al., 2020). François et al. (2020) recently published their evaluation of several multivariate bias adjustment methods to aid users in their choice of method.

Aside from the statistical adjustment approaches, new work is emerging that takes into account the performance of physical climate processes in the models. "A fundamental assumption of bias correction is that the considered climate model produces skillful input for a bias correction, including a plausible representation of climate change" (Maraun 2016). This kind of skill is simply not present in many models, and bias adjustment of a poorly simulated climate does not "correct" for physical misrepresentations (Gates and Rood 2021). Maraun (2016) suggests developing new stochastic models for downscaling and approaches that explicitly include an understanding of physical processes. Similarly, Ivanov, Luterbacher, and Kotlarski, (2018) recommend "[f]uture research needs to focus on developing process-based bias corrections that depend on simulated intensities rather than preserving the raw model [climate change signal] CCS."

Over the last few years GLISA has undertaken the evaluation of temperature and precipitation biases in three commonly used climate model ensembles: CMIP5, North-American Coordinated Regional Climate Model Downscaling Experiment (NA-CORDEX), and dynamically downscaled projections for the Great Lakes region - the UW-RegCM4. A detailed summary of annual and seasonal temperature and precipitation biases for each member of the ensembles is available on their website (GLISA, n.d.).

Ultimately, once users are aware of the magnitude of model biases, they will be faced with the decision of whether adjusting the model data is scientifically credible and retains value in the information. GLISA has written a summary white paper providing guidance on how practitioners, with the help of bias experts, can approach this problem and offers practitioners an alternative solution using qualitative scenario planning (Gates and Rood 2021).

Presentation Summaries

As stated earlier, the purpose of session 2 was to initiate conversations with regional modeling experts on model biases in the Great Lakes region and discuss bias adjustment methods and best practices. Presentations featured GLISA's perspective on bias and bias correction for practitioner audiences, an overview of bias adjustment methods and pitfalls, and regional precipitation biases in the WRF model. Next, we provide a brief summary of each of these presentations.

Bias and Bias Correction: Challenges to Credibility and Plausibility

Richard Rood, GLISA

Rood provided a general overview of bias, important attributes of bias, how practitioners can interpret bias information, and how models should be used as guidance as opposed to forecasts. Bias in climate models can be large, and although there are existing methods for bias correction that adjust model outputs, model errors are obscured. Rood discussed the way that bias in model outputs can propagate when the outputs are used to calculate secondary quantities, such as lake levels. With extensive bias adjustments and the subsequent use of these quantities in other models or calculations, it is difficult to trust the credibility of the final output when used to manage uncertainty in planning for climate change. Rood discussed qualitative methods for managing this uncertainty that do not require the use of the bias-adjusted model outputs. In GLISA's experience, many practitioners only need these qualitative methods. These concerns can be avoided using qualitative scenario planning approaches. See Gates and Rood (2021) for a detailed summary of how practitioners can understand and manage model biases in the information they use.

Bias ~~Correction~~ Adjustment, Statistical Downscaling and Other Things (That Go Bump in the Night)

John Lanzante, Geophysical Fluid Dynamics Laboratory, U.S. National Oceanic and Atmospheric Administration

Lanzante presented on bias adjustment and statistical downscaling, which are often paired post processing techniques. Statistical downscaling in practice includes bridging spatial scale mismatches, bias adjustment, and calculation of variables not produced by the physical model. The goal of bias adjustment is to develop a transfer function that adjusts model outputs to more closely mirror historical observations, which requires the assumption that the statistics of the past will persist into the future. There are two specific paradigms for adjustment: bias adjustment and change factor, or the delta method. Bias adjustment aims to statistically remove bias from the model while the change factor aims to add the model climate change signal to observations. The hierarchy of application of these types of adjustment goes from simplest, where the adjustment is applied only to the mean, to distributional, where a separate adjustment is applied by quartile, to combined, where both bias adjustment and a change factor are applied distributionally. The choice of method depends on the application. Lanzante also discussed the difficulty of assessing the accuracy of the transfer function for future projections as the climate is changing and it is impossible to know if the transfer function will be the same in the future.

Climate Model Biases and Impact Modeling

Andre Erler, University of Toronto, Aquanty

Erler discussed precipitation biases in WRF along with hydrologic simulations using WRF output. The simulations used to investigate biases and future projections are from the WRF ensemble, forced by the CESM ensemble, along with the FLake column lake model. Depending on the configuration of WRF, there are different biases in the outputs. Another important aspect of bias is the fact that summer precipitation bias increases with increasing resolution. In general, there is a scale dependency of bias. When looking at future projections, large biases can cast doubt on precipitation simulations. It is important to look at whether or not the climate change response is consistent across simulations. The different WRF configurations produced different summer precipitation trends. In addition, the biases were notably larger than the climate change signal. This greatly reduces confidence in the projections. The WRF precipitation simulations were then used in hydrologic simulations to study climate change impacts on surface and groundwater using a fully integrated 3D ground and surface water model. Simulations were run with an annual average adjustment bias correction and with no bias correction. As anticipated, the model with precipitation declines showed decreasing groundwater supply and vice versa. Interestingly, bias-correction altered the quantitative response of the system but the qualitative response was similar— the magnitude of wetting/drying was altered but the system was still wet/dry with and without bias-correction.

Facilitated Discussion

After the presentations, session co-chairs led workshop participants through a facilitated discussion in two breakout groups. The following guiding questions were used to steer the discussion, and key themes from the conversation are noted under each.

Bias Correction Methods and Best Practices

<u>When can bias-correction add value to projection information or when should bias-correction be avoided/not used?</u>

- It is important to investigate the underlying source of model biases, especially when they are large. In some cases it is not scientifically defensible to bias adjust model output, because bias adjustment does not “fix” the underlying model errors.

<u>When is bias too large to be defensible in impacts modeling (e.g., hydrological, ecological, etc.)?</u>

- Model biases can easily be larger than the climate change signal, which begs the question whether or not the model information is usable and should be adjusted. Ultimately, the user will have to decide how much bias is too much for the results to be meaningful.

<u>What factors should be considered when selecting a bias-correction method?</u>

- The research questions and/or climate impacts that are being investigated should inform the bias-adjustment method that is chosen. Methods range from simple to complex, and each method has its strengths and weaknesses. Users interested in mean changes can typically rely on simple bias adjustment methods or the delta method. Users interested in a range of values or extremes should use distributional adjustment methods. Users interested in maintaining physical representation and consistency between multiple climate variables (e.g., wildfire simulations require temperature, relative humidity, winds, and solar

radiation) should consider multivariate adjustment methods. Users interested in "spells" of weather should consider stochastic weather generators.
- Some of the biggest challenges for bias adjustment in the Great Lakes region is climate non-stationarity (patterns of the past are not going to be the same in the future) and areas of land/water contrast. As stated earlier, process based evaluation of crucial model features, such as the representation of the Great Lakes and important lake-land-atmosphere interactions, is necessary to assess whether or not bias adjustment can add value. If the processes are not adequately simulated, bias adjustment does not add value to an already erroneous simulation.

Model Biases in the Great Lakes Region

Discuss the magnitude of temperature and precipitation bias (and other variables) for the region

- GLISA evaluated 65 models from the Coupled Model Intercomparison Project 5, North-American Coordinated Regional Climate Downscaling Experiment, and the University of Wisconsin's RegCM4 ensemble; of those models only 17 had less than 2.5°C temperature bias and <25% precipitation bias during any given season, and five models had greater than 5°C and more than 100% precipitation bias. In many of the models the bias is larger than the climate change signal.

Is there a known cause for these model biases?

- There are many causes for model bias, and large biases are not necessarily associated with the simulation quality of the lakes but also atmospheric processes, such as surface radiation and convective schemes. In some cases, models with better lake simulations can have stronger model biases due to other processes. Biases also often increase at higher spatial resolution, rather than decrease (as one might expect).

What model improvements should be made to reduce model biases?

- An exhaustive list of improvements was not generated during the discussion, but generally speaking improvements should focus on better representing important processes, such as convective precipitation (including lake-effects) using convection-resolving models, and lake dynamics (e.g., horizontal and vertical mixing) and lake-atmospheric interactions (e.g., moisture fluxes) using 3D lake models.

Bias Information Translation

How is bias information incorporated into other modeling efforts, such as hydrological modeling?

- Many regional practitioners are not using information about model biases in their work.

How is/should bias information be communicated to end users?

- Users are typically not necessarily aware of model biases when they use model data in their work.
- Information about model biases is often omitted from reports and products that practitioners use.
- The accumulation of bias from climate models to, for example, hydrological models is often not communicated to end users.

New Recommendations for Climate Modelers

- Develop guidance for which physical climate processes (e.g., convective precipitation, lake-effects, lake ice climatology, etc.) should be evaluated in climate models prior to bias adjustment procedures or other uses.
- Evaluate model biases to determine if bias adjustment adds value or conceals major model uncertainties.

New Recommendations for Climate Modelers, Information Users, and Translators

- Before using bias-adjusted data or asking what bias adjustment method should be applied, information about the underlying model biases is needed to understand if bias-adjustment adds value or conceals major model uncertainties.
- Practitioners should not use bias-adjusted projections based on models where physical climate processes are poorly represented, since the underlying model information is erroneous and bias-adjustment does not correct those deficiencies.
- Alternatives to quantitative projection information (e.g., scenario planning) should be explored with the help of experts when model biases are large.

New Recommendations for Climate Information Users and Translators

- Explore alternatives to quantitative projection information (e.g., scenario planning) when model biases are large.

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Workshop Session 3:

Lake Level Impact Modeling

Wednesday, March 24, 2021: 1-3 EST
Session Co-Chairs:

- *Canada: Frank Seglenieks (Environment and Climate Change Canada)*
- *United States: Drew Gronewold (University of Michigan School for Environment and Sustainability)*

The Great Lakes provide essential functions and services to many practitioners and the public in and around the basin. Fluctuations in water levels have important implications for those who live in the basin and rely on the lakes for business, recreation, or any other purpose. Low water levels cause issues relating to navigation and shipping while also impacting recreation. Conversely, high water levels coupled with high wind and wave events can lead to shoreline erosion and flooding. Because of this, practitioners in the Great Lakes region are increasingly interested in future water level projections.

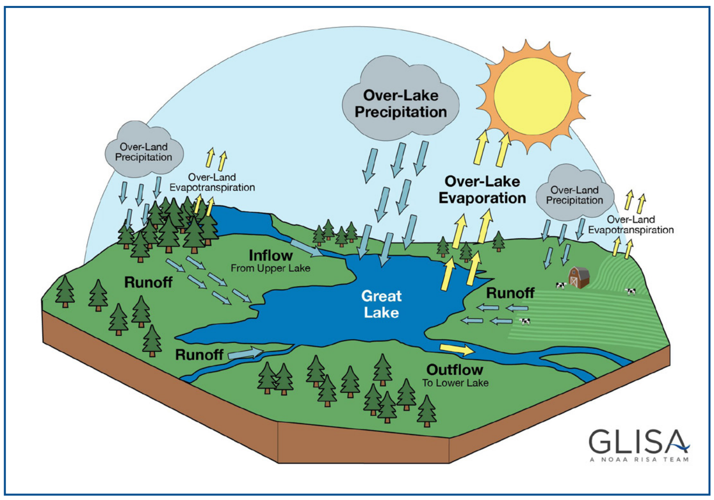

Figure 10. *Water balance components that affect Great Lakes water levels. Source: GLISA*

Lake Levels are driven by many different natural processes, including evaporation, precipitation, and runoff, but also influenced by consumptive use, diversions, and outflow regulation. Changes in these components can lead to high or low water levels in the lakes. Recently, the Great Lakes have seen a sustained period of high water levels and subsequent flooding and shoreline erosion. This recent period of high water levels was preceded by an extended period of low lake levels. This demonstrated variability has increased interest in model projections of future lake levels. However, it is difficult to reliably and accurately predict future lake levels due to uncertainties in climate and hydrological models. Biases in the net basin supply components (e.g., precipitation, evaporation, and runoff) produced by climate models can propagate to the hydrological models that simulate lake levels, leading to even greater uncertainty in water level projections.

The goal of the Lake Level Impact Modeling session of the 2021 Great Lakes Climate Modeling Workshop was to provide an overview of past trends, possible future scenarios in lake levels, and the factors that impact them, while identifying guidance that can be provided to practitioners about how current and future climate conditions may impact lake levels.

Recent Research

Recent lake level research shows progress in the areas of understanding past and present NBS and water levels, including new data products, and work towards improving hydrological simulations and projecting future NBS and water levels. “Coasts, water levels, and climate change: A Great Lakes perspective” (2013) provides an overview of historic water level variability, water level drivers, and implications for future water level management. Discussion of the Lake Ontario flood of 2017 that was induced by weather extremes and climate variability is described in Gronewold and Rood (2019), and a detailed discussion of historic water level extremes is available in Annin (2018).

Several new hydrologic data products are now available for studying past conditions, examining water availability in the region, and benchmarking hydrological models. These products have not been developed without challenges, especially data discontinuities along the US/Canada border (Gronewold et al., 2018). A summary of these challenges and how the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data have overcome some of them are available in Gronewold et al. (2018). A new hydrometeorological database for over-lake and over-land precipitation and air temperature, runoff, and over-lake evaporation is now available for public use from the Great Lakes Environmental Research Laboratory (Hunter et al. 2015). Several lake variables and descriptions of how the observations are recorded, processed, and reported are available. Another new product consisting of estimates of monthly water balance components from 1950 to 2019 for the Great Lakes are published in Do et al. (2020). Lake storage changes and water balance components were estimated using the Large Lakes Statistical Water Balance Model.

Recent modeling advancements are informing researchers which models offer the best platforms and information for studying past and future hydrologic regimes. The Great Lakes Runoff Inter-comparison Project (GRIP) compares different hydrologic models in their ability to estimate runoff for different watersheds. Results from the Lake Michigan GRIP (GRIP-M) and Lake Ontario GRIP (GRIP-O) are now available (Fry et al., 2014 and Gaborit et al., 2017). Model comparisons are also available for assessing streamflow, including GEM-Hydro (based on the Soil, Vegetation and Snow, or SVS, land-surface scheme and the WATROUTE routing scheme), MESH and WATFLOOD. GEM-Hydro proved competitive with the other models, and streamflows in GEM-Hydro were evaluated over the Lake Ontario basin with results validating the model's representation of runoff for a large basin with ungauged portions (Gaborit et al. 2017). SVS is anticipated to replace previous land surface schemes in Environment and Climate Change Canada's (ECCC) operational models in the future (Gaborit et al. 2017).

Climate model improvements are also benefiting hydrologic research. A new 2-way coupled 3D lake-

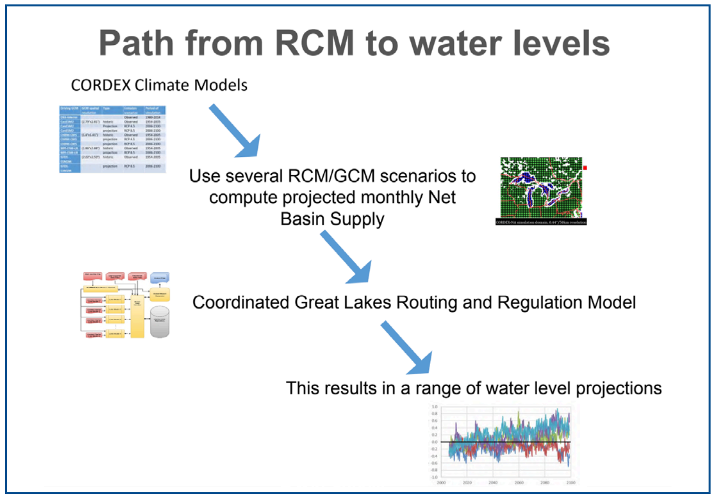

Figure 11. *Modeling pathway depicting how lake levels are derived from climate model projections. Source: Frank Seglenieks (Environment and Climate Change Canada)*

ice–climate modeling system [Great Lakes–Atmosphere Regional Model (GLARM)] was recently developed to "improve the simulation of large lakes in regional climate models and accurately resolve the hydroclimatic interactions" (Xue et al. 2017). This emphasis on better resolving important physical climate and hydrologic processes to improve the quality of information coming from the models was also a major theme of session 1. It is also echoed in Lofren and Rouhana (2016), where they show more physically based methods for projecting water level changes offer significantly different representations of evapotranspiration, runoff, NBS, and ultimately higher water levels as compared to temperature-based predictor methods, like the large basin runoff model (LBRM). They critique the commonly used LBRM and caution researchers to distinguish between the effects of radiation versus air temperature in driving changes in the NBS components, as LBRM relies heavily on near-surface air temperature as a primary predictor of evapotranspiration and it is shown to violate a fundamental principle of conservation of energy at the land surface.

Several recent research efforts have focused on simulations of future water supplies, including surface water, streamflows, NBS, and water levels. Wet and dry scenarios for streamflow and water availability were published in Erler et al. (2017). The divergent scenarios (wetter versus drier) are a result of an opposing climate change signal in future summer precipitation projections. In a separate study, future hydrologic simulations resulted in one future high and one future low water level scenario, despite consistent projected increases in annual air temperature, precipitation, and all NBS components by the downscaled GCM (Notaro, Bennington, and Lofgren, B.

2015). These results indicate the importance of the relative magnitude of the NBS components in the calculation of future water levels. A much larger study assessed future hydrological conditions using 28 simulations from five regional climate models under two future emission scenarios (RCP4.5 and RCP8.5) and found small increases in NBS out to 2100 with seasonal variability (Mailhot et al. 2019).

Presentation Summaries

Four presentations were given during the Lake Level Impact Modeling session of the 2021 Great Lakes Climate Modeling Workshop. These presentations featured past, present, and future lake level information, compound flood events, and understanding precipitation drivers. Next, we provide a brief summary of each of these presentations.

Fluctuations in Hydrologic Extremes Across Large Lake Systems

Andrew Gronewold, University of Michigan School for Environment and Sustainability

Gronewold provided an overview of Great Lakes water levels. This included a discussion of historical water levels in the Great Lakes, the physical drivers that determine water levels, and discussion of future water level projections. The water balance in the region has shifted in recent years and Gronewold questioned whether models were able to recreate this shift, which contributes to the credibility of a model's future simulation. The Great Lakes region is not expected to experience a monotonic increase or decrease in future water levels, but rather increased variability.

Projections of Key Climate Variables and Great Lakes Water Levels Under Climate Change

Frank Seglenieks, Environment and Climate Change Canada

Seglenieks provided an introduction to hydrological modeling in the Great Lakes region, specifically for projecting future lake levels. He described his team's approach using multiple regional climate model projections under multiple future greenhouse gas scenarios from the NA-CORDEX. These projections were bias adjusted and used to calculate monthly NBS which was then used as input to the Coordinated Great Lakes Routing and Regulation Model to produce a range of water level projections. The multiple steps in the process of calculating water level projections lead to the possibility of error propagation and larger potential biases. A comparison of this study to previous works shows that there is a potential for a greater range of lake levels in the future.

Multivariate Statistical Analysis of Compound Flooding Over the Great Lakes Coastal Zones: Characterizing the Joint Behaviour of Coastal Water Levels, Heavy, Rainfall, and River Flows

Reza Najafi, Western University, Department of Civil and Environmental Engineering

Najafi discussed the drivers of different types of flooding and their possible interrelationships and subsequent impacts. Flooding events are impacted by both terrestrial and marine processes including precipitation and waves, respectively. Compound relationships between these processes can aggravate and increase the possible impacts of flooding. Large ensemble simulations are needed to assess the bivariate structure of the drivers of compound events for the future.

Understanding Precipitation Changes in the Great Lakes

Sarah Kapnik, Geophysical Fluid Dynamics Laboratory (GFDL), U.S. National Oceanic and Atmospheric Administration

Kapnick provided an overview of precipitation in the context of global climate modeling and how we study precipitation. Kapnick showed how model outputs of

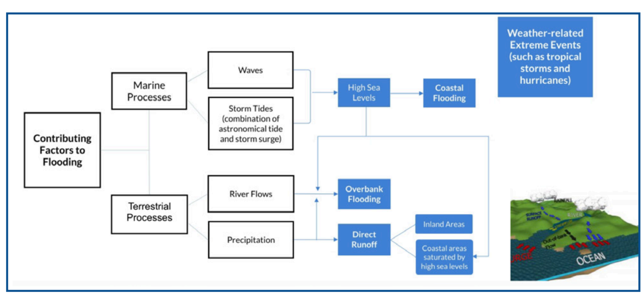

Figure 12. *Marine and terrestrial processes and events that contribute to flooding. Source: Western University*

precipitation extremes increase in accuracy at finer spatial resolutions. Through testing and development, it has been determined that the minimum resolution for a model predicting precipitation extremes must be 50 kilometers or finer. These models provide an extreme risk quantification "testbed" when large ensembles are available. In general, precipitation extremes in the United States are projected to increase in the coming decades. In the future, GFDL plans to expand the capability of their model to quantify weather and climate risks as well as expand to applications and risks.

Facilitated Discussion

After the presentations, session co-chairs led workshop participants through a facilitated discussion. The following guiding questions were used to steer the discussion, and key themes from the conversation are noted under each.

<u>Is there any indication (from models) of a long-term trend in components of the Great Lakes regional water balance that might foreshadow future trends in water level mean and variability?</u>

- Before asking the models to give us information about future NBS, details about the model's representation of the Great Lakes and NBS components are needed.
- Climate modelers could use guidance on what metrics they should investigate (e.g., precip, evap, runoff, etc.) to assess their model's performance and provide guidance to end users about how well the model performs and where improvements need to be made.

<u>What drove the recent multi-year surge in precipitation across central North America (including the Great Lakes)?</u>

- Lake evaporation is a dominant component of moisture to the region, and we have to ask how the lakes and lake evaporation are represented in the models to have a sense of model credibility.

<u>What are the implications of incorrectly representing (or not representing) the lakes in climate models on our understanding of the future water balance and water level variability?</u>

- The Great Lakes have not been the focus of GCM modeling efforts, but this may start to stand out as GCMs move to finer spatial resolution.
- Simulating lake processes, like evaporation, is key to accurately representing regional moisture supply.

New Recommendations for Climate Modelers

- Climate models used in the Great Lakes region should include lake simulations, especially 3D lake simulations when available, which are needed to accurately represent the role of lake ice cover and the annual lake ice cycle in climate models.
- Create an active inventory of who is conducting climate and lake modeling in the region to stay informed of the latest available data sets and state-of-the-art research and foster new collaborations/ partnerships.
- Develop multiple tiers of model diagnostics based on the sophistication of the models being assessed (e.g., GCMs versus RCMs with lake simulations) to help modelers know where improvements need to be made and to help translators and end users know which models offer the most credible information. Proposed diagnostics include:
- Metrics for how well NBS components are simulated.
- Metrics for how well means and/or extremes are represented for different
    - Variables (e.g., temperature, precipitation, snow, etc.).
    - Uncertainty quantification for the choice of GCM, forcing scenario (i.e.,
    - Representative Concentration Pathway), and representation of important physical processes in the RCM.

New Recommendations for Climate Modelers, Information Users and Translators

- Additional research into future lake level variability is needed to understand future risks and communicate those risks to practitioners.

New Recommendations for Climate Modelers, Information Users and Translators

- Increase transparency of model biases in climate and hydrologic models to end users.
- Inquire about model biases to assess the fit of projection information.
- Incorporate an increased chance for more variable future lake levels (highs and lows) into coastal planning activities.

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Workshop Session 4:

Translating Climate Information

Friday, March 26, 2021: 11-1 EST
Session Co-Chairs:

- *Canada: Frances Delaney (Environment and Climate Change Canada)*
- *United States: Laura Briley (Great Lakes Integrated Sciences and Assessments)*

Climate information is used by a variety of stakeholders with varying degrees of knowledge on how this information is developed and the ways in which it can be applied. Collaboration between end users, translators, and developers can help to make climate information more understandable and usable. Professional guidance and co-development of resources are common strategies for approaching the application of climate data and information across multiple disciplines and groups including engineers, municipalities, and communities.

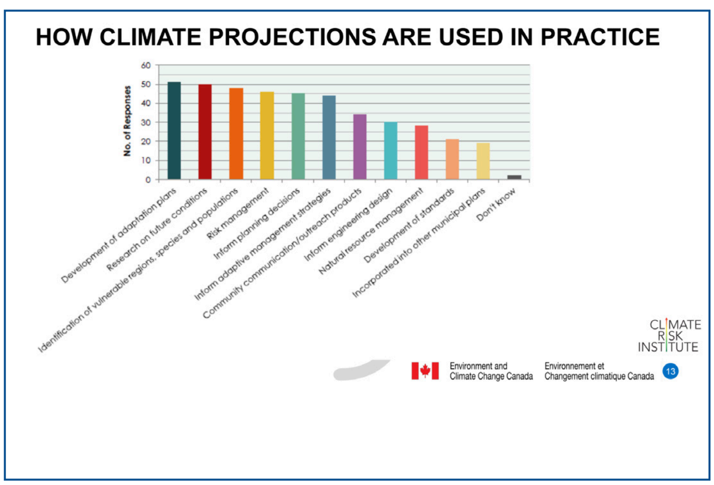


Figure 13. *Breakdown of how climate projections have been used in Ontario. Source: (Morand et al., 2015)*

Session 4 of the 2021 Great Lakes Climate Modeling Workshop was dedicated to the discussion of translating climate information and built on the foundation laid in 2019. The 2019 report summarizes the various types of users of climate information, climate service providers in the region, and common approaches to applying climate information in practice. The purpose of this session was to provide an overview of existing tools and translational services as well as to discuss bridging translational gaps identified in 2019. Other goals of the session included taking inventory of who is providing translational services in the region, what stakeholder groups are being served, and identifying needs and gaps along with best practices.

Recent Research

Recent climate translation research and work relevant to this session include an array of new products and tools available to practitioners. Translational products on the impacts of climate change on the Great Lakes region, including case studies in some cases, are available from a variety of sources with varying levels of detail (GLISA, U.S. Climate Resilience Toolkit, and Wuebbles et al., 2019). GLISA's new climate information consumer reports framework offers a novel approach to translating information about climate models and model projections for practitioner audiences (Briley et al., 2020).

A recently developed tool that is garnering national attention is the First Street Foundation's Flood Factor tool (available online), that summarizes U.S. flood risk down to the property level (Bates et al. 2021). Another new tool developed with governmental, commercial, and industrial groups in mind is ECCC's Water Cycle Prediction System (WCPS). "WCPS is the first short-to-medium-range

ENGINEERING VS. CLIMATE SCIENCE

What Engineers Need	What Climate Science Can Typically Provide
▪ Extreme events (e.g., snowpacks, high winds based on thresholds)	▪ Best with averages ▪ Highly specialized approaches needed for extreme events ▪ Some future trends not certain yet
▪ Sub-hourly extreme rainfall (minutes)	▪ Typically monthly or daily extreme rainfall ▪ Uncertainties increase with finer time and space scales
▪ Complex climate events (e.g., snowmelt + rainfall, ice accretion, wind driven rain, etc.)	▪ Very difficult to calculate for current climate and more challenging for future climate ▪ Needs professional judgement

CLIMATE RISK INSTITUTE

9

Figure 15. *Breakdown of the types of climate information engineers typically need for design and planning versus what is scientifically available. Source: Climate Risk Institute*

prediction system of the complete water cycle to be run on an operational basis anywhere" (Durnford et al., 2018).

A main theme of this session was on the topic of rainfall Intensity Duration Frequency (IDF) curves, which are quantitative metrics for extreme precipitation events used in water resources engineering and water management. Under a changing climate, IDF curves based on past rainfall statistics are not accurate for the future, so there is currently high demand from the practitioner community to update IDF curves to account for future precipitation trends. The difficulty, however, is future precipitation trends are quite uncertain, especially at the local scale. There is a vast array of current research working to address this information gap (Wu et al., 2019, Gaur, Schardong, and Simonovic 2020, Butcher et al., 2021, Yan et al., 2021). Requena, Burn, and Coulibaly (2021) provide "practical guidelines and recommendations for helping federal and provincial agencies, as well as others who might produce practice guidelines, to develop standardized procedures for the estimation of future IDF curves in Canada that can then be used by practitioners in infrastructure design, management and risk assessment."

Presentation Summaries

Four presentations were given during the Translating Climate Information session of the 2021 Great Lakes Climate Modeling Workshop. These presentations featured an introduction to translation including GLISA's role as a translator in the region, a presentation on the Climate Explorer — a translational tool — and two presentations featuring climate information needs from an engineering perspective. Next, we provide a brief summary of each of these presentations.

Translating Climate Information

Laura Briley, Great Lakes Integrated Sciences and Assessments

Briley provided an overview of the climate data and information lifecycle consisting of information production, information translation, and information use. A variety of actors work in the translation realm, including climate service providers, climate data visualization and tool providers, and other information facilitators. Briley discussed GLISA's role in the Great Lakes region as a climate information translator and shared about some of their available products. GLISA relies on stakeholder engagement and feedback to co-develop resources that are effective for end users. Interfacing with end users is one of the key considerations in climate translation, along with understanding the level of technical detail that is required for the application and characterizing future uncertainty in a way that is usable.

Climate Explorer: LOCA-Downscaled Data in Support of the Chicago Regional Climate Action Plan

Ned Gardiner, U.S. National Oceanic and Atmospheric Administration

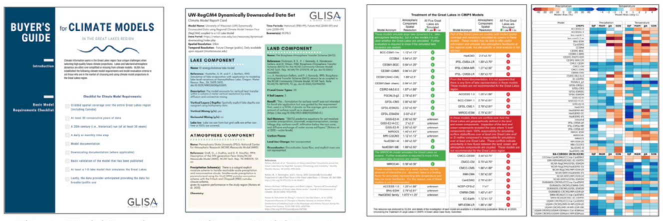
Gardiner highlighted the Climate Explorer tool, a part of the U.S. Climate Resilience Toolkit, with a case study in the Chicago region. This specific case study focused on the intersection between heat and health. The use of climate information in a project such as this involves different kinds of stakeholders and a spatial hierarchy of information (e.g., local, community, state, national, etc.). These interactions are important to understand how information is used and interpreted. The Climate Explorer's main advantage is the ability to provide local climate data to inform decision making.

Building Capacity Through Training: Bridging the Gap from Climate Science to Engineering

Glenn Milner, Climate Risk Institute

Milner discussed the end user perspective of using climate products and climate information in support

Consumer Reports for Climate Information



Climate Model Buyer's Guide

Climate Model Report Cards

Climate Model Evaluation & Comparison

Figure 16. *Example GLISA products in consumer-report style formats.*

of risk assessment, infrastructure decision making, and engineering. These disciplines often have specific needs for climate data but may not be as familiar with the processes for developing that information. Because of this there is a need to translate and communicate climate data to help avoid the confusion that can slow adaptation efforts. Translation of the data, collaboration across disciplines, and guidance about the application of climate data are necessary steps for this communication. Milner also discussed helping practitioners understand exactly what climate information they may need for their application and the fact that they may not need all of the information available. There are basic, intermediate, and advanced products that have varying levels of specificity and uncertainty. Not all products are necessary or useful for all applications. Milner provided examples of organizations that work in the translation of climate information in Canada, including one specific to the engineering field, and an example of a training program for engineers.

From Climate Projections to Engineering Design: The Case of IDF Curves

Ryan Ness, Canadian Institute for Climate Choices

The specific needs of engineers and design practitioners relating to climate information include future projections for IDF curves. Ness discussed the development of these projections and their applications. There is a lot of uncertainty inherent in IDF curves due to the fact that many are calculated using data sets with limited temporal coverage, leading to large confidence intervals. This uncertainty is magnified for future projections. The nonstationarity of rainfall regimes, uncertainties in future emissions, uncertainties in climate modeling, and the many different approaches for estimating future rainfall extremes also augment the difficulty of producing future projections for IDF curves. Ness shared results of the Southern Ontario IDF Comparison Project that concluded the range of future precipitation projections is large and there is no way to produce singular future IDF curves; the selection of values within the projected ranges is not purely an engineering decision, and other stakeholders should be aware of the value selection process.

Facilitated Discussion

Discussion with workshop participants was facilitated in two breakout groups covering the topics of "Translational Tools, Services, and Gaps" and "Future IDF Curves." The specific questions posed in each breakout session and participant responses are below.

Translational Tools, Services, & Gaps

<u>Are there barriers you come across when trying to find and/or use climate information? What are they?</u>

- Access to information in underserved communities is challenging - access to tools, who to talk to, etc. is not necessarily accessible. It is important to remember not all people access information in the same ways.
- Listening is key to effective translation.

<u>How can/do stakeholders obtain and apply the most appropriate projection data?</u>

- Translators should showcase what practitioners can do with the information to help with uptake.
- Translators should be aware some communities may not frame challenges with a climate lens and may instead approach problems from an engineering perspective.
- Translators should help technical city staff/engineers understand what is actionable - how projections can be used.

<u>What partners do you include or would you like to include in your work to improve the translation of climate information?</u>

- Translators should widen their circle of inclusion to bring in new partners intentionally; it's easy to leave people out.

Future IDF Curves

What uncertainties already exist in IDF statistics, and how are they currently managed in practice?

- IDFs are based on station data, which is challenging in areas without a long-term record (e.g., Canada). Some statistics are augmented.
- Some stakeholders use IDF statistics without regarding their confidence intervals, which omits information about the uncertainty.

What are the primary challenges with developing future IDF statistics that incorporate a changing climate?

- Large ensembles, which are in limited supply, are needed to simulate 100 year storms and greater magnitude events.
- The uncertainty with future precipitation projections is large, models do not agree on the sign of change (wetter or drier) at the regional scale, and information about extremes at the local scale is even more uncertain.

How can we shift the focus from precise future IDF statistics in water management design?

- Some practitioners are starting to apply an arbitrary percent increase (20% has been noted) to current IDF statistics for future planning. This approach greatly simplifies the processes of updating IDF statistics and can be easily used by practitioners.

The following discussion questions were posed, but not discussed, due to time constraints:

- What do you like about these tools/services? What could be improved?
- What other existing tools/products does this audience find helpful in their work?
- What existing tools/products would this audience like to know more about?
- What information do you currently lack to make informed decisions in your work?
- What kinds of no-regrets water management strategies are available that address the greatest risks and provide multiple benefits?

New Recommendations for Climate Modelers, Information Users, and Translators

- Collaborations between researchers, translators, and end users should expand their networks to bring in underserved stakeholders to inform adaptation work.

New Recommendations for Climate Users and Translators

- Showcase case studies utilizing climate projection information to help with uptake.
- Advance research on developing future IDF curves with special attention to communicating uncertainties.
- Explore approaches such as arbitrary precipitation increases as an alternative to translating specific climate projections into IDF information.
- Practitioners can help translators develop new mediums for communicating climate information to stakeholders who may not access information using conventional means.

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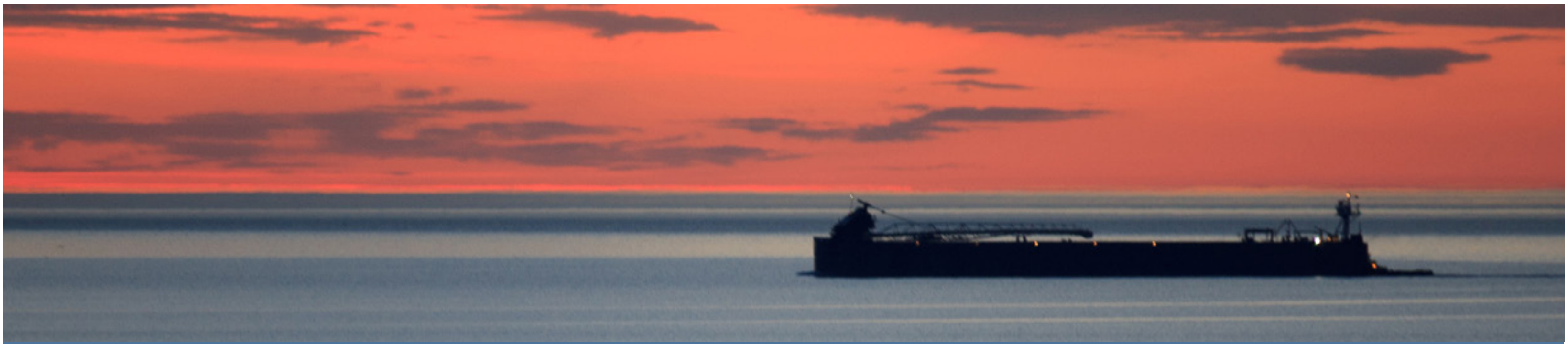
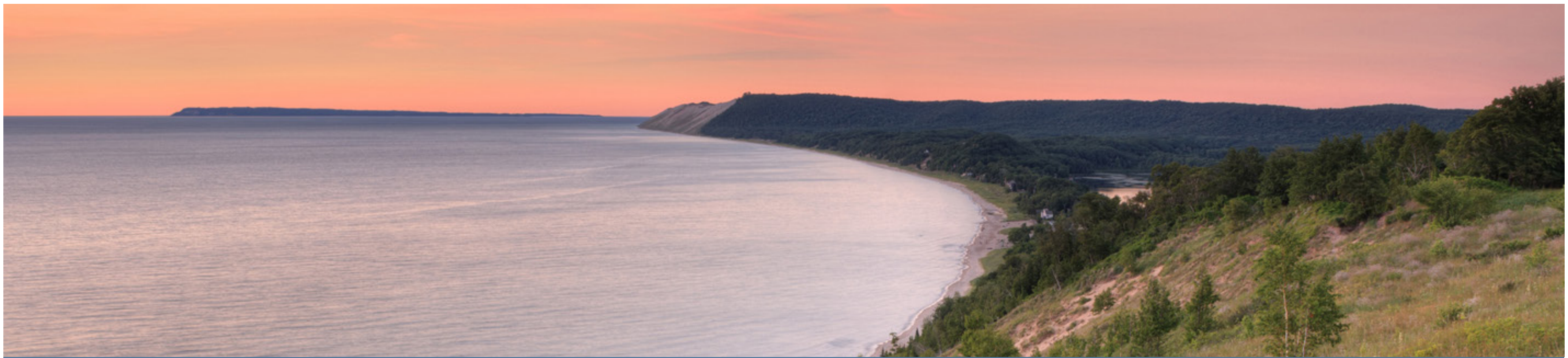


Next Steps

Originally planned as an in-person workshop in Ann Arbor (MI), it was encouraging to have strong attendance start to finish for all four sessions with representation from both the U.S. and Canadian local, state, and federal governments, Tribes and Indigenous communities, universities, non-profits, and businesses. A survey was distributed to all attendees to solicit feedback and while input was still being collected during the writing of this report, initial responses indicate climate modelers found the workshop relevant for their work, in particular learning about recent research not yet published and examples of real-life applications of climate information for decision making. Translators and practitioners enjoyed hearing from and interacting with the modelers directly to better understand current challenges and limitations as well as new projects and tools. A common theme noted across participating modelers, translators, and practitioners was the benefit of an open exchange of dialogue between these groups and a request for more time for interactions and discussion in future workshops.

The June 4, 2021 meeting of the GLWQA Annex 9 on Climate Change Impacts Extended Subcommittee featured a webinar presentation from GLISA summarizing the workshop and a live poll to collect input for a potential, new climate modeling discussion group. Results indicated most respondents would attend a workshop held annually or every other year and also participate in ongoing conversations between workshops (i.e., every 6 months). Research/modeling update presentations were of most interest, followed by facilitated discussions, and then networking. There were about 25 respondents who completed a separate google form indicating their interest in joining, presenting, and/or chairing such a group focusing on the same four themes covered in the 2021 workshop. Given the interest from workshop participants and webinar attendees, Annex 9 is pursuing options to facilitate a more structured series of ongoing modeling conversations between workshops (intended to be held every other year).



Appendix A

Workshop Agenda

The agenda for the 2021 Great Lakes Climate Modeling Workshop is presented below:

MONDAY 3/22 11-1:30 (EST): INTRODUCTION & PHYSICAL CLIMATE MODELING I

*Co-chairs: Biljana Music (Ouranos), Brent Lofgren (NOAA Great Lakes Environmental Research Laboratory)

- 11-12: Welcome & Introductions
  - Workshop Goals & Objectives: Shaffina Kassam (Environment and Climate Change Canada) and Jennifer Day (U.S. National Oceanic and Atmospheric Administration), (Great Lakes Water Quality Agreement Annex 9 (Co-chairs)
  - Attendee Introductions
  - Gaps in Regional Knowledge & Modeling – Review of 2019 Workshop & Report: Frances Delaney (Environment and Climate Change Canada) and Glenn Milner (Climate Risk Institute)
  - Break (10 minutes)
- 12-1:30: Physical Climate Modeling I
  - Session Introduction & Context: Michael Notaro (University of Wisconsin – Madison)
  - Impact of the Atmospheric Moisture Budget on the Seasonality of Great Lakes Precipitation: Samar Minallah (University of Michigan, Climate & Space Science and Engineering)
  - Climate Science for Adaptation and Resilience: Donald Wuebbles (University of Illinois)
  - Question & answer, facilitated discussion

TUESDAY 3/23 11-1 (EST): PHYSICAL CLIMATE MODELING II – BIAS & BIAS CORRECTION

*Co-chairs: Alex Cannon (Environment and Climate Change Canada), Laura Briley (Great Lakes Integrated Sciences and Assessments)

- Framing Bias and Bias Correction of Model Simulations for Climate Adaptation Applications: Ricky Rood (University of Michigan, GLISA)
- Impacts of Climate Model Bias Correction on Hydrologic Simulations: Andre Erler (Aquanty/ University of Toronto)
- Bias Correction Adjustment, Statistical Downscaling And Other Things (That Go Bump In The Night): John Lanzante (NOAA Geophysical Fluid Dynamics Laboratory)
- Break (10 minutes)
- Question & answer, facilitated discussion

WEDNESDAY 3/24 11-1 (EST): LAKE LEVEL IMPACT MODELING

*Co-chairs: Frank Seglenieks (Environment and Climate Change Canada), Drew Gronewold (University of Michigan School for Environment and Sustainability)

- Session Introduction & Context: Frank Seglenieks (Environment and Climate Change Canada) and Drew Gronewold (University of Michigan, SEAS)
- Multivariate Statistical Analysis of Compound Flooding over the Great Lakes Coastal Zones: Characterizing the Joint Behaviour of Coastal Water Levels, Heavy Rainfall and River Flows: Reza Najafi (Western University)
- Global Climate Modeling of Hydroclimate & Projected Precipitation Extremes: Sarah Kapnik (NOAA Geophysical Fluid Dynamics Laboratory)
- Break (10 minutes)
- Question & answer, facilitated discussion

FRIDAY 3/26 11-1 (EST): TRANSLATING CLIMATE INFORMATION

*Co-chairs: Frances Delaney (Environment and Climate Change Canada), Laura Briley (Great Lakes Integrated Sciences and Assessments)

- Session Introduction & Context: GLISA's Climate Translator Role in the Region: Featuring Consumer Reports for Climate Information: Laura Briley (University of Michigan, GLISA)
- Building Capacity Through Training: Bridging the Gap from Climate Science to Engineering: Glenn Milner (Climate Risk Institute)
- From Climate Projections to Engineering Design: The Case of IDF Curves: Ryan Ness (Canadian Institute for Climate Choices)
- The Climate Explorer: serving LOCA downscaled climate projections in support of climate adaptation: Ned Gardiner (NOAA)
- Break (10 minutes)
- Question & answer, facilitated discussion

Appendix B

Workshop Attendees

Name	Affiliation	Stakeholder Group *self-identified
Robert Metcalfe	OMNR	Researcher
Greg Mayne	ECCC - Great Lakes Ecosystem Management	Researcher, Translator
Dae Il Jeong	ECCC	Researcher
Deanna Apps	U.S. Army Corps of Engineers	Translator, End User
John Lanzante	NOAA/GFDL	Researcher
Madeline Magee	Wisconsin Department of Natural Resources	Researcher, Modeler, End User
Alex Cannon	ECCC	Researcher
Liang Chen	University of Illinois Urbana-Champaign	Researcher
Scott Steinschneider	Cornell University	Researcher
John Haugland	USEPA Great Lakes National Program Office	Translator, End User
Michael Notaro	University of Wisconsin-Madison	Researcher, Modeler
John Liu	Ontario Ministry of Environment, Conservation and Parks	Researcher, Translator, Modeler
Kim Channell	Great Lakes Integrated Sciences and Assessments	Translator
Stephanie Swart	Michigan EGLE	End User
Pengfei Xue	Michigan Tech	Researcher, Modeler
Ashish Sharma	University of Illinois Urbana Champaign	Researcher, End User, Modeler
Sharon Lam	Ontario Climate Consortium	Translator
Kristina Dokoska	Ontario Climate Consortium	Translator
Rajesh Shrestha	ECCC	Researcher
Nicole O’Brien	ECCC	Researcher
Jeff Andresen	Michigan State University	Researcher

Eva Gnegy	Great Lakes Integrated Sciences and Assessments	Researcher
Sarah Hutchinson	Great Lakes Integrated Sciences and Assessments	Researcher, Translator
Jennifer Day	NOAA	Translator
Heidi Roop	University of Minnesota	Researcher, Translator
Narayan Shrestha	ECCC	Modeler
Caroline Sevigny	ECCC	Researcher, Modeler
Doug Kluck	NOAA	Translator
Ayumi Fujisaki-Manome	CIGLR, University of Michigan	Researcher, Modeler
Samar Minallh	University of Michigan Ann Arbor	Researcher
Lauren Fry	NOAA GLERL	Researcher
Ana Sirviente	GLOS	Researcher, End User, Modeler
Paul Hirschberg	NOAA	Translator
Shannon DesRochers	Keweenaw Bay Indian Community	End User
Mohammad Reza Najafi	Western University	Researcher
Sean Bath	UCAR/NOAA Climate Programs Office	
Virginia Selz	NOAA Climate Program Office	Researcher
Frank Marsik	University of Michigan	Researcher
William Farmer	USGS Midwest Climate Adaptation Science Center	Researcher, Modeler
Martha Gerig	Michigan Sea Grant	Researcher, Translator, End User
Hannah Panci	Great Lakes Indian Fish and Wildlife Commission	End User
Jennifer Boehme	IJC Windsor Office	Translator
Allison Steiner	University of Michigan	Researcher, Modeler
Rachel Jacobson	ASAP	
Scott Parker	Parks Canada	Researcher, Translator, End User
Frances Delaney	ECCC	Researcher, Translator, End User
Ned Gardiner	NOAA	Translator
Susan Doka	Fisheries and Oceans Canada	Researcher, End User
Nancy Beller-Simms	NOAA/Climate Program Office	Translator
Shadaesha Green	NOAA CPO	Researcher, Translator
John Lenters	Michigan Technological University	Researcher
Veronica Fall	University of Illinois	Researcher, Translator
Andre Guy Temgoua	National Hydrological Services Meteorological Services of Canada	
Wendy Leger	National Hydrological Services Meteorological Services of Canada	
Noura Randle	NOAA/CPO	Translator
Dan Barrie	NOAA	Modeler
Catherine Masson	Trent University	Researcher

Patrick Rivers	ECCC	Translator, End User
Scudder Mackey	Ohio Department of Natural Resources	End User
Dick Peltier	University of Toronto	
Fengy Xie	University of Toronto	
John Scinocca	Canadian Centre for Climate Modelling and Analysis	Modeler
Chris Derksen	ECCC	Researcher
Jenna Sherwin	University of Michigan	Researcher
Barrie Bonsal	ECCC	Researcher
Omar Gates	Great Lakes Integrated Sciences and Assessments	Researcher, Translator
Kenneth Chow	Canadian Centre for Climate Services	
Laura Van Vliet	Canadian Centre for Climate Services	
Trevor Murdock	Canadian Centre for Climate Services	
Carrington Pomeroy	ECCC	
Elaine Barrow	Canadian Centre for Climate Services	
Sarah Rayfield	Canadian Centre for Climate Services	
Jenna Jorns	Great Lakes Sciences and Assessments	Translator
Laura Briley	Great Lakes Integrated Sciences and Assessments	Researcher, Translator
Shaffina Kassam	ECCC	
Frank Seglenieks	ECCC	
Karsten Shein	University of Illinois	
Andrew Gronewold	University of Michigan	
Erin Maher	Great Lakes Integrated Sciences and Assessments	Translator, Researcher
Biljana Music	Ouranos	
Brent Lofgren	NOAA/GLERL	
Glenn Milner	Climate Risk Institute	
Don Wuebbles	University of Illinois	
Ricky Rood	University of Michigan/GLISA	
Andre Erler	Aquanty/University of Toronto	
Sarah Kapnik	Geophysical Fluid Dynamics Laboratory	
Ryan Ness	Canadian Institute for Climate Choices	