Commentary article

The need for an integrated land-lake-atmosphere modeling system, exemplified by North America's Great Lakes region

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Abstract

In the face of future climate change, it is prudent to seek sustainable adaptation strategies to address regional and local impacts. These impacts are multidimensional, involving interdependencies between systems (weather, urban landuse, etc.) that are typically modeled independently. To achieve a holistic understanding, and thus more effective strategies for addressing and/or mitigating impacts, an integrated interdisciplinary research approach is essential. Here we discuss the broader challenges and threats faced by regions with large water bodies, illustrating them for the case of the North America's Great Lakes region, and how an integrated model of climate and hydrology can provide critical information to inform managers seeking best solutions. We also stress the need to include diverse stakeholder priorities in the development of such tools to ensure usability of impact assessments. Research investments should engage multiple disciplines including atmospheric sciences, hydrodynamics, hydrology, and biogeochemistry as well as underlying data analytics techniques and modeling strategies. In addition, detailed measurement and documentation of urban and agricultural landuse, lake surface temperature and ice-cover, and observations of energy and mass exchanges at the interfaces of atmosphere, land, and lakes are needed. We envision development of an integrated set of modeling tools that will improve both the utility of weather forecasts and long-term climate predictions related to impacts to the Great Lakes ecosystem sustainability, hydrometeorological extremes, engineering design, human health, and socio-economic factors. Such a modeling system could be a template for other regions with large lakes and enclosed seas, as these face similarly significant climate change impacts.

Three key points:

- Land-lake-atmosphere interactions impact human and natural systems in the Great Lakes region, but the uncertainty in observations and modeling remains large.
- Land, lake, and atmosphere are typically modeled independently rather than as the complex multiscale systems that they represent.
- There is a need for a collaborative framework for stakeholders to design interdisciplinary and coupled tools for evaluating impacts.

1. Introduction

The Great Lakes megaregion, one of the largest and most populated networks of metropolitan areas in North America, is home to 55.5 million people, many of whom are located at the urban-water nexus of coastal cities such as Chicago, Detroit, Cleveland, and Toronto (Todorovich 2009). The Great Lakes – Erie, Huron, Michigan, Ontario, and Superior – contain 20% of the world's surface freshwater supplies, and exert strong influence on the physical, environmental, economic, and cultural environment in the region. Due to their substantial depth, geographic extent, and thermal inertia, the Lakes play an important role in influencing local weather patterns and climatic processes. However, gaps in numerical modeling capabilities currently limit our ability to predict meteorological hazards and degrade ability to assess the potential impacts of anthropogenic climate change, thereby increasing the vulnerability of the region's citizens.

The Great Lakes' influence on regional climate provides diverse benefits and challenges to surrounding urban and rural landscapes. Impacts range from moderate (e.g., mild cooling breezes that help lakeshore orchards and vineyards flourish) to extreme (e.g., harsh lake effect snow and ice storms that close airports, shut down interstate freeways and knock out power grids). Global climate change has already begun to modify both the regional climate and the physical behavior of the Great Lakes (Lofgren *et al.* 2002; Kling *et al.* 2003; Wuebbles and Hayhoe 2004; Wuebbles *et al.* 2010), and intensify regional hydrometeorological and thermal extremes (Winkler *et al.* 2012). In recent decades a panoply of such changes have been documented: a statistically significant warming trend (Schoof 2013; Zobel *et al.* 2017, 2018), an increase in extreme summertime precipitation (Kunkel *et al.* 2003, 2012), changing lake levels (Gronewold *et al.* 2013), and a reversal of the increasing trends in lake-effect snows (Norton *et al.* 1993; Kunkel *et al.* 1999; Bard and Kristovich 2012; Notaro *et al.* 2013; Clark *et al.* 2016; Suriano and Leathers 2017). The region has also recently witnessed unprecedented extreme changes in the timing of precipitation and runoff which have important implications for flooding, soil erosion, nutrient export, and agricultural practices (Carpenter *et al.* 2017; Kelly *et al.* 2017).

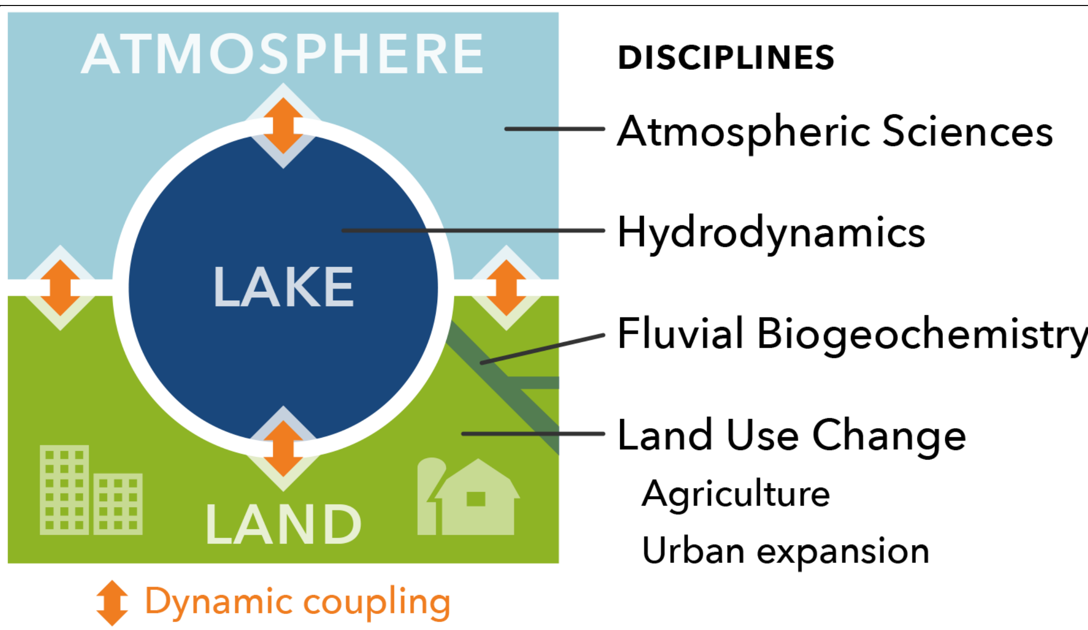

Figure 1. Integrated modeling framework for the Great Lakes region.

These observed changes create challenges to sustainable and resilient design of infrastructure in the Great Lakes region (Keeley *et al.* 2013), ecosystem management (Lubchenco and Sutley 2010; Sierszen *et al.* 2012; Bunnell *et al.* 2013; Goodspeed *et al.* 2016), and also regional agricultural production (Mueller *et al.* 2016). Projections of climate change indicate increasing extremes, with projections of regional warming to as high as 10 °C by 2100 (Byun and Hamlet 2018). Precipitation extremes, especially in winter and spring, can increase the input of nutrients (phosphorus, nitrogen) moving through rivers and streams into the Lakes, degrading water quality and causing harmful algal blooms (Verhougstraete *et al.* 2010; Allinger and Reavie 2013; Michalak *et al.* 2013; Watson *et al.* 2016).

The Great Lakes climate underpinning these changes is inextricably tied to interconnections between the atmosphere, land (and its use), water, and ice. Understanding of these interconnections is limited both by a lack of observations and well-validated, dynamically coupled land-lake-atmospheric numerical modeling systems for operational weather and long-term climate impact assessments (Figure 1). Global circulation model (GCM) simulations at adequately high resolution are currently intractable due to high computational expenses, requiring the use of finer resolution regional climate models (RCMs) at local to continental scales (e.g. Wang and Kotamarthi 2014; Liu *et al.* 2016). One of the primary reasons for the lack of an integrated modeling system for the Great Lakes is the difficulty in representing the exchanges and feedbacks between the models (Mallard *et al.* 2015). For example, the Lakes are often unresolved in GCMs due to their coarse spatial resolutions (Mallard *et al.* 2014). RCMs that resolve the Lakes are limited due to the lack of an integrated lake model and questionable lake surface temperature (LST) boundary condition assumptions (e.g., in some experiments an average of Atlantic and Pacific Ocean temperatures has been prescribed, Winkler *et al.* 2012; Mallard *et al.* 2014). Operational models often utilize remotely sensed LST, do not account for hydrodynamic feedbacks, and do not explicitly simulate the fluxes of moisture, heat and momentum across the interfaces. The inadequate representation of these complex processes limits the utility of such models in climate change research.

The difficulty of examining the interconnectedness of these physical processes has meant that they are typically modeled as independent subsystems, with at best rudimentary representation of interactions between them. Consequently, infrastructure design, operation, and resource management decisions made with the best intentions can lead to unintended consequences (Adam *et al.* 2015). Physical processes at multiple space-time scales knit these decisions (and the resulting infrastructure and systems) with the climatic elements discussed above, which are in turn driven by such factors as lake dynamics (stratification and lake water levels, ice cover, water temperature), lake-induced storms, river in- and out-flows, atmospheric heat and humidity, and urban and agriculture influences. Multiple environmental, human health and safety, and financial impacts are linked to the Great Lakes due to inter- and intra-system dependencies that impact energy production, ecosystem conservation, water resource management and agriculture in the Great Lakes region. Thus, it is imperative to understand the evolving and dynamically coupled changes in the Great Lakes themselves in response to regional climate change, and ultimately use this understanding to re-evaluate current and future impact assessments for the Great Lakes region.

Given recent national policy decisions that drastically affect environmental research, the Great Lakes communities (e.g., Metropolitan Mayors Caucus) are individually and collectively developing policy and striving to make infrastructure and resource management decisions to adapt to climate change. Yet the climate tools at their disposal are often inadequate to inform local or regional policy development. A holistic modeling system integrating land, air, and water will be essential for science, but equally critical for these policymakers (Weaver *et al.* 2013). In making such an integrated set of tools, inclusion of stakeholders' needs and priorities on various mitigation and adaptation strategies will increase the usability of integrated products to inform important societal decisions related to the Great Lakes management, disaster preparedness, infrastructure investments, ecosystem management, and agricultural practices in the region.

Recently, Gronewold and Fortin (2012) organized a workshop and identified broad binational research needs for Great Lakes hydrological modeling with an emphasis on improving regional hydrological and hydrodynamic science. This discussion was focused primarily on research and development needs in the context of operational modeling and forecasting. In this commentary, we focus somewhat more broadly on key science needs and the importance of strengthening integrated research capacity. Specifically, we emphasize the need to improve the skill of weather forecasts and long-term climate projections, with the overarching goals of identifying important impact pathways in the region, and developing tools to support sustainable and resilient climate change adaptation strategies for the Great Lakes region.

The overall aim of this commentary is to provide a foundation for impact-driven integrated research explicitly incorporating a dynamic coupling between land, lake, and atmosphere. The goal of this commentary is two-fold. First, this article aims to promote focused scientific activity in the Great Lakes region by providing a framework for productive discussions among members of the scientific community that emphasizes the need to move towards more fully integrated and well-structured physical models that encompass the specific scientific, management, and community needs discussed above. Secondly, this article aims to provide a vision statement intended to encourage scientists, researchers, practitioners, managers and citizens to get involved in collaborative efforts to improve the health and well being of the Great Lakes region. It is our hope that these efforts to frame the problem at hand will provide motivation to the scientific community, managers, and stakeholders to write joint proposals to jump-start projects and enhance fundamental knowledge of coupled land-lake-atmospheric processes as well as generate meaningful products for societal applications at the intersection of integrated themes (Figure 1). Primarily, the audience for this commentary is the scientists, however, the most important beneficiaries are likely to be policy makers, natural resources managers, urban planners, and the near and far coastal communities who benefit from the many ecosystem services provided by the Great Lakes. At the same time, we also aim to reach out to stakeholders and citizens to participate in planning discussions so that scientists can ask the right questions for impactful and translational research outcomes. Thus, the next steps would be to conduct interviews and workshops on this theme to collect concrete ideas from science leaders, listen to the needs of policy makers, city and natural resource managers, practitioners and citizens, and plan a way forward for an interdisciplinary team to address this vision. In parallel, scientists can reach out to funding agencies with white papers and proposals to secure funding to make progress towards this vision. Overall, this will provide an inclusive platform for interested colleagues and citizens to join and contribute in a meaningful way.

2. Current state of Great Lakes numerical modeling

Standalone hydrodynamic Great Lakes models range in physical complexity from 1- to 3-dimensions (1-D to 3-D), and encompass a wide range of statistical, empirical, and physically based approaches. Such tools have been used to better understand important lake processes such as stratification, vertical and horizontal mixing/diffusion, and circulation/currents. Attempts to couple lake models with atmospheric models have proven challenging.

Researchers have developed several different types of 1-D lake models with different complexities for the Great Lakes region: (i) the Large Lake Thermodynamics Model (LLTM) (Croley 1989; Lofgren 2004); (ii) a slab type thermodynamic model, the Mixed-Layer Model (Goyette et al. 2000; Subin *et al.* 2012), Canadian Small Lake Model (CSLM) (MacKay *et al.* 2017); (iii) a simple two-layer model based on similarity theory, Freshwater Lake (FLake: Mironov *et al.* 2010; Gula and Peltier 2012; Mallard *et al.* 2014); and (iv) a thermal diffusion model with parameterized eddy diffusivity (Hostetler model, Hostetler and Bartlein 1990; Stepanenko *et al.* 2010). Efforts to dynamically couple 1-D lake models with atmospheric models have gained much momentum. For instance, the WRF model (Skamarock *et al.* 2005) is coupled with Community Land Model (CLM) that has a 1-D ten-layer lake model (Subin *et al.* 2012; Gu *et al.* 2015; Xiao *et al.* 2016). Gula and Peltier (2012) have attempted an offline coupling of the FLake (Mironov 2008) model with WRF in regional climate simulations. Yet 1-D lake models could not capture the thermodynamic behavior of lakes, especially for Lake Superior (Mallard *et al.* 2014). The Regional Climate Model, version 4 (RegCM4) has also been coupled with a 1-D lake model to investigate the influence of the Great Lakes on historical climate and lake-effect snows (Notaro *et al.* 2013; Vavrus *et al.* 2013; Bennington *et al.* 2014).

3-D lake hydrodynamic models are able to simulate many lake processes absent in 1-D models. The Princeton Ocean Model (POM) has been widely used operationally at the U.S. National Oceanic and

Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory (GLERL) and for research (e.g., Beletsky *et al.* 2006; Huang *et al.* 2010; Beletsky *et al.* 2013; Fujisaki *et al.* 2013). POM has now been replaced by an unstructured 3-D Finite Volume Community Ocean Model (FVCOM; Chen *et al.* 2006), which is being used for simulations of Lake Superior (Xue *et al.* 2015), flow in the Straits of Mackinac connecting Lakes Michigan–Huron (Anderson and Schwab 2013), and basin-scale climatological studies (Bai *et al.* 2013). Meanwhile, Environment Canada has developed a 3-D coupled lake-atmosphere-hydrological modeling system based on the Global Environmental Multiscale model (GEM); the MESH (Modelisation Environnementale Surface et Hydrologie) surface and river routing model; and, a 3-D hydrodynamic model based on the Nucleus for European Modeling of the Ocean (NEMO) system (Dupont *et al.* 2012). Recently, Arifin *et al.* (2016) tested and refined the stand-alone 3-D hydrodynamic Environmental Fluid Dynamics Code (EFDC) for Lake Ontario (Hamrick 2007). Similarly, Wang *et al.* (2010) developed a Great Lakes Ice-circulation Model (GLIM) to study the seasonal cycle of Lake Erie temperatures on lake circulation and thermal structures.

Research efforts to couple atmospheric models with 3-D hydrodynamic models have made less progress. Xue *et al.* (2017), for example, coupled FVCOM with the regional climate model RegCM4 to provide better representation of hydroclimatic interactions. Similarly, the Nucleus for European Modelling of the Ocean (NEMO) model has been used with the Canadian Regional Climate Model (CRCM), but without any direct coupling (Long *et al.* 2016). Such modeling advances in simulating the 3-D hydrodynamic components of the Great Lakes and coupling them to atmospheric models is critical to developing a more integrated modeling system.

One of the key drawbacks is the lack of a sufficiently detailed lake climatology to feed the coupled models for initialization as well as observations of energy exchanges at the interfaces of the land, lake, and air to develop and evaluate model performance. Initialization data from observations, including lake temperatures (Spence *et al.* 2013; Van Cleave *et al.* 2014), ice cover – Great Lakes Ice Atlas (Assel 2003), precipitation from remote sensing (Colton 2013); and lake sensible/latent heat (Blanken *et al.* 2011), are available, but the ability to ground truth these observations is often limited. Estimation of over-lake precipitation and evaporation has been poor over the Great Lakes, partially because of instrumentation limitations, monitoring network insufficiency, and spatial inhomogeneity (DeMarchi *et al.* 2009). Energy exchanges between the lakes, air, and ice are observed even less frequently (Laird and Kristovich 2002). Thus, modeling lake ice is difficult and sensitive due to inaccurate and poor observations of heat, momentum and mass flux. A field study over Lake Superior sought to measure evaporation via surface energy balance using an eddy covariance system at a point location. It investigated its spatial distribution and variability with concurrent satellite and climate model data, then extrapolated evaporation measurements across the entire lake (Blanken *et al.* 2011; Spence *et al.* 2011). Heat fluxes over ice-covered Lake Erie were observed by Gerbush et al. (2008). Aircraft observations allow for collection of spatial variations in energy exchanges, thermodynamic characteristics and over-lake snowfall, such as those obtained by aircraft observations in the University of Chicago lake-effect snow project (Braham and Kelly 1982), Lake-induced Convection Experiment (Kristovich *et al.* 2000) and the Ontario Winter Lake-Effect Systems project (Kristovich *et al.* 2017). These kinds of detailed research observations, however, are only taken over time periods of a few hours.

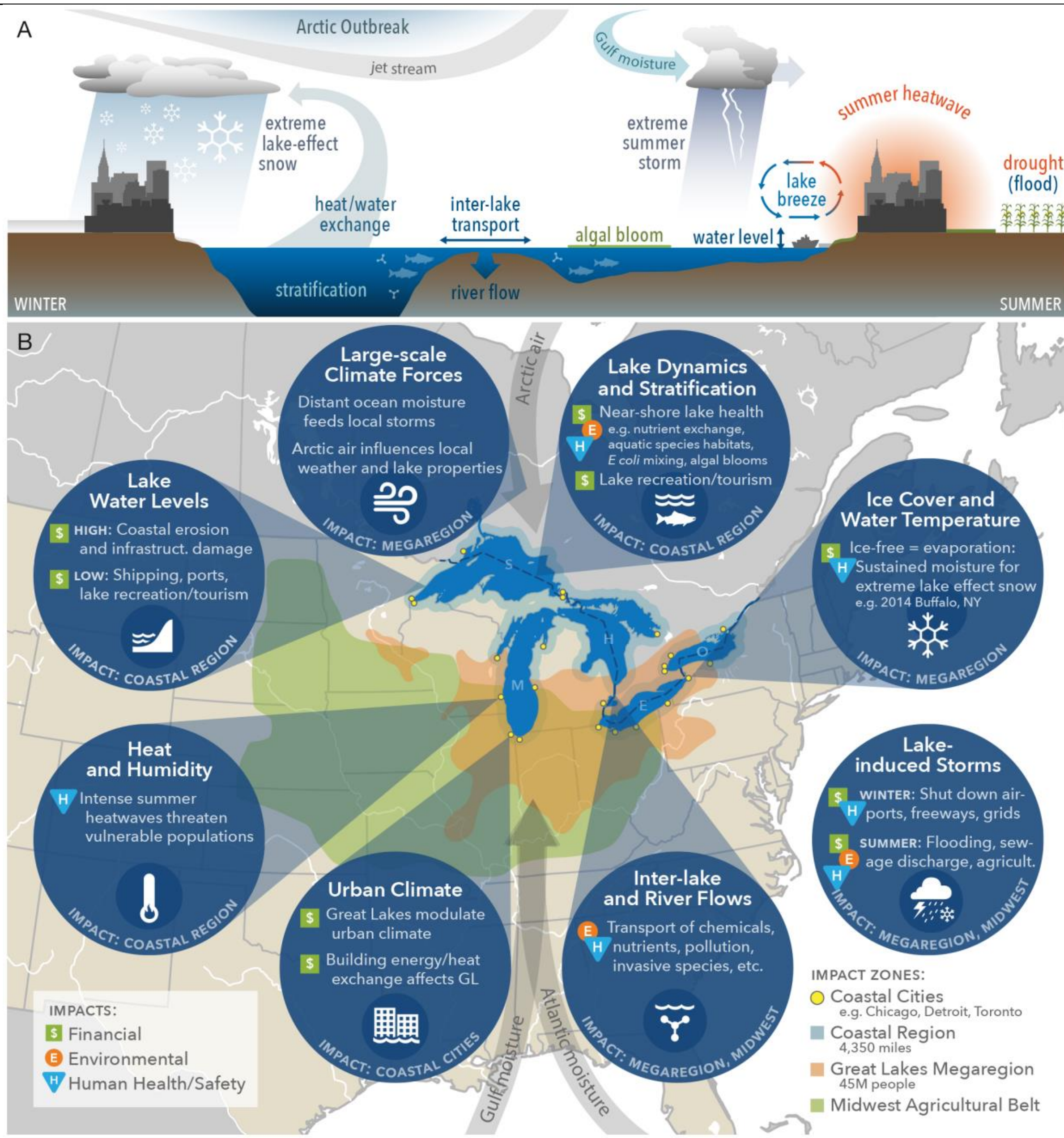

Figure 2: A conceptual approach to address (A) different physical phenomena occurring in the Great Lakes, over, and around them during summers and winters; and (B) a schematic diagram of multiple processes, their financial, environmental, and human health and safety impacts, and linkages to the land-lake-atmosphere coupling. Note the points leading from each circle connect the processes to the map and refer to example locations that exhibit the processes, not the only location where it is important.

3. Toward an integrated and coupled land-lake-atmosphere modeling system

These major knowledge gaps in Great Lakes research can be narrowed by dynamic coupling of 3-D hydrodynamic lake models with existing RCMs that simulate couple atmospheric and land processes. With improved parameterizations, the dynamic coupling is intended to produce a self-consistent and physically based time evolution of LST and ice, and the resulting in the dynamic simulation of lake-atmosphere fluxes. Advanced, targeted field studies could lead to further development of parameterizations and evaluation of model results. This coupling will simultaneously and synchronously exchange surface wind, precipitation and radiation flux information of an atmospheric model with LST, evaporation, latent heat, and roughness height of a lake model.

Thus, a fully integrated and coupled land-lake-atmospheric modeling system would provide a nexus between lake dynamics, inter-lake flows, exchange with regional rivers, different atmospheric phenomena over the lakes, as well as their regional impact on coastal urban communities and agricultural areas (Figure 2A). Integrated land-lake-atmospheric coupling will help us to better understand interactions between extreme summer storms and overlake stable atmospheric boundary layers (Workoff *et al.* 2012); the Gulf of Mexico and Atlantic Ocean moisture teleconnection via horizontal flux transport to the Great Lakes and Midwest region; summer heat waves; lake and land breezes (Sharma *et al.* 2017); and, coastal floods in the Midwest and their impact human and natural environments. For winter, this approach will help improve simulations of important lake-atmosphere interactions, such as lake-effect snow, that are governed by complex interactions of lake surface temperature, ice cover, Arctic air outbreaks, and changes in jet streams that control storm track behavior (e.g., Angel and Isard 1998).

Further, this approach would improve the utility of operational and forecasting model predictions to prepare for short- and long-term impacts of climate change. Inclusion of real-time data assimilation in models would create better tools for lake management, shipping and navigation, stormwater management, agriculture, and infrastructure planning (Diak *et al.* 1998; Kitchen 2008; Crétaux *et al.* 2011; Kerkez *et al.* 2016). The same design would link local and regional-scale effects of agriculture and urban land use. Figure 2B outlines key processes and their financial, environmental and human health/safety impacts and impact zones. To develop such a comprehensive modeling system would require a careful synthesis of disparate modeling components, and would draw on knowledge across multiple disciplines and space-time scales.

In addition, we could decrease computational time for RCMs by including prognostic changes in LST and ice state in future publicly-available GCM output datasets. At the same time, variance of ensemble RCM runs from multiple GCM outputs can provide information on variability of future global projections at regional and local scales. Meanwhile, efforts are needed to develop better initial boundary conditions for the lakes and avoid a long spin up simulation by creating a spatial and temporal Great Lakes climatological database based on observations or off-line simulations. The Lake's spin-up time can further be reduced in the coupled and integrated system by providing direct feedback from lake to atmosphere and vice versa (Mallard *et al.* 2015).

While many researchers and some funding agencies have broadly supported this vision in the past, as a community we have yet to create a new generation of models that can help us fully understand and quantify climate change impacts in the Great Lakes region. We have seen advances in operational forecasting, yet the long-term development of research models has lagged behind the operational upgrades. With more frequent and intense extreme events occurring over the last decade, this commentary vision is timely. We argue that we are already running behind and need to begin the labor-intensive process of developing appropriate modeling systems as soon as possible. However, it is a complex scientific problem and we imagine it would require considerable time, say 5-10 years, for the research community to generate resources and develop a robust integrated system for forecasting and climate needs as well as to develop impact assessment tools based on revised regional climate projections. Such integrated simulations need to be run at a minimum 4-km spatial resolutions for the coupled systems. However, these simulations may need to be run at ultra-high 1-km spatial resolutions for capturing fine-scale phenomena and developing sound impact assessment tools for Great Lakes communities. It is, therefore, essential that we invest more resources in integrated climate research that will improve the quantity and quality of environmental information available to Great Lakes communities. This system, in turn, can help reduce the adverse impacts on various kinds of infrastructure (e.g. transportation, energy, stormwater infrastructure), including social or economic impacts for dozens of Midwestern and Canadian communities, and guide long-term planning for Great Lakes ecosystems.

4. Potential Benefits

4.1 Adaptation to a changing climate - future and current climate projections: The land-lake-atmospheric coupled modeling system would test the hypothesis that extreme storms and their impacts are expected to increase. Such integrated models would capture vital physical processes at varying spatial scales, from regional to local (Conry *et al.* 2015). For example, atmospheric moisture that feeds intense storm systems around the Great Lakes may originate in the Atlantic Ocean or the Gulf of Mexico, and appear as a continuous band of storms that connect the Gulf of Mexico and upstate New York and Canada, via the Great Lakes. Similarly, an Arctic outburst may produce extreme lake-effect snows via heat and moisture exchange over the Lakes. These teleconnections from large-scale storms are frequently not well captured over the Great Lakes region because the atmospheric dynamics over the Lakes are poorly represented in the climate models. Thus, current regional models often fall short in capturing intensity, duration and timing of these large-scale storms. At the same time, the observed historical decline in annual average Great Lakes ice cover (Wang et al. 2012), longer period of year with open lake water, and warmer lake surface temperature have contributed to both significant local increases and decreases in lake-effect precipitation in ways not yet fully understood (e.g., Austin and Colman 2007; Bard and Kristovich 2012; Hartnett *et al.* 2014; Suriano and Leathers 2017). Therefore, a coupled framework will show realistic atmospheric conditions over the lakes, which is expected to improve forecasts and long-term large scale precipitation predictions. In addition, this approach has potential to improve current weather forecasts that often miss the amplitude and location of storms. Figure 3 shows how simulations without dynamic land-lake-atmospheric coupling can drastically miss the location of an extreme snowfall event. When snow forecasts are this inaccurate, they can greatly hamper the readiness of emergency management personnel, as well as the general public. The forecasts for this storm, for example, identified the most extreme impacts in the wrong county due to errors in the storm path.

4.2 Prediction of Changing Lake Levels and Water Quality: Changing lake water levels can lead to coastal erosion and wave damage to infrastructure which typically intensify during high water, whereas low-water conditions impede shipping, port activities, lake recreation and tourism (Wall 1998; Millerd 2011; Dawson and Scott 2010). The Great Lakes water levels have decreased in the past (Gronewold and Stow 2014a), and are expected to do so in the future due to climate change (Lofgren and Rouhana 2016). Water levels in recent years have been highly variable, and have called attention to deficiencies in our understanding of the Great Lakes water balance. Water levels for Lake Ontario, for example, changed dramatically from a record low in 2013 to a near-record high in late Spring 2017 -- one of the most rapid increases in recorded history. Fluctuations in lake levels are linked to the timing and magnitude of the regional water budget, with relatively low levels in winter months, followed by a rise in spring and a decrease in late summer and early fall (Gronewold and Stow 2014b). Since the variability of over-lake precipitation and evaporation are key drivers of lake levels, integrating climate and lake models will be crucial for predicting lake levels under a changing climate. Additionally, this integrated system will address hydrologic issues of inter-lake (Anderson *et al.* 2010; Anderson and Schwab 2013), river and stream flow as well as surface runoff and subsurface flows and their relationship with biogeochemistry (Beaulieu *et al.* 2011). Similarly, prediction of short-term lake level fluctuations due to wind, pressure perturbations or storm surge (seiches, storm surge, meteotsunamis) would be better forecasted with the integrated system.

In addition, the Great Lakes also suffer from excess phosphorus and nitrogen nutrients entering the Lakes via streams and rivers which degrade the water quality and cause harmful algae blooms (HABs) (Allinger and Reavie 2013; Michalak *et al.* 2013; Watson *et al.* 2016). They kill fish, foul up nearby coastlines and produce conditions that are dangerous to aquatic life, as well as humans. HABs require restrictions on fisheries, coastal recreational, and drinking water (Verhougstraete *et al.* 2010; Brooks *et al.* 2016; Ji 2017). Understanding temporal variations in the occurrences of HABs and their relationship to climate variability and change is challenging. One question is whether such changes are present in observations, while other relates to the long-term implications of climate change on HABs. The climatic variations in magnitude, frequency, and duration of HABs in inland and coastal Great

Lakes waters and their interaction with agricultural systems are poorly understood across relevant spatiotemporal scales. For example, how do HABs interact with agricultural systems and lake conditions to affect near-shore water quality? Specifically, a dynamically coupled modeling system would better capture storm dynamics and statistics affecting nutrient loading to the Lakes. Thus, there is a high probability of improving our understanding of location and duration of HABs and other water quality issues with an improved modeling and assessment system.

4.3 Connection of Great Lakes to coastal communities and their meteorological implications: The Great Lakes are also a powerful modulator of coastal urban climate (Conry *et al.* 2015; Sharma *et al.* 2016, 2017). There are many potential benefits of a coupled land-lake-atmosphere modeling system related to hydrometeorological extremes in coastal communities. These include: improved evaluation and better preparedness for adverse impact of climate variability on extreme heating; coastal flooding, changes in water level; and resiliency of coastal urban communities to extreme precipitation, including lake-effect snow and rain. Future urban development choices, modification of land cover and land use, use of climate change adaptation practices like green and cool roofs, and green ecological and conservational infrastructure can all be assessed with greater mechanistic fidelity within this coupled system. Increased coastal urbanization and urban heating modifies the lake breeze and winds over the lakes (Sharma *et al.* 2016), and warmer lake temperatures may exacerbate these effects. Weakened lake breeze may also violate National Ambient Air Quality Standards by significantly enhancing the ozone concentrations along the Lake coastlines when urban emissions react within the shallow, stable, marine boundary layer (Pierce *et al.* 2017). Thus, the effects of urban heat, humidity, and pollution in major cities such as Chicago and Toronto create mounting health risks to vulnerable populations (such as aging adults) as summer heat waves increase in intensity due to regional climate change.

Recent lake studies have found that declining duration of ice cover over the lakes and increasing lake surface water temperatures (Mason *et al.* 2016) have caused major summer convective storm water impacts in Midwestern cities (Kessler 2011). Other meteorological impacts include wintertime lake-effect snow in coastal communities, induced by rapid heat and moisture exchange over the Great Lakes (Fujisaki-Manome *et al.* 2017). For example, in November 2014, an extreme lake-effect storm in Buffalo, New York, delivered more than seven feet of snow. Climatically decreasing ice cover enhances opportunities for these conditions. Figure 3 shows a lake-effect storm that resulted in massive snowfall for northern Indiana's Porter and St. Joseph counties in January 2011. Such extreme winter storms are affected both by large, regional-scale storms and more local impacts from lake-effect snow, and are influenced by large-scale atmospheric circulations (e.g., arctic air outbreaks) and ice cover/water temperature in the Great Lakes (e.g., Gerbush *et al*. 2008).

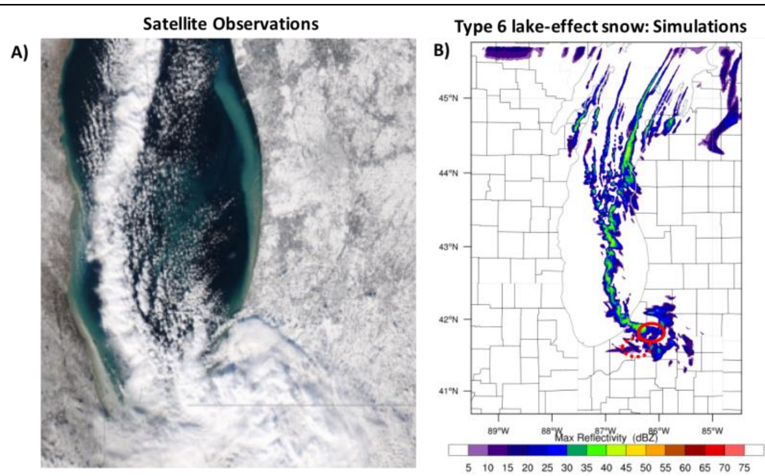

Figure 3: Satellite observations of type 6 lake-effect snow event, which is simulated using WRF model at 1-km resolution for 1-January 2011. Here, a mesoscale vortex structure is formed in southern Lake Michigan and adjoining single band over the Lake Michigan. Red circles show shift in total snow accumulations (solid red circle is simulations and dotted observations).

There is a consensus that the effects of increasing temperature and precipitation changes could also impact urban sustainability by affecting public health (Haines *et al.* 2006; Patz *et al.* 2005; Pierce *et al.* 2017). Extreme weather events lead to health problems in Great Lakes communities. Changing climate threaten public health by worsening urban air pollution and increasing rates of infectious (particularly waterborne and vector-borne) disease transmission (Patz *et al.* 2008, 2014a,b). Better public health tools can help prepare Great Lakes communities to minimize heat stroke, asthma, waterborne illness, diseases spread by ticks and mosquitos, and other health problems worsened by climate change. Building Resilience Against Climate Effects (BRACE-Illinois), Indiana University's tackling Environmental and Health Grand Challenges, University of Notre Dame's Environmental Change Initiative, University of Minnesota's Institute on the Environment and GLERL are a few initiatives or programs at specific institutions among many performing impact assessment and developing tools for Great Lakes communities. Such actions would be better informed by a robust, integrated and coupled land-lake-atmosphere modeling system which will provide physically based projections of current and future impacts mostly unavailable at the time of this commentary writing to city planners and engineers.

4.4 Infrastructure and economic benefits: Increased precipitation extremes from summer convective storms and winter lake effect storms have also inflicted unprecedented infrastructure damage and economic losses in the Great Lakes megaregion, for example, summer 2013 coastal flooding in Toronto cost more than CA$ 900M (Wang *et al.* 2014). These types of changes are expected to substantially increase flood damage in major cities across the U.S. (Ntelekos *et al.* 2010). To complicate matters, many cities in the Great Lakes megaregion face a backlog of aging urban stormwater and transportation infrastructure – roads, bridges, tunnels, ports, sewers etc. – that must be retrofitted or replaced (Winters *et al.* 2015). Thus, cities must cope with added pressures placed on their infrastructure by increasing urban populations and weather damage from climate change. Also, the current design for new infrastructure is based on climate data that fails to account for the realities of today – not to mention decades from now. The envisioned dynamic land-lake-atmosphere modeling system will help engineers and practitioners to design robust infrastructure using green and conventional management alternatives that would reduce the impact of natural disasters, and foster environmental and economic health.

4.5 Agricultural impacts: This approach will also reap benefits for a larger region around the Great Lakes. For example, the Midwestern U.S. "corn belt" is expected to shift northward to follow the climate conditions favorable for important cash crops (Diffenbaugh *et al.* 2012). In winter and spring, increased precipitation and more rain than snow is expected in coming decades, as well as an increase in storm intensity (Hayhoe *et al.* 2010, Byun and Hamlet 2018). Future high temperature extremes during the growing season can reduce agricultural production in the Midwest U.S., and may require increased use of irrigation to maintain current levels of productivity. At the same time, more agriculture production will be required on a global basis to support an increase in projected future populations (Ray *et al.* 2013). Thus, forced agricultural intensification (i.e. higher crop yields per acre) to support rise in projected future populations can increase the potential for evapotranspiration, leading to cooler temperatures and contributing to increased precipitation recycling (Mueller *et al.* 2016). The coupled land-lake-atmospheric interactions will help to capture impacts of changing land cover, precipitation, and the timing and intensity of runoff, which influence the biogeochemistry of streams and rivers. Future increase in intensity of extreme summer storms (Kunkel *et al.* 1999; Zobel *et al.* 2017) and biogeochemical cycles are closely tied to hydrological response, both as a mechanism for solute transport (e.g., Royer *et al.* 2004, 2006) and as a driver of redox potential in soils (Christopher *et al.* 2008). Thus, agriculture intensification via increase in fertilizer consumption would cause more problems related to HABs. Such changes might require stricter regulations or compliance of Best Management Practices (BMPs) over the Great Lakes region to avoid detrimental impacts to water quality. Therefore, land-lake-atmospheric coupling can expect to reduce the knowledge gaps related to climate change effects on agro-ecosystems of the larger Great Lakes region.

5. Summary of Science and Policy Needs

Numerical modeling of Earth's climate system has been marked by the steady progression from atmosphere-only GCMs (Manabe and Wetherald 1967) to the state-of-the-science multicomponent (i.e., atmosphere, ocean, land surface, sea ice, land ice, carbon cycle, etc.) Earth System Models used in contemporary climate assessment reports such as the IPCC AR5 (Allen *et al.* 2014) and the Fourth National Climate Assessment (USGCRP 2017). This steady march of progress, made possible by sustained resource allocation, interagency cooperation, and contemporaneous computing power advances has facilitated an increased understanding of the natural world and the influential role of human civilization on natural systems. In addition, modeling advances have led to more integrated, higher resolution, and actionable prediction capabilities, facilitating risk reduction and adaptation planning and implementation. Despite these significant advances, substantial knowledge and modeling gaps remain. For the 55.5 million citizens of the Great Lakes megaregion, the lack of a fully integrated land-lake-atmosphere modeling system has significant consequences. Without integration of these Earth system components long-range meteorological hazard prediction will remain elusive, advancement of basic and translational climate and meteorological research will remain inhibited, and decision makers will operate with potentially malinformed predictions. By building a robust, high-resolution, and integrated land-lake-atmosphere modeling system, the Great Lakes hazard prediction and climate change impact assessments can move toward more accurate and informed resource protection. In addition, the tools developed to model the Great Lakes region are likely to provide considerable and analogous benefits to other global communities adjacent to large lakes and enclosed seas (e.g., multiple lakes in Africa and Aral Sea in Asia (Sharma *et al.* 2018)).

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References:

Adam, J.C., Stephens, J.C., Chung, S.H., Brady, M.P., Evans, R.D., Kruger, C.E., Lamb, B.K., Liu, M., Stöckle, C.O., Vaughan, J.K. and Rajagopalan, K., 2015. BioEarth: Envisioning and developing a new regional earth system model to inform natural and agricultural resource management. *Climatic Change*, *129*(3-4), pp.555-571.

Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K. and Edenhofer, O., 2014. IPCC fifth assessment synthesis report-climate change 2014 synthesis report. http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT.pdf

Allinger, L.E. and Reavie, E.D., 2013. The ecological history of Lake Erie as recorded by the phytoplankton community. *Journal of Great Lakes Research*, *39*(3), pp.365-382.

Anderson, E.J., and D.J. Schwab. 2013. Predicting the oscillating bi-directional exchange flow in the Straits of Mackinac, *Journal of Great Lakes Research* 39(4):663-671 (2014).

Anderson, E.J., Schwab, D.J. and Lang, G.A., 2010. Real-time hydraulic and hydrodynamic model of the St. Clair River, Lake St. Clair, Detroit River system. *Journal of Hydraulic Engineering*, *136*(8), pp.507-518.

Angel, J.R. and Isard, S.A., 1998. The frequency and intensity of Great Lake cyclones. *Journal of Climate*, *11*(1), pp.61-71.

Arifin, R.R., James, S.C., de Alwis Pitts, D.A., Hamlet, A.F., Sharma, A. and Fernando, H.J., 2016. Simulating the thermal behavior in Lake Ontario using EFDC. *Journal of Great Lakes Research*, *42*(3), pp.511-523.

Assel, R.A., 2003. *NOAA Atlas: An Electronic Atlas of Great Lakes Ice Cover, Winters 1973-2002*. Great Lakes Environmental Research Laboratory.

Austin, J.A. and Colman, S.M., 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. *Geophysical Research Letters*, *34*(6).

Bai, X., Wang, J., Schwab, D.J., Yang, Y., Luo, L., Leshkevich, G.A. and Liu, S., 2013. Modeling 1993–2008 climatology of seasonal general circulation and thermal structure in the Great Lakes using FVCOM. *Ocean Modelling*, *65*, pp.40-63.

Bard, L. and D.A.R. Kristovich, 2012: Trend reversal in Lake Michigan contribution to snowfall. *J. Appl. Meteorol. Climatol*., 51, 2038-2046.

Beaulieu, J.J., Tank, J.L., Hamilton, S.K., Wollheim, W.M., Hall, R.O., Mulholland, P.J., Peterson, B.J., Ashkenas, L.R., Cooper, L.W., Dahm, C.N. and Dodds, W.K., 2011. Nitrous oxide emission from denitrification in stream and river networks. *Proceedings of the National Academy of Sciences*, *108*(1), pp.214-219.

Beletsky, D., Hawley, N. and Rao, Y.R., 2013. Modeling summer circulation and thermal structure of Lake Erie. *Journal of Geophysical Research: Oceans*, *118*(11), pp.6238-6252.

Beletsky, D., Schwab, D. and McCormick, M., 2006. Modeling the 1998–2003 summer circulation and thermal structure in Lake Michigan. *Journal of Geophysical Research: Oceans*, *111*(C10).

Bennington, V., Notaro, M. and Holman, K.D., 2014. Improving climate sensitivity of deep lakes within a regional climate model and its impact on simulated climate. *Journal of Climate*, *27*(8), pp.2886-2911.

Blanken, P.D., Spence, C., Hedstrom, N. and Lenters, J.D., 2011. Evaporation from Lake Superior: 1. Physical controls and processes. *Journal of Great Lakes Research*, *37*(4), pp.707-716.

Braham, R. R., Jr., and R. D. Kelly, 1982: Lake-effect snow storms on Lake Michigan, U.S.A. Cloud Dynamics, E. M. Agee and T. Asai, Eds., D. Reidel, 87–101.

Brooks, B.W., Lazorchak, J.M., Howard, M.D., Johnson, M.V.V., Morton, S.L., Perkins, D.A., Reavie, E.D., Scott, G.I., Smith, S.A. and Steevens, J.A., 2016. Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems?. *Environmental toxicology and chemistry*, *35*(1), pp.6-13.

Bunnell, D.B., Barbiero, R.P., Ludsin, S.A., Madenjian, C.P., Warren, G.J., Dolan, D.M., Brenden, T.O., Briland, R., Gorman, O.T., He, J.X. and Johengen, T.H., 2013. Changing ecosystem dynamics in the Laurentian Great Lakes: bottom-up and top-down regulation. *BioScience*, *64*(1), pp.26-39.

Byun, K. and Hamlet, A.F., 2018. Projected changes in future climate over the Midwest and Great Lakes region using downscaled CMIP5 ensembles. *International Journal of Climatology*. doi:10.1002/joc.5388.

Carpenter, S.R., Booth, E.G. and Kucharik, C.J., 2017. Extreme precipitation and phosphorus loads from two agricultural watersheds. *Limnology and Oceanography*. doi:10.1002/lno.10767.

Clark, C.A., T.J. Elless, A.W. Lyza, B. Ganesh-Babu, D.M. Koning, A.R. Carne, H.A. Boney, A.M. Sink, S.K. Mustered, and J.M. Barrick, 2016: Spatiotemporal Snowfall Variability in the Lake Michigan Region: How is Warming Affecting Wintertime Snowfall? *J. Appl. Meteorol. Climatol*., 55 (8), 1813-1830.

Crétaux, J.F., Jelinski, W., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., Gennero, M.C., Nino, F., Del Rio, R.A., Cazenave, A. and Maisongrande, P., 2011. SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in space research*, *47*(9), pp.1497-1507.

Changnon, S.A. and Jones, D., 1972. Review of the influences of the Great Lakes on weather. *Water Resources Research*, *8*(2), pp.360-371.

Chen, C., Beardsley, R.C. and Cowles, G., 2006. An unstructured grid, finite-volume coastal ocean model (FVCOM) system. *Oceanography*, *19*(1), pp.78-89.

Christopher SF, Mitchell MJ, McHale MR, Boyer EW, Burns DA, Kendall C. 2008. Factors controlling nitrogen release from two forested catchments with contrasting hydrochemical responses. *Hydrological Processes* 22: 46-62.

Colton, M.C., 2013. Developing a Great Lakes remote sensing community. *Journal of Great Lakes Research*, *39*, pp.6-7.

Conry, P., Sharma, A., Potosnak, M.J., Leo, L.S., Bensman, E., Hellmann, J.J. and Fernando, H.J., 2015. Chicago's heat island and climate change: bridging the scales via dynamical downscaling. *Journal of Applied Meteorology and Climatology*, *54*(7), pp.1430-1448.

Croley, T.E., 1989. Verifiable evaporation modeling on the Laurentian Great Lakes. *Water Resources Research*, *25*(5), pp.781-792.

Diak, G.R., Anderson, M.C., Bland, W.L., Norman, J.M., Mecikalski, J.M. and Aune, R.M., 1998. Agricultural management decision aids driven by real-time satellite data. *Bulletin of the American Meteorological Society*, *79*(7), pp.1345-1355.

Dawson, J. and Scott, D., 2010. Climate change and tourism in the great lakes region: A summary of risks and opportunities. *Tourism in Marine Environments*, *6*(2-1), pp.119-132.

DeMarchi, C., Dai, Q., Mello, M.E. and Hunter, T.S., 2009. Estimation of overlake precipitation and basin runoff uncertainty. *International Upper Great Lakes Study*.

Diffenbaugh, N.S., Pal, J.S., Trapp, R.J. and Giorgi, F., 2005. Fine-scale processes regulate the response of extreme events to global climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(44), pp.15774-15778.

Dupont, F., Chittibabu, P., Fortin, V., Rao, Y.R. and Lu, Y., 2012. Assessment of a NEMO-based hydrodynamic modelling system for the Great Lakes. *Water Quality Research Journal*, *47*(3-4), pp.198-214.

Fujisaki-Manome, A., Fitzpatrick, L.E., Gronewold, A.D., Anderson, E.J., Lofgren, B.M., Spence, C., Chen, J., Shao, C., Wright, D.M. and Xiao, C., 2017. Turbulent Heat Fluxes during an Extreme Lake Effect Snow Event. *Journal of Hydrometeorology*, (2017).

Fujisaki, A., Wang, J., Bai, X., Leshkevich, G. and Lofgren, B., 2013. Model-simulated interannual variability of Lake Erie ice cover, circulation, and thermal structure in response to atmospheric forcing, 2003–2012. *Journal of Geophysical Research: Oceans*, *118*(9), pp.4286-4304.

Gerbush, M.R., Kristovich, D.A. and Laird, N.F., 2008. Mesoscale boundary layer and heat flux variations over pack ice–covered Lake Erie. *Journal of Applied Meteorology and Climatology*, *47*(2), pp.668-682.

Goodspeed, R., Riseng, C., Wehrly, K., Yin, W., Mason, L. and Schoenfeldt, B., 2016. Applying design thinking methods to ecosystem management tools: Creating the Great Lakes Aquatic Habitat Explorer. *Marine Policy*, *69*, pp.134-145.

Goyette, S., McFarlane, N.A. and Flato, G.M., 2000. Application of the Canadian Regional Climate Model to the Laurentian Great Lakes region: Implementation of a lake model. *Atmosphere-Ocean*, *38*(3), pp.481-503.

Gronewold, A.D. and Fortin, V., 2012. Advancing Great Lakes hydrological science through targeted binational collaborative research. *Bulletin of the American Meteorological Society*, *93*(12), pp.1921-1925.

Gronewold, A.D. and Stow, C.A., 2014a. Water loss from the Great Lakes. *Science*, *343*(6175), pp.1084-1085.

Gronewold, A.D. and Stow, C.A., 2014b. Unprecedented seasonal water level dynamics on one of the Earth's largest lakes. *Bulletin of the American Meteorological Society*, *95*(1), pp.15-17.

Gronewold, A.D., Fortin, V., Lofgren, B., Clites, A., Stow, C.A. and Quinn, F., 2013. Coasts, water levels, and climate change: A Great Lakes perspective. *Climatic Change*, *120*(4), pp.697-711.

Gu, H., Jin, J., Wu, Y., Ek, M.B. and Subin, Z.M., 2015. Calibration and validation of lake surface temperature simulations with the coupled WRF-lake model. *Climatic Change*, *129*, pp.471-483.

Gula, J. and Peltier, W.R., 2012. Dynamical downscaling over the Great Lakes basin of North America using the WRF regional climate model: the impact of the Great Lakes system on regional greenhouse warming. *Journal of Climate*, *25*(21), pp.7723-7742.

Haines A, Kovats RS, Campbell-Lendrum D, Corvalan C. 2006. Climate change and human health: impacts, vulnerability and public health. Public Health 120:585–596.

Hamrick, J.M., 2007. The environmental fluid dynamics code: theory and computation. *US EPA, Fairfax, VA*, pp.10-15.

Hartnett, J.J., Collins, J.M., Baxter, M.A. and Chambers, D.P., 2014. Spatiotemporal snowfall trends in central New York. *Journal of Applied Meteorology and Climatology*, *53*(12), pp.2685-2697.

Hayhoe K, VanDorn J, Croley II T., Schlegal N, Wuebbles D. 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research* 26: 7-21.

Hostetler, S.W. and Bartlein, P.J., 1990. Simulation of lake evaporation with application to modeling lake level variations of Harney-Malheur Lake, Oregon. *Water Resources Research*, *26*(10), pp.2603-2612.

Huang, A., Rao, Y.R. and Lu, Y., 2010. Evaluation of a 3-D hydrodynamic model and atmospheric forecast forcing using observations in Lake Ontario. *Journal of Geophysical Research: Oceans*, *115*(C2).

Ji, Z.G., 2017. *Hydrodynamics and water quality: modeling rivers, lakes, and estuaries*. John Wiley & Sons.

Keeley, M., Koburger, A., Dolowitz, D.P., Medearis, D., Nickel, D. and Shuster, W., 2013. Perspectives on the use of green infrastructure for stormwater management in Cleveland and Milwaukee. *Environmental management*, *51*(6), pp.1093-1108.

Kelly, S.A., Takbiri, Z., Belmont, P. and Foufoula-Georgiou, E., 2017. Human amplified changes in precipitation–runoff patterns in large river basins of the Midwestern United States. *Hydrology and Earth System Sciences*, *21*(10), p.5065.

Kerkez, B., Gruden, C., Lewis, M., Montestruque, L., Quigley, M., Wong, B., Bedig, A., Kertesz, R., Braun, T., Cadwalader, O. and Poresky, A., 2016. Smarter stormwater systems. *Environmental Science & Technology* **2016** *50* (14), 7267-7273. don: 10.1021/acs.est.5b05870.

Kessler, R., 2011. Stormwater strategies: cities prepare aging infrastructure for climate change. *Environmental health perspectives*, *119*(12), p.a514.

Kitchen, N.R., 2008. Emerging technologies for real-time and integrated agriculture decisions. *Computers and Electronics in Agriculture*, *61*(1), pp.1-3.

Kling, G.W., Hayhoe, K., Johnson, L.B., Magnuson, J.J., Polasky, S., Robinson, S.K., Shuter, B.J., Wander, M.M., Wuebbles, D.J. and Zak, D.R., 2003. Confronting climate change in the Great Lakes region.

Kristovich, D.A., Clark, R.D., Frame, J., Geerts, B., Knupp, K.R., Kosiba, K.A., Laird, N.F., Metz, N.D., Minder, J.R., Sikora, T.D. and Steenburgh, W.J., 2017. The Ontario winter lake-effect systems field campaign: scientific and educational adventures to further our knowledge and prediction of lake-effect storms. *Bulletin of the American Meteorological Society*, *98*(2), pp.315-332.

Kristovich, D.A., Young, G.S., Verlinde, J., Sousounis, P.J., Mourad, P., Lenschow, D., Rauber, R.M., Ramamurthy, M.K., Jewett, B.F., Beard, K. and Cutrim, E., 2000. The Lake—Induced Convection Experiment and the Snowband Dynamics Project. *Bulletin of the American Meteorological Society*, *81*(3), pp.519-542.

Kunkel, K.E., Easterling, D.R., Redmond, K. and Hubbard, K., 2003. Temporal variations of extreme precipitation events in the United States: 1895–2000. *Geophysical research letters*, *30*(17).

Kunkel, K.E., Easterling, D.R., Kristovich, D.A., Gleason, B., Stoecker, L. and Smith, R., 2012. Meteorological causes of the secular variations in observed extreme precipitation events for the conterminous United States. *Journal of Hydrometeorology*, *13*(3), pp.1131-1141.

Kunkel, K.E., Pielke Jr, R.A. and Changnon, S.A., 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society*, *80*(6), pp.1077-1098.

Laird, N.F. and Kristovich, D.A., 2002. Variations of sensible and latent heat fluxes from a Great Lakes buoy and associated synoptic weather patterns. *Journal of Hydrometeorology*, *3*(1), pp.3-12.

Liu, C., K. Ikeda, R. Rasmussen, M. Barlage, A. Newman, A. Prein**,** F. Chen, L. Chen, M. Clark, A. Dai, J. Dudhia, T. Eidhammer, D. Gochis, E. Gutman, S. Kurkute, Y. Li, G. Thompson, and D. Yates, 2016: Continental-Scale Convection-Permitting Modeling of the Current and Future Climate of North America. *Climate Dynamic, doi:10.1007/s00382-016-3327-9.*

Lofgren, B.M. and Rouhana, J., 2016. Physically Plausible Methods for Projecting Changes in Great Lakes Water Levels under Climate Change Scenarios. *Journal of Hydrometeorology*, *17*(8), pp.2209-2223.

Lofgren, B.M., 2004. A model for simulation of the climate and hydrology of the Great Lakes basin. *Journal of Geophysical Research: Atmospheres*, *109*(D18).

Lofgren, B.M., Quinn, F.H., Clites, A.H., Assel, R.A., Eberhardt, A.J. and Luukkonen, C.L., 2002. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. *Journal of Great Lakes Research*, *28*(4), pp.537-554.

Long, Z., Perrie, W., Chassé, J., Brickman, D., Guo, L., Drozdowski, A. and Hu, H., 2016. Impacts of climate change in the Gulf of St. Lawrence. *Atmosphere-Ocean*, *54*(3), pp.337-351.

Lubchenco, J. and Sutley, N., 2010. Proposed US policy for ocean, coast, and Great Lakes stewardship. *Science*, *328*(5985), pp.1485-1486.

MacKay, M.D., Verseghy, D.L., Fortin, V. and Rennie, M.D., 2017. Wintertime Simulations of a Boreal Lake with the Canadian Small Lake Model. *Journal of Hydrometeorology*, (2017).

Mallard, M.S., Nolte, C.G., Bullock, O.R., Spero, T.L. and Gula, J., 2014. Using a coupled lake model with WRF for dynamical downscaling. *Journal of Geophysical Research: Atmospheres*, *119*(12), pp.7193-7208.

Mallard, M.S., Nolte, C.G., Spero, T.L., Bullock, O.R., Alapaty, K., Herwehe, J.A., Gula, J. and Bowden, J.H., 2015. Technical challenges and solutions in representing lakes when using WRF in downscaling applications. Geoscientific Model Development, 8(4), p.1085.

Manabe, S. and Wetherald, R.T., 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *Journal of the Atmospheric Sciences*, *24*(3), pp.241-259.

Mason, L.A., Riseng, C.M., Gronewold, A.D., Rutherford, E.S., Wang, J., Clites, A., Smith, S.D. and McIntyre, P.B., 2016. Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. *Climatic Change*, *138*(1-2), pp.71-83.

Michalak, A.M., Anderson, E.J., Beletsky, D., Boland, S., Bosch, N.S., Bridgeman, T.B., Chaffin, J.D., Cho, K., Confesor, R., Daloğlu, I. and DePinto, J.V., 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences*, *110*(16), pp.6448-6452.

Millerd, F., 2011. The potential impact of climate change on Great Lakes international shipping. *Climatic Change*, *104*(3), pp.629-652.

Mironov, D., Rontu, L., Kourzeneva, E. and Terzhevik, A., 2010. Towards improved representation of lakes in numerical weather prediction and climate models: Introduction to the special issue of *Boreal Environment Research*, 15, 97–99.

Mueller, N.D., Butler, E.E., McKinnon, K.A., Rhines, A., Tingley, M., Holbrook, N.M. and Huybers, P., 2016. Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, *6*(3), p.317.

Norton, D.C. and Bolsenga, S.J., 1993. Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great Lakes, 1951–1980. *Journal of Climate*, *6*(10), pp.1943-1956.

Notaro, M., Zarrin, A., Vavrus, S. and Bennington, V., 2013. Simulation of Heavy Lake-Effect Snowstorms across the Great Lakes Basin by RegCM4: Synoptic Climatology and Variability*,+. *Monthly Weather Review*, *141*(6), pp.1990-2014.

Ntelekos, A.A., Oppenheimer, M., Smith, J.A. and Miller, A.J., 2010. Urbanization, climate change and flood policy in the United States. *Climatic Change*, *103*(3-4), pp.597-616.

Patz, J. A., Campbell-Lendrum, D., Holloway, T., & Foley, J. A. (2005). Impact of regional climate change on human health. *Nature*, *438*(7066), 310-317.

Patz, J.A., Vavrus, S.J., Uejio, C.K. and McLellan, S.L., 2008. Climate change and waterborne disease risk in the Great Lakes region of the US. *American journal of preventive medicine*, *35*(5), pp.451-458.

Patz, J.A., Frumkin, H., Holloway, T., Vimont, D.J. and Haines, A., 2014a. Climate change: challenges and opportunities for global health. *Jama*, *312*(15), pp.1565-1580.

Patz, J.A., Grabow, M.L. and Limaye, V.S., 2014b. When it rains, it pours: future climate extremes and health. *Annals of global health*, *80*(4), pp.332-344.

Pierce, B., Kaleel, R., Dickens, A., Bertram, T., Stanier, C., Kenski, D., 2017. White Paper: Lake Michigan Ozone Study 2017 (LMOS 2017).
http://www.ladco.org/reports/ozone/post08/Great_Lakes_Ozone_Study_White_Paper_Draft_v6.pdf

Ray, D.K., Mueller, N.D., West, P.C. and Foley, J.A., 2013. Yield trends are insufficient to double global crop production by 2050. *PloS one*, *8*(6), p.e66428.

Royer TV, David MB, Gentry LE. 2006. Timing of riverine export of nitrate and phosphorus from agricultural watersheds in Illinois: implications for reducing nutrient loading to the Mississippi River. *Environmental Science & Technology* 40: 4126–4131.

Royer TV, Tank JL, David MB. 2004. Transport and fate of nitrate in headwater agricultural streams in Illinois. *Journal of Environmental Quality* 33: 1296–1304.

Schoof, J.T., 2013. Historical and projected changes in human heat stress in the Midwestern USA. In: *Climate Change in the Midwest: Impacts, Risks, Vulnerability, and Adaptation*, S.C. Pryor, ed., Indiana University Press, 146-157.

Sharma, A., Conry, P., Fernando, H.J.S., Hamlet, A.F., Hellmann, J.J. and Chen, F., 2016. Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: evaluation with a regional climate model. *Environmental Research Letters*, *11*(6), p.064004.

Sharma, A., Fernando, H.J., Hamlet, A.F., Hellmann, J.J., Barlage, M. and Chen, F., 2017. Urban meteorological modeling using WRF: a sensitivity study. *International Journal of Climatology*. doi: 10.1002/joc.4819.

Sharma, A., Huang, H.P., Zavialov, P. and Khan, V., 2018. Impact of Desiccation of Aral Sea on the Regional Climate of Central Asia Using WRF Model. *Pure and Applied Geophysics*, *175*(1), pp.465-478.

Sierszen, M.E., Morrice, J.A., Trebitz, A.S. and Hoffman, J.C., 2012. A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes. *Aquatic ecosystem health & management*, *15*(1), pp.92-106.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Wang, W. and Powers, J.G., 2005. A description of the Advanced WRF Version 2. *National Center for Atmospheric Research, Boulder, CO, Technical Note No. NCAR/TN-468+ STR*.

Spence, C., Blanken, P.D., Hedstrom, N., Fortin, V. and Wilson, H., 2011. Evaporation from Lake Superior: 2: Spatial distribution and variability. *Journal of Great Lakes Research*, *37*(4), pp.717-724.

Spence, C., Blanken, P.D., Lenters, J.D. and Hedstrom, N., 2013. The importance of spring and autumn atmospheric conditions for the evaporation regime of Lake Superior. *Journal of Hydrometeorology*, *14*(5), pp.1647-1658.

Stepanenko, V.M., Goyette, S., Martynov, A., Perroud, M., Fang, X. and Mironov, D., 2010. First steps of a Lake Model intercomparison project: LakeMIP. *Boreal environment research*, *15*, pp.191-202.

Subin, Z.M., Riley, W.J. and Mironov, D., 2012. An improved lake model for climate simulations: model structure, evaluation, and sensitivity analyses in CESM1. *Journal of Advances in Modeling Earth Systems*, *4*(1).

Suriano, Z.J. and D.J. Leathers, 2017: Synoptically classified lake-effect snowfall trends to the lee of Lakes Erie and Ontario. *Climate Res*. 74:1, 1-13.

Todorovich, P., 2009. America's emerging megaregions and implications for a national growth strategy. *International Journal of Public Sector Management*, *22*(3), pp.221-234.

Van Cleave, K., Lenters, J.D., Wang, J. and Verhamme, E.M., 2014. A regime shift in Lake Superior ice cover, evaporation, and water temperature following the warm El Niñ winter of 1997–1998. *Limnology and Oceanography*, *59*(6), pp.1889-1898.

Verhougstraete, M.P., Byappanahalli, M.N., Rose, J.B. and Whitman, R.L., 2010. Cladophora in the Great Lakes: impacts on beach water quality and human health. *Water Science and Technology*, *62*(1), pp.68-76.

Wall, G., 1998. Implications of global climate change for tourism and recreation in wetland areas. *Climatic change*, *40*(2), pp.371-389.

Wang, J., Bai, X., Hu, H., Clites, A., Colton, M. and Lofgren, B., 2012. Temporal and spatial variability of Great Lakes ice cover, 1973–2010. *Journal of Climate*, *25*(4), pp.1318-1329.

Wang, J., Hu, H., Schwab, D., Leshkevich, G., Beletsky, D., Hawley, N. and Clites, A., 2010. Development of the Great Lakes ice-circulation model (GLIM): application to Lake Erie in 2003–2004. *Journal of Great Lakes Research*, *36*(3), pp.425-436.

Wang, J., V. R. Kotamarthi, 2014. Downscaling with a nested regional climate model in near-surface fields over the contiguous United States. Journal of Geophysical Research 119(14): 8778–8797. DOI: 10.1002/2014JD021696.

Wang, X., G. Huang, and J. Liu, 2014. Projected increases in intensity and frequency of rainfall extremes through a regional climate modeling approach, *Journal of Geophysical Research Atmospheres*, 119, 13,271–13,286, doi:10.1002/2014JD022564.

Watson, S.B., Miller, C., Arhonditsis, G., Boyer, G.L., Carmichael, W., Charlton, M.N., Confesor, R., Depew, D.C., Höök, T.O., Ludsin, S.A. and Matisoff, G., 2016. The re-eutrophication of Lake Erie: harmful algal blooms and hypoxia. *Harmful Algae*, *56*, pp.44-66.

Weaver, C.P., Lempert, R.J., Brown, C., Hall, J.A., Revell, D. and Sarewitz, D., 2013. Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews: Climate Change*, *4*(1), pp.39-60.

Winkler, J.A., Arritt, R.W. and Pryor, S.C., 2012. Climate projections for the midwest: availability, interpretation and synthesis. *US National Climate Assessment Midwest Technical Input Report*.

Winters, B.A., Angel, J.R., Ballerine, C., Byard, J.L., Flegel, A., Gambill, D., Jenkins, E., McConkey, S.A., Markus, M., Bender, B.A. and O'Toole, M.J., 2015. *Report for the urban flooding awareness act*. Illinois Department of Natural Resources. https://www.dnr.illinois.gov/waterresources/documents/final_ufaa_report.pdf

Workoff, T.E., Kristovich, D.A., Laird, N.F., LaPlante, R. and Leins, D., 2012. Influence of the Lake Erie overlake boundary layer on deep convective storm evolution. *Weather and Forecasting*, *27*(5), pp.1279-1289.

Wuebbles, D.J. and Hayhoe, K., 2004. Climate change projections for the United States Midwest. *Mitigation and Adaptation Strategies for Global Change*, *9*(4), pp.335-363.

Wuebbles, D.J., Hayhoe, K. and Parzen, J., 2010. Introduction: Assessing the effects of climate change on Chicago and the Great Lakes.

USGCRP, Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 470, 2017.

Xiao, C., Lofgren, B.M., Wang, J. and Chu, P.Y., 2016. Improving the lake scheme within a coupled WRF-lake model in the Laurentian Great Lakes. *Journal of Advances in Modeling Earth Systems*, *8*(4), pp.1969-1985.

Xue, P., Pal, J.S., Ye, X., Lenters, J.D., Huang, C. and Chu, P.Y., 2017. Improving the Simulation of Large Lakes in Regional Climate Modeling: Two-Way Lake–Atmosphere Coupling with a 3D Hydrodynamic Model of the Great Lakes. *Journal of Climate*, *30*(5), pp.1605-1627.

Xue, P., Schwab, D.J. and Hu, S., 2015. An investigation of the thermal response to meteorological forcing in a hydrodynamic model of Lake Superior. *Journal of Geophysical Research: Oceans*, *120*(7), pp.5233-5253.

Zobel, Z., Wang, J., Wuebbles, D.J. and Kotamarthi, V.R., 2017. High-Resolution Dynamical Downscaling Ensemble Projections of Future Extreme Temperature Distributions for the United States. *Earth's Future*.

Zobel, Z., Wang, J., Wuebbles, D.J. and Kotamarthi, V.R., 2018. Evaluations of high-resolution dynamically downscaled ensembles over the contiguous United States. *Climate Dynamics*, *50*(3-4), pp.863-884.