2025 Great Lakes Modeling Workshop

Executive Summary

In June 2025, the Great Lakes Water Quality Agreement (GLWQA) Annex 9 Climate Change Impacts co-leads hosted the 2025 Great Lakes Modeling Workshop. This three-day, virtual workshop convened Great Lakes researchers, model users, and academics from 34 unique entities (see Appendix C for attendee list) throughout Canada and the United States to share new research findings, identify challenges and opportunities - including highlighting data resources and tools, and set priorities and goals. The first day focused on Lake Modeling, the second on Climate Projections and Analysis, and the third on next steps for Great Lakes Modeling. The workshop format consisted of both presentations from keynote speakers, covering a wide range of topics within the daily themes, as well as facilitated breakout discussions, engaging all participants to enable connection-building and knowledge exchange. We heard from presenters and participants about finer resolution, downscaled projections for the region currently in development, exploration and application of 3D lake models, and Artificial Intelligence (AI) integration in some hydrological applications. Group breakout discussions also helped identify key priority areas for the community to focus on moving forward to strengthen Great Lakes modeling. These included enhancing binational collaboration to bridge gaps in observations and other data sets; focusing on end-user needs in early development to increase usability of products; creating a centralized space for data sharing; and continued engagement of the Great Lakes modeling community. In-meeting and post-meeting surveys indicated that participants appreciated the opportunity to hear updates, exchange ideas and network with others in the Great Lakes research community. The 2025 Great Lakes Modeling Workshop boasted the highest attendance yet of the three modeling workshops held (in 2021, 2019). Furthermore, the group expressed a clear interest to continue collaboration among researchers and other Great Lakes community members via opportunities such as future workshops as well as the formation of dedicated working groups, building off of workshop breakout session discussions.

Acknowledgements

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- **Alisa Young**, NOAA, U.S. Co-Lead Annex 9 - planning committee, facilitator, host
- **Laura Jones**, Canada Water Agency, Canadian Co-Lead Annex 9 - planning committee, facilitator, host
- **Rachel Kelly**, GLISA - planning committee, facilitator
- **Shreya Mishra**, GLISA - planning committee, facilitator
- **Jenna Jorns**, GLISA - planning committee, facilitator
- **Michael Notaro**, Nelson Institute for Environmental Studies, Center for Climate Research - planning committee
- **Narayan Shrestha**, Environment and Climate Change Canada - planning committee, facilitator
- **Frank Seglenieks**, Environment and Climate Change Canada - planning committee, facilitator
- **Don Wuebbles**, Department of Climate, Meteorology, & Atmospheric Science, University of Illinois Urbana-Champaign - planning committee

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Introduction

The Great Lakes play a key role in our region's weather and climate, culture, economy, natural resources, and history. To protect these vast resources, Canada and the United States (US) entered into the Great Lakes Water Quality Agreement (GLWQA) in 1972 to restore and enhance the water quality of the Great Lakes ecosystem (IJC, 2025). The Agreement was subsequently revised or amended in 1978, 1987, and most recently modernized in 2012. The 2012 GLWQA includes ten Annexes, each focusing on a different aspect of the Great Lakes protection and restoration. The purpose of the GLWQA Annex 9 Climate Change Impacts is "coordinating efforts to identify, quantify, understand, and predict the climate change impacts on the quality of the Waters of the Great Lakes, and sharing information that Great Lakes resource managers need to proactively address these impacts". The 2025 Great Lakes Modeling Workshop is a compelling example of how Canada and the US are successfully continuing their work together in meeting binational commitments of the GLWQA and what they are achieving collectively towards the purpose of Annex 9.

2025 Great Lakes Modeling Workshop

The 2025 Great Lakes Modeling Workshop was preceded by two earlier workshops which helped to set the stage for the 2025 meeting (see Appendix B for more details on the 2019 and 2021 sessions).

The 2025 Workshop aligns with Annex 9 key commitments. These include developing and improving regional-scale climate models and linking them to Great Lakes chemical, physical and biological models, in order to better understand and predict the impacts of climate change on Great Lakes water quality; and coordinating binational climate change science activities (including monitoring, modeling and analysis) to quantify, understand and share information that Great Lakes resource managers need to proactively address climate change impacts.

Participation was binational with registrants from Canada and the United States and over 35 different organizations represented, including various universities, local and federal government agencies, and research laboratories. Expertise of attendees covered regional climate modeling, water resources engineering, ecosystem modeling, and more.

The workshop focused on:

- Identifying gaps/needs, understanding existing challenges, and learning about emerging science/capabilities.
- Maturing products and workflows to better support decision making using modeling outcomes/frameworks.
- Enhancing Great Lakes regional modeling coordination and collaboration.
- Promoting data sharing and interoperability.
- Advancing community capacity and knowledge transfer.

Planning and Design

Annex 9 Co-Leads convened a binational planning committee to assist in the workshop design (committee members are listed in the "Acknowledgements" section above). The committee worked collaboratively to establish workshop themes, identify keynote speakers, select meeting format, and compile an invitation list.

Three thematic areas were selected by the planning committee from a list of priority topics identified by previous workshop attendees via a survey sent out early in the planning stages. The meeting format was virtual (Zoom platform) to account for travel restrictions and facilitate broader participation.

The workshop spanned 3 days (June 16, 18, and 23) with one three-hour session per day/theme. Each session included a brief introduction from a member of the planning committee to set the stage, and provide context from previous workshops/sessions. Keynote presentations followed and included brief Question and Answer periods. Each day concluded with facilitated breakout sessions to allow participants a chance to dive deeper into the theme of the day. Participants were divided into three breakout rooms, where facilitators guided conversations using key questions. A moderator and notetaker were assigned to each breakout session. Session recaps follow in the Results section and the full agenda can be found in Appendix A.

Surveys

Two surveys were distributed to participants to collect feedback. The first consisted of an in-meeting subject matter expert (SME) survey which was introduced during the third day of the workshop. The SME survey was intended to complement the breakout sessions by collecting key information regarding priority areas for Great Lakes modeling, and identifying resource gaps and future focus opportunities. (see Appendix D for Survey Results). The second survey was a post-workshop survey intended to collect feedback to assist the planning team in developing future workshops.

Results

The workshop spanned three days, with each day devoted to a key thematic area. The daily agenda consisted of a series of keynote presentations followed by a Q&A session, and concluding with focused small-group breakout discussions. The breakout discussions were facilitated by Anex 9 co-chairs Dr. Alisa Young (NOAA) and Laura Jones (CWA), and planning committee member Dr. Frank Seglenieks (ECCC).

Workshop Session 1: Lake Modeling

Monday, June 16, 2025: 1:00 - 4:00 PM EST

The first session was focused on Lakes Modeling. Presentations scaled a wide range of lake-related topics, including lake ice, lake eutrophication, lake representation within climate models, and more to allow every audience member to engage.

Convergent Applications in Lake Modeling Across Spatial and Temporal Scales

Dr. Andrew Gronewold, University of Michigan

Dr. Andrew Gronewold presented a synthesis of evolving lake modeling efforts in the Great Lakes region, emphasizing the **need for convergent frameworks that bridge hydrological, hydrodynamic, and climate applications across spatial and temporal scales**. He highlighted how integrated modeling approaches, such as coupling lake models with land surface and atmospheric models, have enabled advancements in quantifying lake heat fluxes and evaporation. These improvements support the extension of records for heat wave analysis and lake thermal dynamics over time. Gronewold stressed that machine learning and AI could play a pivotal role in improving long-term lake forecasting and uncertainty quantification. He cautioned that failure to adopt emerging technologies could leave Great Lakes research behind broader global modeling efforts.

Ongoing applications include hydrodynamic simulations using the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) model to improve bathymetric and pollutant transport representation, particularly in the context of Harmful Algal Blooms.

Gronewold also underscored that while significant progress has been made in lake level forecasting, challenges remain in extending predictability across decadal timeframes and incorporating uncertainties.

Climate Impacts on Eutrophication in the Great Lakes

Dr. Philippe Van Cappellen, University of Waterloo

Dr. Philippe Van Cappellen presented research on phosphorus dynamics and re-eutrophication processes in Lake Erie, highlighting the role of climate change and coastal erosion in altering nutrient loading and hypoxia development. Despite reduced watershed phosphorus inputs since the 1970s, symptoms of eutrophication persist, suggesting missing sources in the phosphorus budget. The study identified **intensified coastal erosion as a key contributor, driven by shorter ice cover duration and stronger spring storms**. Weakening nearshore-offshore water exchanges and altered wind regimes further exacerbate bottom water hypoxia.

Dr. Van Cappellen emphasized the **need for integrated climate and water quality modeling to produce management-relevant indicators** such as phosphorus load-response curves and hypoxic factors. He called for enhanced coordination in the modeling community, starting with co-defined spatial and temporal scales and data acquisition strategies, such as improved coastal erosion monitoring and sediment transport observations.

Impacts of Lake Ice on Great Lakes Regional Modeling

Dr. Jiali Wang, Argonne National Laboratory

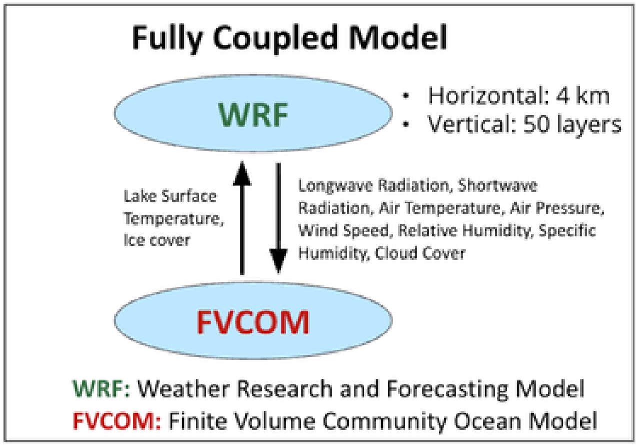
Dr. Jiali Wang and team examined how excessive winter–spring lake-ice fractions in the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis Version Five (ERA5) during 2008-2014 propagate through convection-permitting WRF downscaling over the Great Lakes. Biased ice suppresses turbulent fluxes, producing cold, dry near-surface conditions, weaker 10-m winds, and substantially reduced lake-effect precipitation in canonical snowbelts. Sensitivity **experiments replacing lake surface fields and/or using a fully coupled atmosphere–3D lake model markedly improve over-lake turbulent fluxes, 2-m temperatures, winds, and precipitation structure**. Results highlight surface boundary realism—particularly lake-atmosphere interaction—as a first-order control on winter regional climate simulations for large-lake basins.

Biases and Uncertainties of Modeled Lake Temperatures

Dr. William Pringle, Argonne National Laboratory

Dr. William Pringle discussed a framework for evaluating uncertainty in regional climate models of the Great Lakes region, with a focus on surface temperature simulations. Using a coupled lake-atmosphere model and surrogate modeling techniques, he found that atmospheric physics, particularly radiation parameterizations, are the dominant source of uncertainty. The model exhibited significant biases in Lake Superior's spring warming, which Pringle attributed to misrepresented ice fractions and a lack of thermobaric convection, critical in deep, cold lakes.

Uncertainty in model outputs correlated with lake size, depth, and latitude, with northern deep lakes such as Superior showing the highest variability. Pringle's analysis revealed that nearly half of the surface temperature uncertainty originated from atmospheric parameterizations, with an additional 15% due to interactions with lake and land physics. He **emphasized the need for improved representation of freshwater stratification processes to enhance model reliability**, especially during the spring warming period.



Conceptual diagram of a fully coupled model system. Adapted from Dr. Pringle's June 2025 workshop presentation.

Canada1Water: Application Towards Climate Change Impact Analysis in the Great Lakes Basin

Dr. Steven Frey, University of Waterloo

Dr. Steven Frey presented on Canada One Water (C1W), a fully coupled surface and groundwater modeling initiative applied to the Great Lakes Basin. The C1W model integrates surface hydrology with subsurface flow and is designed to assess seasonal and long-term climate impacts. Research findings show that groundwater contributes 0.5–3% of the positive basin supply depending on lake and season, and can comprise up to 50%, or more, depending on season, of river flow in some tributaries.

Dr. Frey described the **extensive data harmonization required across transboundary watersheds**, covering over 1.9 million square kilometers, including parts of Alaska. The team uses the Weather Research and Forecasting (WRF)-FLake coupled system to generate hydrologic forcing data for climate change simulations. To validate their models, they have also incorporated Gravity Recovery and Climate Experiment (GRACE) satellite gravity data, detecting strong correlations between terrestrial water storage anomalies and model outputs. Frey highlighted that open-access datasets and model outputs are a core objective of the C1W initiative to support basin-wide resource management.

Session 1 | Breakout Discussions Summary

The breakout discussions were guided by the following questions:

1. What model dimensionality (i.e. 1D, 2D, 3D) is required of lake models to adequately represent lake-atmosphere interactions within coupled regional climate models (RCMs) and what are the computational trade-offs associated with each type?
2. What metrics should be prioritized for evaluating lake model performance in the Great Lakes, including variables such as ice cover, evaporation, surface water temperature, etc.?
3. Are there detectable long-term trends in Great Lakes water balance components (precipitation, runoff, and evaporation) that may signal future changes in mean lake levels and variability?
4. What insights have emerged from previous comparisons of different lake models and which ones are best to apply in the Great Lakes?

Major Takeaways

During the breakout discussions, common themes that emerged are:

- 1D lake models are adequate for large-scale climate applications, but 3D models provide essential process-level improvements for detailed, lake-specific applications.
- Lake evaporation, surface temperature, and ice cover are core metrics for model evaluation, but validation remains limited by data availability.
- Model choice and configuration must align with both goals and resource constraints, and comparison studies are critical for progress. Co-creation among multiple groups can aid in meeting goals, sharing cost, and expanding the use of the product.

Key Recommendations

In breakout discussions many participants noted the importance of:

- Focusing on integration of specialized modeling (i.e., water quality, air quality, etc.) into climate modeling to produce management-relevant indicators for decision makers.
- Incorporating experts from varying fields into early project design to increase collaboration and convergence across modeling efforts.
- Increasing collaboration between modeling teams across varying sectors, especially when setting up experiments.

Workshop Session 2: Climate Projections and Analysis

Wednesday, June 18, 2025: 1:00 - 4:00 PM EST

The second session theme was Climate Projections and Analysis. Day two provided a space for modelers to share current simulations they are working on, highlight available data, discuss modeling challenges specific to the Great Lakes region, and introduce how new technologies can be utilized.

The Impacts of Climate Change on Lake Ice

Dr. Sapna Sharma, York University

Dr. Sapna Sharma presented findings on the influence of climate change on lake ice cover over time, by contextualizing global ice records through the story of Lake Suwa in Japan, which has one of the longest ice records globally. Sharma also discussed the cultural importance of ice records for northern communities around the world, and referenced the Shinto Omiwatari ceremony on Lake Suwa, which tracked ice formation dates since the 1400s. Historically, the lake remained unfrozen only three times in the first 250 years of records. However, from 1700 to 1999, the lake did not freeze one out of every five years, and since 1988, it fails to freeze eight out of every ten years. Sharma also shared projections for lake ice cover across the Northern Hemisphere, **indicating that many lakes are expected to experience intermittent or complete loss of ice by the end of the century**, depending on greenhouse gas emission scenarios. Notably, Lake Superior may lose ice cover entirely by 2060 or 2080, depending on mitigation efforts.

Dr. Sharma emphasized the need for long-term in situ observations of ice phenology and quality, as well as research into the broader implications of changing winters on ecosystems and the services they provide.

On the Need for Physical Constraints in Deep Learning Rainfall-Runoff Projections Under Climate Change

Dr. Scott Steinschneider, Cornell University

Dr. Scott Steinschneider presented research evaluating deep learning (DL) models for hydrologic projections under climate change, comparing them to traditional process-based models. While DL models outperform process-based models for historical data, they can produce unreliable future projections when unconstrained. He tested various DL architectures, including those incorporating physical constraints such as mass conservation and energy-budget based potential evapotranspiration (PET). Models without constraints tended to overestimate streamflow declines under warming. However, models that included both mass conservation and PET constraints yielded projections comparable to process-based hydrologic models with the same forcings. Steinschneider concluded that **adding physical constraints to DL models is necessary to ensure credible future hydrologic projections**, particularly in the context of climate change-induced evapotranspiration shifts, which are driven more by energy budgets than by temperature increases.

The Canadian Regional Climate Model: New Version and Simulations

Dr. Alejandro Di Luca, ESCER Centre

Dr. Alejandro Di Luca presented recent developments of version 6 of the Canadian Regional Climate Model - Global Environmental Multiscale 5 (CRCM6-GEM5), highlighting its enhanced performance and configuration. The CRCM6-GEM5 is being developed collaboratively by the ESCER Centre, Ouranos Consortium, and Environment and Climate Change Canada (ECCC). Its atmospheric core is based on the GEM5 model, which is also used operationally by the Canadian Meteorological Centre for weather prediction. The model includes the Canadian Land Surface Scheme (CLASS) and the FLake one-dimensional lake model. Major improvements have been implemented relative to the previous CRCM5 version, including updates to the microphysics, vertical discretization, and physical parameterizations. CRCM6-GEM5 currently operates at two horizontal resolutions: a 12-km version over the North American domain and a 2.5-km convection-permitting configuration (roughly 125 times more computationally demanding) focused on northeastern North America, fully encompassing the Great Lakes region.

Dr. Di Luca presented **evidence of significant improvement in CRCM6-GEM5 compared to CRCM5, particularly in reproducing the seasonal cycle of precipitation over the Great Lakes**. Moreover, the 2.5-km version provides a more realistic representation of hourly extreme precipitation events, although it tends to slightly overestimate the highest intensities relative to radar-based observations. This high-resolution configuration is particularly suited for studying mesoscale convective systems (MCSs) and extratropical cyclones (ETCs).

Ongoing efforts aim to further improve several model components, including the surface and lake schemes, and to perform detailed evaluations of the model's ability to reproduce key fields (precipitation, wind) associated with storms over northeastern North America. Additional analyses will also assess the model's performance in simulating lake-effect snow events. To drive the CRCM6-GEM5 simulations of future projections, the team has selected global climate models (GCMs) that realistically represent the North American storm climatology. The 2.5-km CRCM6-GEM5 configuration is expected to provide substantial added value for future regional climate assessments and impact studies.

Advancing a Tool for Regional Climate Modeling in the Great Lakes Basin

Dr. Michael Notaro, University of Wisconsin–Madison

Dr. Michael Notaro introduced a next-generation climate modeling tool combining National Aeronautics and Space Administration's (NASA's) Unified Weather Research and Forecasting (NU-WRF) model with a 3D lake model (FVCOM) to enhance simulations over the Great Lakes region. This tool improves representation of lake surface temperature, ice cover, and surface-atmosphere interactions compared to earlier 1D lake models. The **coupled model improves simulations of air temperature, wind speed, and latent/sensible heat fluxes over lakes**. Mid-century projections indicate regional warming across all seasons, with the greatest warming during winter. Snowfall is projected to decline throughout the region, and lake ice cover is expected to become limited to nearshore areas. Lake Superior is projected to warm the most in summer.

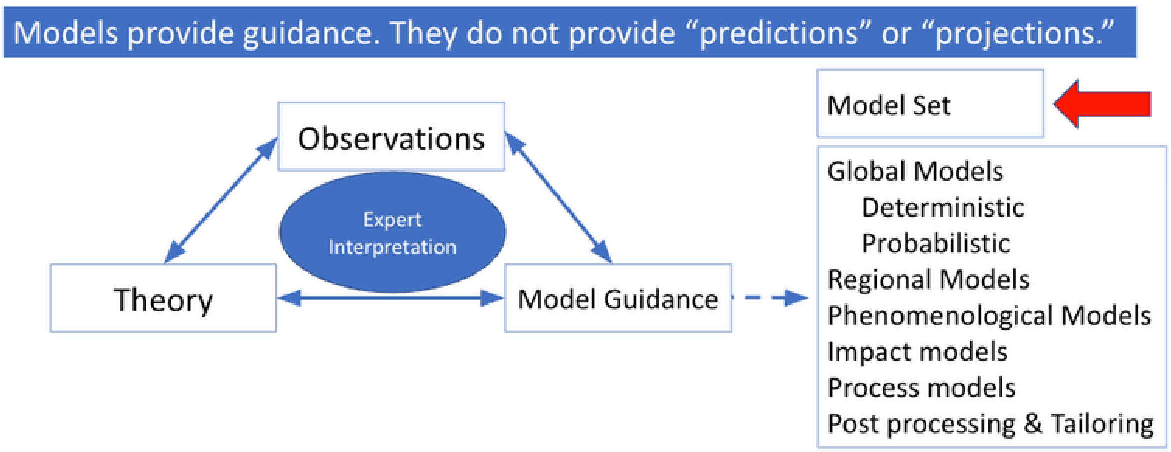
Future work includes expanding the NU-WRF/FVCOM dataset, **evaluating flood risk for coastal communities, and assessing the model's ability to simulate heavy precipitation events**. Notaro detailed the process of GCM selection, focusing on model resolution, compatibility with NU-WRF, and performance in regional climatology. He acknowledged the computational challenges of running high-resolution (3 km) simulations, which currently require the use of 10-year time slices.

Modeling for Great Lakes Climate Adaptation: Elements for a Strategic Approach

Dr. Richard Rood, University of Michigan

Dr. Richard Rood presented a strategic framework for climate modeling in support of adaptation planning in the Great Lakes region. He emphasized that current modeling practices are often fragmented, overly complex, and poorly suited for informing local decision-making. He called for a shift in strategy that focuses on a smaller, purpose-built model set that serves both research and operational needs.

He outlined key challenges, including cost, time, complexity, and the difficulty of evaluating whether models are "fit for purpose." Structural issues, such as poor representation of lakes, orography, and storm systems, further limit model usefulness. Dr. Rood suggested that rather than pushing for ever-larger and more complex models, **efforts should center on using human insight to scale models meaningfully and pragmatically**. He concluded that it is ethically and scientifically sound to build models specifically for adaptation applications, and that success will require convergence across modeling efforts, early design for collaboration, and careful alignment with real-world problems. Geoengineering, adaptation, and tipping point research cannot wait for all-encompassing models, and more effort should be placed on applying existing knowledge effectively.



Model guidance graphic taken from Dr. Rood's June 2025 workshop presentation.

Session 2 | Breakout Discussions Summary

The breakout discussions were guided by the following questions:

1. What is the biggest challenge facing Great Lakes Regional Climate Modeling today and what solutions could be proposed to address them?
2. What can climate models tell us about variability versus long-term climate change?
3. 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?
4. What areas of physical climate modeling need improvement?
5. Which impact sectors would benefit most from analyzing secular change vs. variability?

Major Takeaways

During the breakout discussions, common themes that emerged are:

- Multiple downscaling efforts are underway for the Great Lakes region which show great progress from the 2021 workshop. The different simulations include a 3D lake model (Notaro), convective-permitting parameterization (Di Luca), and deep learning physical constraints (Steinschneider).
- Proper representation of evaporation and non-stationarity, as well as various data gaps are the most pressing modeling challenges for the Great Lakes region.
- A shift from making models more complex to more “fit for purpose” may be needed when facing computational cost limitations, meaning the model is complex enough for its intended use case, but not so complex that it is inefficient or too difficult to use.
- Success depends on cross-border collaboration, better observational networks, and making model outputs actionable for communities and sectors.
- Addressing both long-term secular trends and short-term variability is essential for planning, from infrastructure and agriculture to ecosystems and recreation.

Key Recommendations

In breakout discussions many participants noted the importance of:

- Developing a shared, binational data repository allowing for easier access to available products. Data sharing can help fill in gaps, reduce duplicative efforts, and allow different modeling teams to collaborate easier.
- Exploring machine learning and AI applications to improve forecast skill, improve resolution, detect trends, and reduce parameterization uncertainty.
- Refining stakeholder engagement by demonstrating practical use cases and offering outputs tailored to local sectors.
- Utilizing higher resolution models to evaluate parameterization to improve model performance.

Workshop Session 3: Next Steps for Great Lakes Modeling

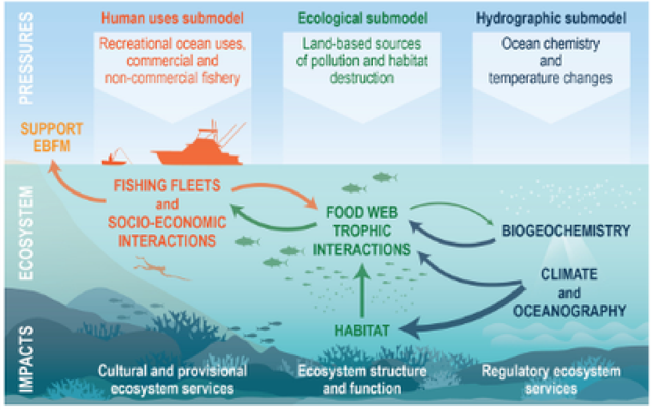
Monday, June 23, 2025: 1:00 - 4:00 PM EST

The final workshop session was intended to facilitate open discussion and collaboration between participants to collectively map out the challenges faced by the Great Lakes modeling community and determine how to prioritize efforts to address these moving forward. The session started with presentations showcasing current collaborative efforts within the region (see below). These were followed by breakout sessions tailored to various participant interests and experiences: Data Management and Sharing, Downstream Model Applications, Tools/Products for End Users.

NOAA Changing Ecosystems & Fisheries Initiative

Dr. Peter Alsip and Dr. Joe Langan, NOAA GLERL

Dr. Peter Alsip presented on the NOAA Changing Ecosystems and Fisheries Initiative (CEFI), which aims to incorporate climate data into fisheries management in the Great Lakes region. Unlike NOAA's direct management role in coastal fisheries, Great Lakes fisheries are managed by state and tribal agencies, necessitating strong collaboration with partners including universities and nonprofits. CEFI consists of three key components: regional ocean modeling, a data portal, and decision-support teams. Dr. Alsip highlighted the implementation of the Modular Ocean Model version 6 (MOM6) for the Great Lakes, with initial modeling results focused on Lakes Michigan and Huron. The program supports data sharing and fosters collaborative research across institutions.



Atlantis ecosystem model graphic taken from Dr. Alsip's June 2025 workshop presentation.

Key challenges include technical barriers such as inconsistent data formats and limited access, fragmented communication among scientific and management communities, and difficulties aligning climate projections with the shorter timeframes used in fisheries management. Other compounding issues include competing management priorities such as invasive species control.

The Atlantis ecosystem model was also introduced as a tool for simulating environmental and biological interactions under various climate and management scenarios. A Lake Michigan model has been developed to investigate warming and mussel dynamics, while a Lake Superior version is currently in early development, in partnership with the Lake Superior Technical Committee. CEFI represents an effort to operationalize NOAA climate model data in fisheries decision-making. However, Dr. Alsip emphasized that barriers persist, including the need for region-specific tools and integrated, long-term planning frameworks that reflect the complexity of climate impacts on aquatic systems.

Development of Extreme Precipitation Data Resources for the Great Lakes Region

Dr. Jeff Andresen, Michigan State University

Dr. Jeff Andresen presented on the upcoming NOAA Atlas 15, an updated resource intended to provide high-quality precipitation frequency data for infrastructure design and climate resilience planning. He noted that extreme precipitation events, particularly those in the top 1st percentile, are increasing in both frequency and intensity across the Great Lakes region, with Michigan already experiencing a 15% increase in precipitation magnitude. These trends highlight the need for updated tools that account for non-stationarity in historical precipitation data and incorporate future climate projections.

Atlas 15 is designed to **support resilient, cost-effective infrastructure investments by offering consistent, science-based estimates for historical and projected precipitation**. Accurate estimates are especially important for stormwater drainage systems, floodplain planning, and climate-resilient transportation infrastructure. Atlas 15 is positioned to become a trusted national standard for infrastructure design and planning under changing climate conditions, empowering local governments and engineers to make data-driven decisions in the face of increasing hydrologic extremes.

Session 3 | Breakout Discussions Summary

For Session 3 discussions, breakout sessions were divided into subgroups based on the following themes:

1. Data Management and Sharing;
2. Downstream Model Applications;
3. Tools/Products for End Users.

Each group was given a series of accountability questions as well as theme-specific questions/activities to guide conversation.

Accountability Questions (all groups)

- What actions do we want to take to continue to build a greater capacity for a climate informed GL Modeling Framework?
- Who is willing to reconvene?
- How frequently can we meet?
- What resources can we provide?
- List of data sharing platforms that can be updated by the group semi-annually?
- Survey to participants of where they get their information/what information they maintain?
- What is a low-hanging fruit priority this group could tackle first?
- Time permitting: What are basic steps that need to be taken to accomplish it? Who might be interested in what?

Data Management and Sharing

1. *Can we develop a centralized list of models, configuration details, repository info etc. to help promote research collaboration and data sharing?*
2. *How are teams managing data access and storage? With long-term 3D simulations at hi-resolutions, there will be large volumes of data. Is any of the hi-res data downscaled during post processing?*
3. *What are the minimum computational requirements needed for running high-resolution ~5km vs 10km simulations?*
4. *Have any of the teams been able to run their models in the cloud processing via AWS or Microsoft Azure and if yes, has cloud computing been easier to manage compared to on-prem processing?*

Tools/Products for End Users

1. *What tools/products are your groups using most frequently?*
2. *What areas are well covered and what areas are lacking in tool/product availability for users?*
3. *How can we better share tools/products across the community?*
4. *Are developers pushing their data into any tools that are utilized by resource managers or the public in general?*

Downstream Model Applications

1. *Do we understand the outputs and timescales needed for supporting downstream ecosystem models? For example, what variables and timescales are needed for fish species distribution models vs. nutrient modeling?*
2. *Linking/Coupling with other downstream models will help to address the following;*
   a. *How will climate-driven changes influence species distributions, phenology and food web dynamics?*
   b. *What are the ecosystem service impacts of climate change particularly for fisheries, water quality, shipping economics, and recreation?*
   c. *How will changing precipitation patterns and runoff affect nutrient loading, algal blooms and hypoxia?*
   d. *How does climate change interact with invasive species dynamics and native biodiversity loss?*
3. *Can hydrodynamic models do it all (can one model accurately simulate ALL variables of concern for Climate Change Annex 9 - ice cover, HABS and coastal erosion)? Or, is convergence needed between different models built at different temporal and spatial scales?*

Major Takeaways

During the breakout discussions, common themes that emerged are:

- Most participants were eager to continue engagement with the goal of advancing Great Lakes modeling through either smaller working groups, more periodic workshops, or webinar-style update meetings.
- Leveraging existing datasets, cloud computing, and collaborative infrastructure is key to scaling up both science and impact.
- Great Lakes climate modeling is advancing, but must become more coordinated, user-centric, and accessible.
- High-resolution, 2-way coupled lake-atmosphere models are needed, but their utility depends on data access, post-processing tools, and communication with end-users.

Key Recommendations

In breakout discussions many participants noted the importance of:

- Developing a central registry of models, shared data repositories, and subsetting tools to increase open access.
- Utilizing coordination measures (Annex 9, conferences, newsletters, etc.) to continue regular engagement of the Great Lakes modeling community.

Conclusion

The 2025 Climate Modeling Workshop successfully achieved its objectives (See Planning and Design). After a four-year hiatus, the workshop was well received by the binational Great Lakes modeling community, with the highest registration recorded to date, and attendance by government employees, academics, and researchers from Canada and the US.

The mixed format design of the workshop with keynote presentations and facilitated breakout discussion sessions, along with the selective focus on the topics of lake modeling, climate projections and analysis and next steps for Great Lakes Modeling, enabled knowledge exchange and feedback in these key thematic areas. Participants shared a range of rich information regarding common gaps, and existing challenges as well highlighting current research, and emerging science and opportunities (See Results for key takeaways).

Insights and recommendations included the following key points:

- *Great Lakes modeling is advancing, but must become more strategic, end user-focused, and accessible to continue progressing in stride.*
- *Creating a centralized repository for the Great Lakes modeling community to share data and tools would promote further collaboration and reduce duplicative efforts.*
- *Further exploration into machine learning and AI applications in modeling could help improve model simulations.*

Collectively, the insights gained at the Great Lakes Modeling Workshop will help to inform priority areas of research and strategically direct binational resources moving forward.

The workshop's more dynamic format, with focused, thematic breakout discussions also enabled connection-building and enhanced collaborative capacity. Multiple graduate students from across the region were able to join given the free and virtual format, allowing new researchers to join the conversation, including researchers in the public policy space. Leveraging the progress made at the workshop, the participants expressed a strong interest in forming thematic Working Groups to further the connections that were made at the meeting, build off the knowledge gained, and, potentially, explore opportunities for collaboration.

Revisiting the workshop objectives presented above after the workshop, we can identify progress and opportunities highlighted during the sessions:

- I**dentifying gaps/needs, understanding existing challenges, and learning about emerging science/capabilities.**
  - Both keynote speakers and breakout sessions identified gaps/needs, existing challenges and possible solutions, and showcased new science and capabilities.
- **Maturing products and workflows to better support decision making using modeling outcomes/frameworks.**
  - The need to incorporate end-user input to increase the value of tools and products for decision makers was a recurrent theme throughout the three day session. This helped to identify a focus area for our group to continue to improve upon.

- **Enhancing Great Lakes regional modeling coordination and collaboration.**
  - Holding the workshop in and of itself provided an important opportunity for Great Lakes modeling research coordination and collaboration, but the need to have more consistent opportunities to connect was noted throughout the workshop. Continuing to host the Great Lakes Modeling workshop, sharing other networking opportunities hosted by related organizations, and encouraging/supporting smaller focused working groups are all ways to achieve this objective.
- **Promoting data sharing and interoperability.**
  - Creation of a centralized data and tool repository for the Great Lakes modeling community to share resources and build off of one another's work emerged as a strong recommendation, raised consistently by multiple participants across the three sessions.
- **Advancing community capacity and knowledge transfer.**
  - Continuing engagement opportunities as discussed in objective 3 as well as the creation of a centralized repository (objective 4) will also support this objective.

Future Opportunities

A follow-up survey was sent to all attendees to collect feedback regarding the workshop. The survey respondents unanimously expressed that they were interested in further engaging with the Great Lakes modeling community. All survey respondents also confirmed they were likely to recommend the workshop to their colleagues. Survey respondents also indicated that the breakout room discussions were very valuable. However, respondents also noted that for future sessions, an in-person workshop would be preferable to a virtual setting, if feasible, to ensure networking is even more accessible.

Based on feedback, it is recommended that the workshop series continue with the next sessions building off of the group's strong momentum. In the meantime, smaller thematic working groups developed during the Session 3 breakout discussions could have the chance to convene to continue their conversations and work collectively to achieve some of the goals identified.

Acknowledgements

Finally, the 2025 Great Lakes Modeling Workshop team would like to again extend our deepest gratitude to all of our presenters, organizers, facilitators, and attendees for making this workshop a success!

Appendix A: Workshop Agenda

The agenda for the 2025 Great Lakes Climate Modeling Workshop is presented below:

MONDAY 6/16 1-4:00 (EST): LAKE MODELING

- 1:00 - 1:30 pm: Welcome & Introductions
  - Workshop Goals & Objectives: Alisa Young (NOAA) and Laura Jones (CWA)
- 1:30 - 2:30 pm: Presentations with built in Q&A
  - Session Introduction & Context: Rachel Kelly (GLISA) and Frank Seglenieks (ECCC)
  - Convergent Applications in Lake Modeling Across Spatial and Temporal Scales: Andrew Gronewold (University of Michigan)
  - Climate Impacts on Eutrophication in the Great Lakes: Philippe Van Cappellen (University of Waterloo)
  - Impacts of Lake Ice on Great Lakes Regional Modeling: Jiali Wang (Argonne National Laboratory)
- 2:30 - 2:45 pm: Break (15 minutes)
- 2:45 – 3:25 pm: Presentations with built in Q&A
  - Biases and Uncertainties of Modeled Lake Temperatures: William Pringle (Argonne National laboratory)
  - Canada1Water: Application Towards Climate Change Impact Analysis in the Great Lakes Basin: Steven Frey (University of Waterloo)
- 3:25 – 4:00 pm: Breakout Rooms and Discussion
  - Leaders: Alisa Young (NOAA), Laura Jones (CWA), and Frank Seglenieks (ECCC)

WEDNESDAY 6/18 1-4PM (EST): CLIMATE PROJECTIONS AND ANALYSIS

- 1:00 - 1:10 pm: Welcome, Recap, and Introductions:
  - Workshop Goals & Objectives: Rachel Kelly (GLISA) and Alisa Young (NOAA)
- 1:10 - 2:15 pm: Presentations with built in Q&A
  - The Impacts of Climate Change on Lake Ice: Sapna Sharma (York University)
  - On the Need for Physical Constraints in Deep Learning Rainfall-Runoff Projections Under Climate Change: Scott Steinschneider (Cornell University)
  - The Canadian Regional Climate Model: New Version and Simulations: Alejandro Di Luca (ESCER Centre)
- 2:15 - 2:30 pm: Break (15 minutes)
- 2:30 – 3:20 pm: Presentations with built in Q&A
  - Advancing a Tool for Regional Climate Modeling in the Great Lakes Basin: Michael Notaro (University of Wisconsin-Madison)
  - Modeling for Great Lakes Climate Adaptation: Elements for a Strategic Approach: Richard Rood (University of Michigan)
- 3:25 - 4:00 pm: Breakout Rooms and Discussion
  - Leaders: Alisa Young (NOAA), Laura Jones (CWA), and Frank Seglenieks (ECCC)

MONDAY 6/23 1-4PM (EST): NEXT STEPS FOR GREAT LAKES MODELING

- 1:00 - 1:20 pm: Session Introduction & Recap
  - Welcome, Recap, Goals for the Day: Laura Jones (CWA)
- 1:20 - 2:00 pm: Presentations with built in Q&A
  - NOAA Changing Ecosystems & Fisheries Initiative: Peter Alsip and Joe Langan (NOAA GLERL)
  - Development of Extreme Precipitation Data Resources for the Great Lakes Region: Jeff Andresen (Michigan State University)
- 2:00 - 2:20 pm: Break (10 minutes)
- 2:10 - 4:00 pm: Theme Breakout Group Discussion and Brainstorming Next Steps
  - Theme 1: Downstream Model Applications: Facilitated by Alisa Young (NOAA)
  - Theme 2: Tools/Products for End Users: Facilitated by Laura Jones (CWA)
  - Theme 3: Data Management and Sharing: Facilitated by Frank Seglenieks (ECCC)

Appendix B: Past Workshops

2021 Great Lakes Modeling Workshop

The Great Lakes Water Quality Agreement (GLWQA) Annex 9 Climate Change Impacts with support from the U.S. National Oceanic and Atmospheric Administration (NOAA) Great Lakes Regional Collaboration Team, and Environment and Climate Change Canada worked alongside GLISA to co-host the second iteration of the Great Lakes Modeling Workshop in 2021. This workshop was held virtually through a Zoom video conference. Working off the progress made during the 2019 workshop, the second workshop set priorities 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 (Briley & Jorns, 2021). A workshop report was prepared summarizing the four different sessions, the state of Great Lakes modeling, and updates to the 2019 recommendations. New recommendations were also developed during the 2021 workshop to further advance modeling in the Great Lakes region.

Link to 2021 Report

2019 Great Lakes Modeling Workshop

The first workshop was held in 2019 in Ann Arbor, Michigan and co-hosted by the Ontario Climate Consortium (OCC) and GLISA. This binational meeting was one of the first orchestrated efforts to bring together climate modelers from Canada and the United States. Participants reviewed existing Great Lakes regional climate modeling efforts, shared preliminary results from relevant research, identified current gaps and uncertainties, and developed recommendations to steer future work. OCC produced a summary report for the 2019 workshop (Delaney & Milner, 2019). It includes an overview of the state of Great Lakes modeling, current modeling methodologies, and the recommendations developed during the workshop process.

Link to 2019 Report

Appendix C: Workshop Attendees

Affiliation	Position
CIGLR	Assistant Research Scientist
NOAA	Scientist
Toronto Metropolitan University	Post Doctoral Research Fellow
University of Michigan	Associate Professor
University of Michigan, Civil and Environmental Engineering	PhD Candidate
Toronto Metropolitan University and GCTW	Professor
Trent University	Academic
Michigan Technological University	Assistant Research Scientist
USACE - Detroit District	Physical Scientist
Canada Water Agency	Program Officer
Wilfred Laurier University	Student/RA

Affiliation	**Position**
York University	Masters student
ECCC	Water Resources Engineer
Great Lakes Indian Fish and Wildlife Commission	Climate Scientist
Bureau of Indian Affairs	National Hydropower Compliance Program Manager
Canada1Water	
Pacific Northwest National Laboratory	Earth Scientist
Great Lakes Indian Fish and Wildlife Commission	Tribal Climate Adaptation Specialist
United States Army Corps of Engineers - Detroit	Physical Scientist
GLISA/University of Michigan	GLISA Director
University of Michigan	PhD Student
NOAA GLERL	Scientist

Affiliation	Position
Argonne National Laboratory	Principal Atmospheric and Earth Scientist
Ontario Ministry of the Environment	Senior Science Advisor on Climate Change
Canadian Centre for Climate Modelling and Analysis	Research Scientist
University at Albany	Professor
GLISA - University of Michigan	Climatologist
USDA Midwest Climate Hub	ORISE Fellow
Canada Water Agency	GLWQA Canadian Annex 9 co-lead
NOAA GLERL	Research Physical Scientist
University of Toronto, ECCC	Research Scientist
Wisconsin DNR	Monitoring Lead
University of Toronto and Aquanty	Post Doctoral Researcher

Affiliation	Position
Environment and Climate Change Canada	Physical Scientist
Geological Survey of Canada	Research Scientist
Nelson Institute Center for Climatic Research, University of Wisconsin-Madison	Director
Red Lake Department of Natural Resources & GCTW	Climate change Specialist/Staff
ECCC	Water Resources Engineer
McMaster University	Master's Student
NOAA	Program manager
NOAA GLERL	Ecologist
University of Waterloo	Professor
GLISA - University of Michigan	Climatologist
Environment and Climate Change Canada	Research Scientist

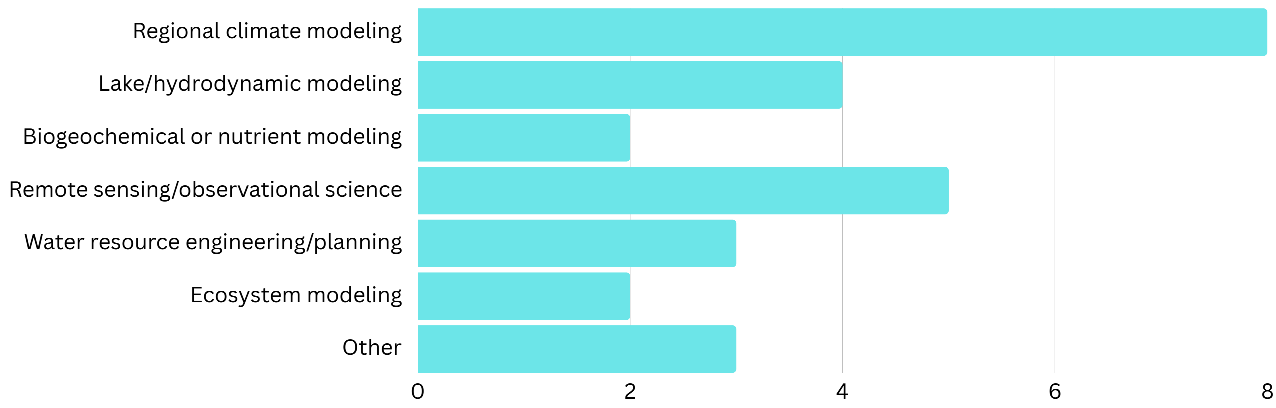
Affiliation	**Position**
University of Michigan	Professor Emeritus
CIGLR	Summer Fellow
York University	Professor
Michigan Public Service Commission	Public Utilities Engineer
NOAA	Scientist/Program Manager
Parks Canada	Great Lakes Ecologist
University of Wisconsin-Milwaukee	Professor, School of Freshwater Sciences
Toronto and Region Conservation Authority	Research Scientist, Ecosystem and Climate Science
University of Michigan/GLISA	Research Assistant
Postdoctoral Research Fellow, Department of Politics & Public Administration Toronto Metropolitan University	Postdoctoral Research Fellow
McMaster University	PDF

Affiliation	Position
USDA-ARS-MCH	Agroclimatology Fellow
PNNL	Scientist
University of Michigan	PhD Student
Global Institute for Water Security	Research Associate

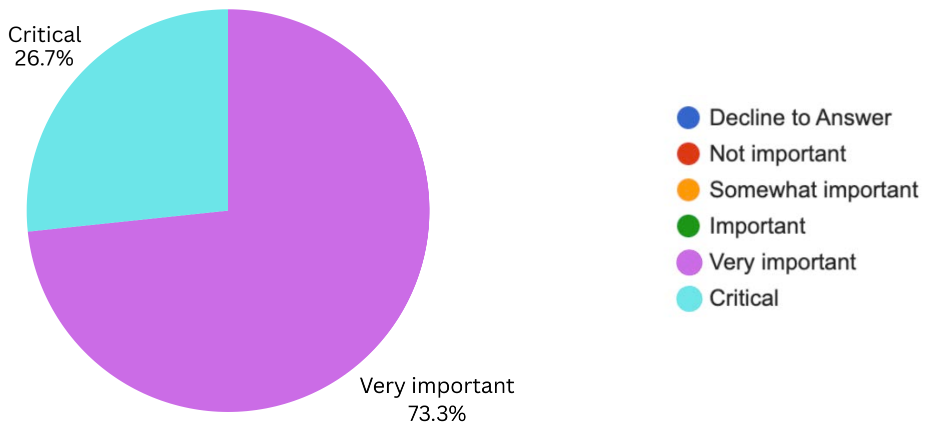
Appendix D: Workshop Survey Results

A subject matter expert survey was introduced during the workshop to gain insights on priorities within the group. The results are below.

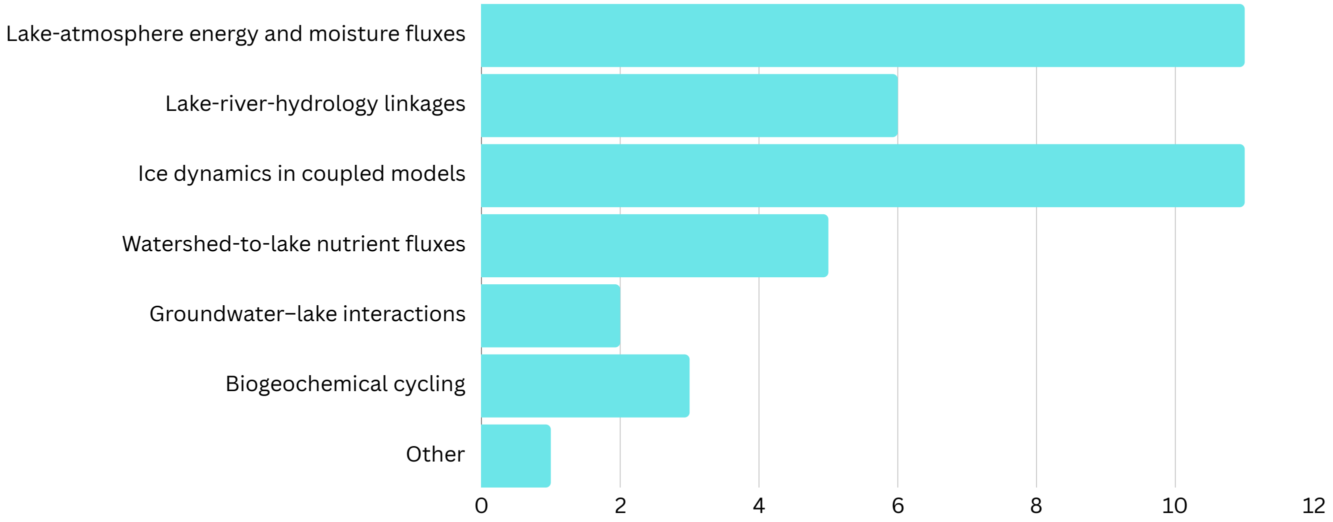
Disciplinary Expertise (Check all that apply):



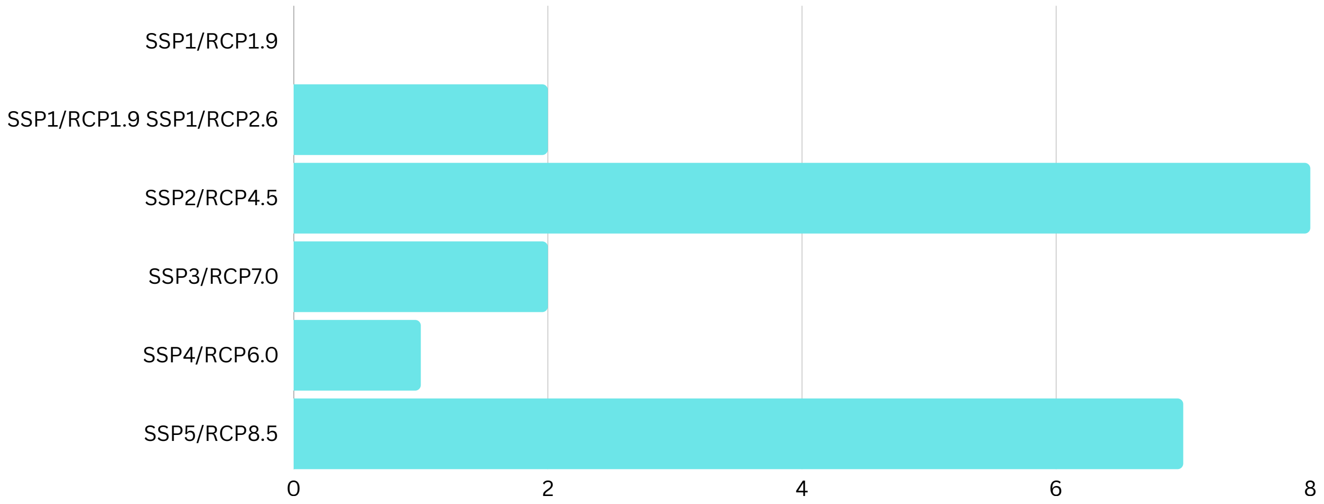
Based on your knowledge, of existing advancements in Great Lakes 2-way coupled lake-atmosphere modeling, how important is it to develop or enhance fully coupled atmosphere-lake-land models for the Great Lakes Basin?



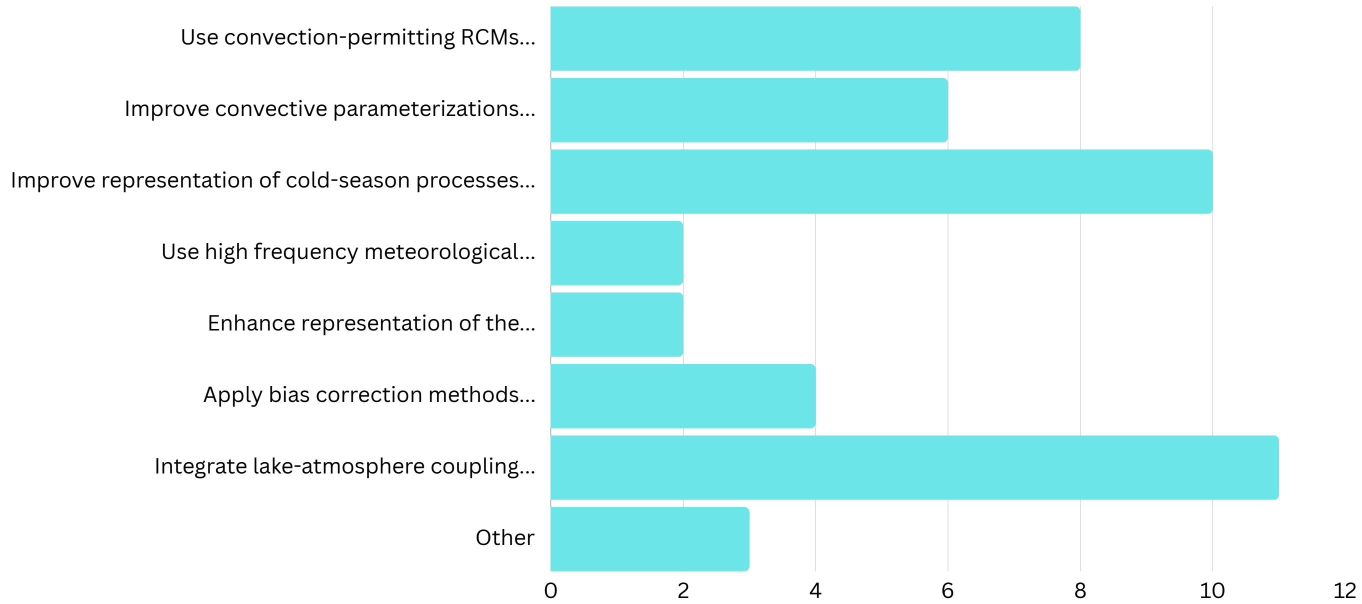
What types of coupling should be prioritized? (Select top 3)



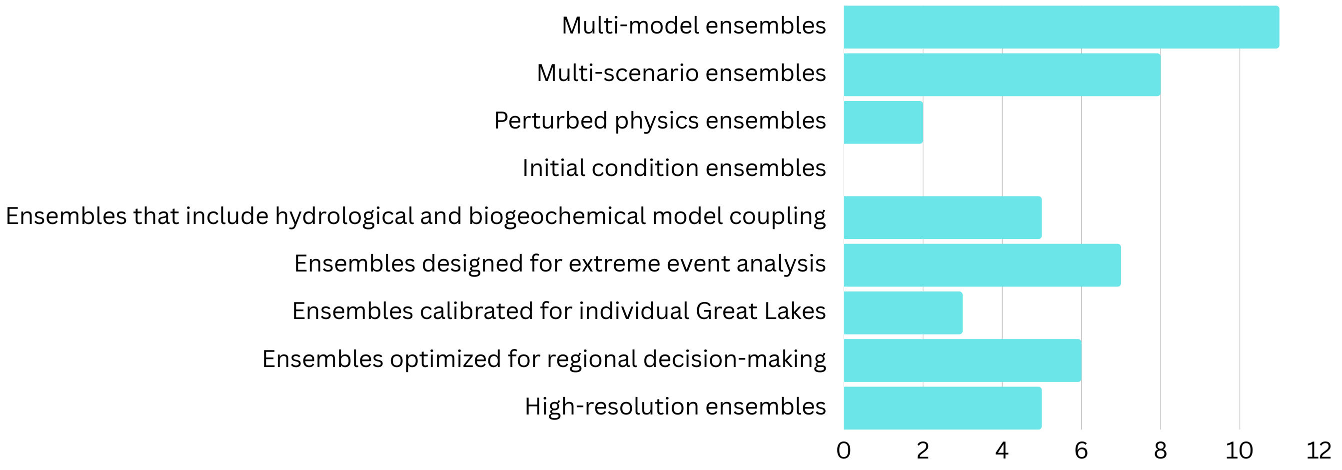
Which climate scenario frameworks below should be prioritized for future modeling? (Select Up To 2 assuming constraints in funding and computational resources)



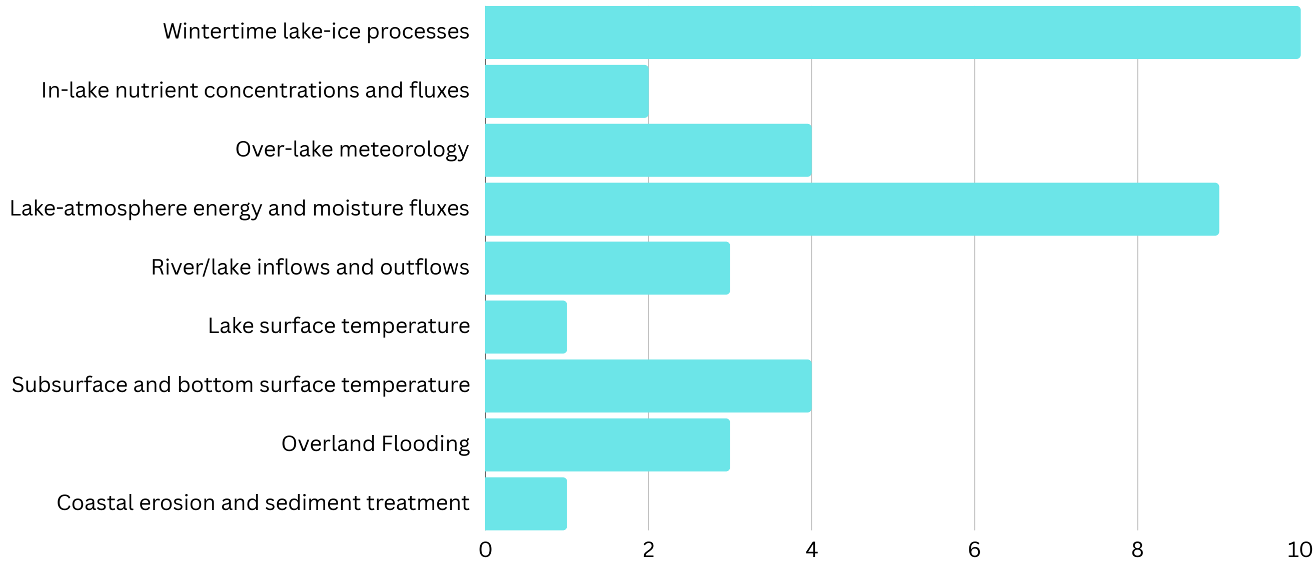
What activities do you view as most effective for improving regional model forcing (Select Top 4)?



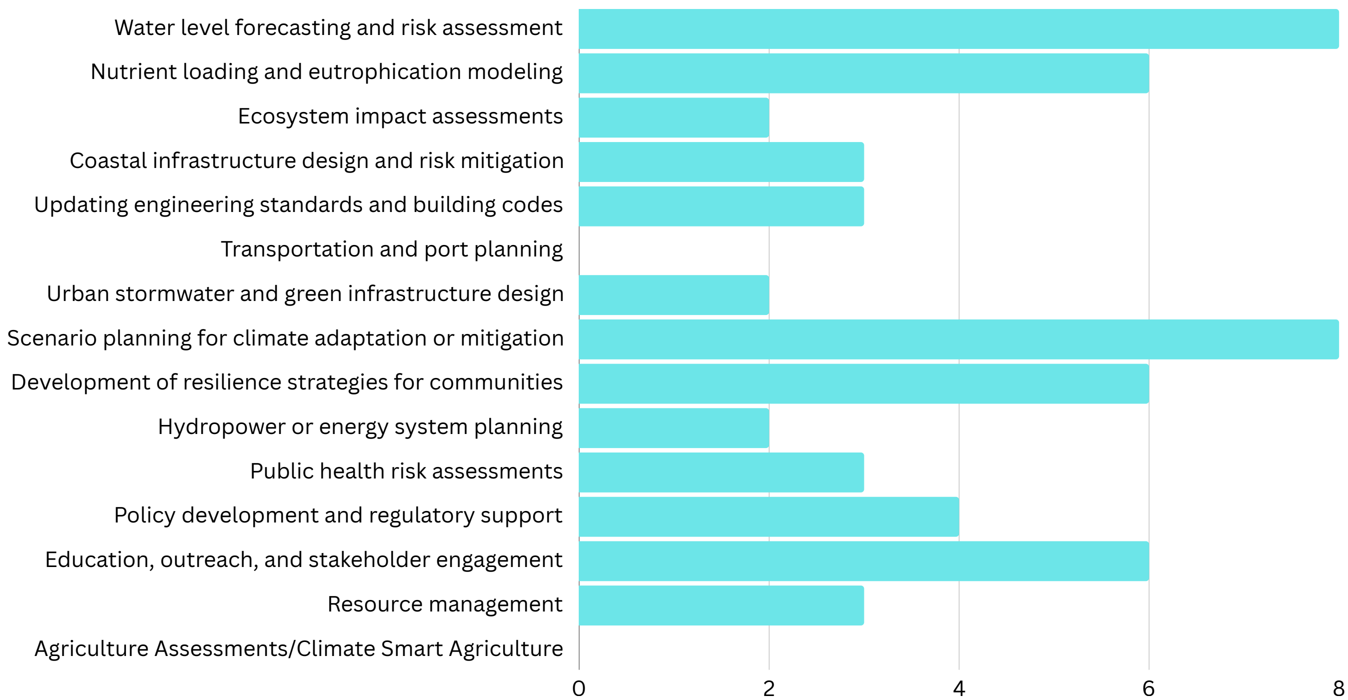
What priorities would you like to see advanced for Great Lakes ensemble modeling approaches? (Select top 4)



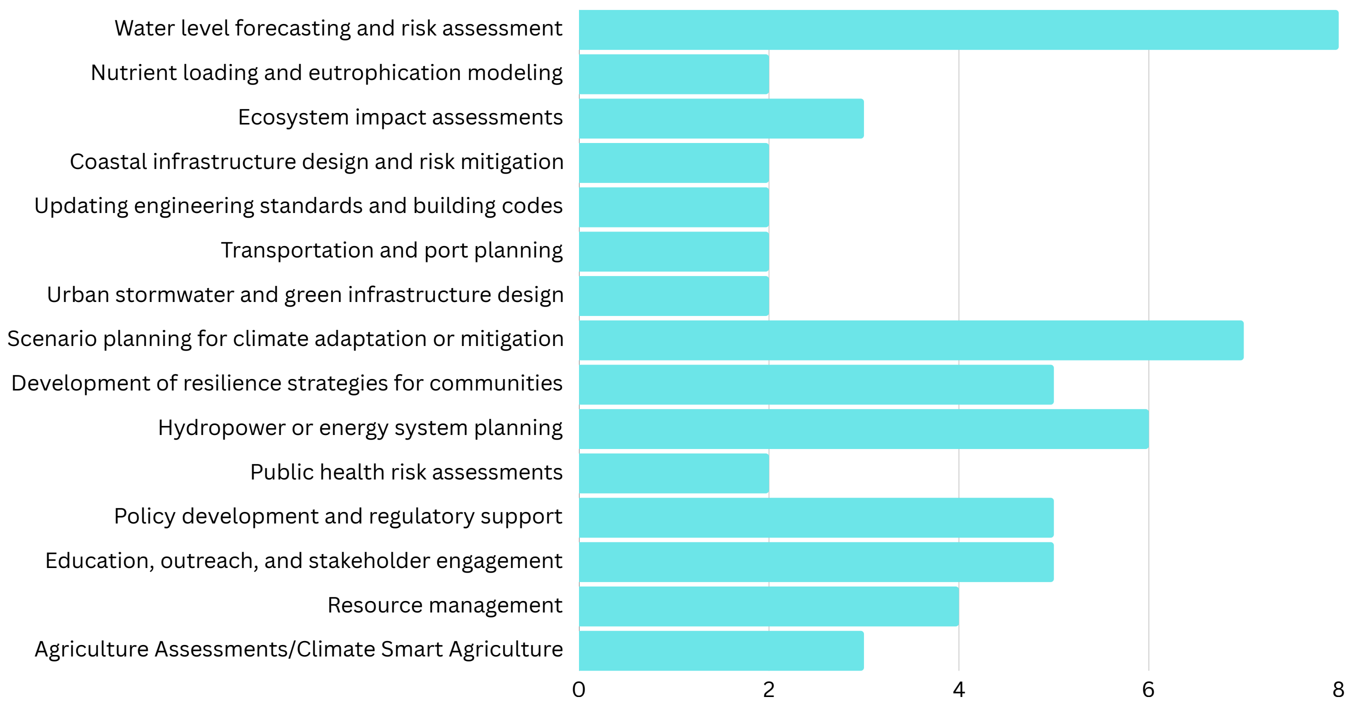
Where are the biggest gaps in in-situ observational data to support model validation and development? (Select top 3)



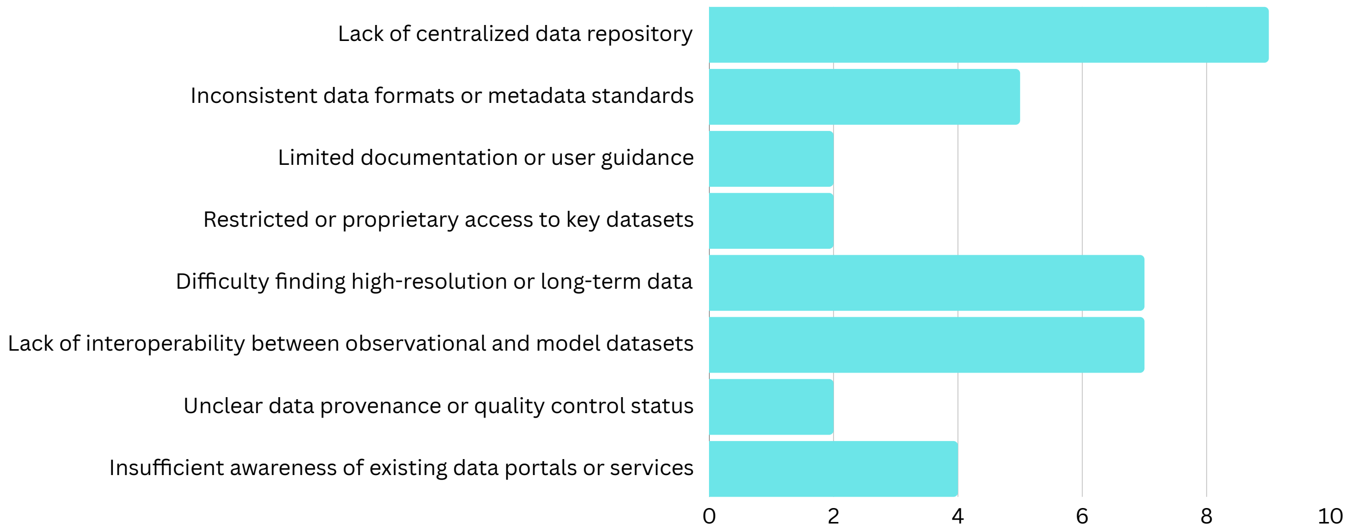
How do you or your organization most commonly apply or assist users in applying climate model data in the context of Great Lakes downstream research applications, planning, or decision-making? (Select top 5)



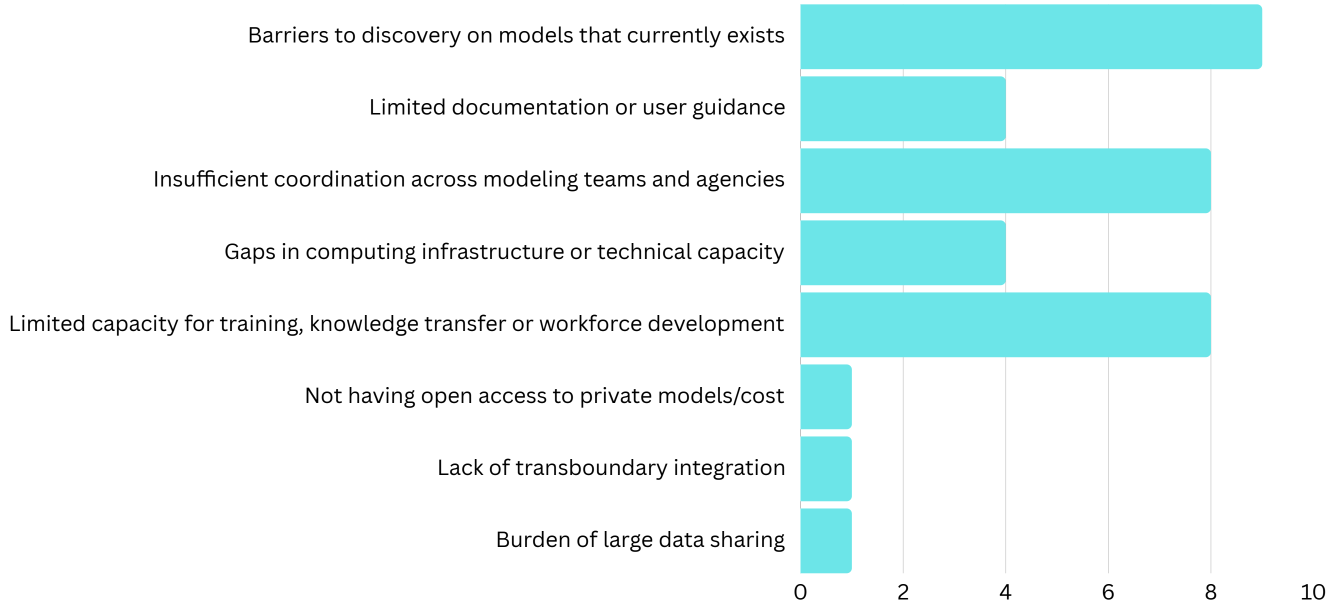
What are the emerging areas where you intend to support users in applying Great Lakes Regional Climate Model data in the future? (Select top 5)



What are the primary barriers to discovering and accessing climate and lake modeling datasets relevant to the Great Lakes? (Select top 3)



What are the primary barriers in furthering the utility and co-development of existing Great Lakes models? (Select top 3)



Are you in favor of a Great Lakes model simulation matrix similar to the NA-CORDEX Simulation Matrix?