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Large lakes in climate models: A Great Lakes case study on the usability of CMIP5

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ABSTRACT

Large lakes have an impact on regional weather. In addition, they can be both sensitive to and influence regional climate changes. In the climate models that are used to investigate future climate changes, lakes are greatly simplified and sometimes absent. At the regional scale, this can have strong implications for the quality of the model information about the future. Through our work with climate information users in the Laurentian Great Lakes region, we have found that basic credibility of the information requires the underlying climate models simulate lake-atmosphere-land interactions. We are not aware of efforts within the scientific community to make known how individual large lakes are represented in models and how those representations translate to the quality of the data for particular regions. We share our framework for identifying how the Laurentian Great Lakes are represented in the Coupled Model Intercomparison Project (CMIP) version 5 climate models. We found that most CMIP5 models do not simulate the Great Lakes in a way that captures their impact on the regional climate, which is a credibility issue for their projections. We provide a perspective on the usability of CMIP5 for practitioners in the Great Lakes region and offer recommendations for alternative options.

Introduction

Large lakes can have significant impacts on regional and local climates, generating much different weather and climate conditions than if lakes were not present. In lake-atmosphere-land systems, local energy (i.e., heat) and hydrologic cycles are modified as conditions at the lake surface interact with the overlying atmosphere and nearby land surfaces. Temperature differences between the lake surface and overlying air drive lake effects such as lake breezes and enhanced lake-effect precipitation. The role of large lakes in, for example, water supply budgets, commerce, and ecosystems are directly related to the behavior of the lake-atmosphere-land system.

Large lakes have also played a role in driving past, and potentially future, climate changes. Their large volume, thermal inertia, and surface area are factors that contribute to their ability to influence climate changes (Xue et al., 2017). Lake surface temperatures, air temperatures, evaporation, precipitation, and lake ice cover are tightly coupled, and a change in any of these variables influences the others. Spence et al. (2013) demonstrate how a lake's heat storage, ice cover, and evaporation can be dependent upon atmospheric conditions at specific times of the year, which emphasizes the importance of two-way lake-atmosphere coupling.

Recent observations for the Laurentian Great Lakes emphasize the non-linear climate response of the lakes and interconnections of lake-atmosphere interactions. For example, Lake Superior surface waters have warmed more rapidly than nearby air temperatures (Austin and Colman, 2007; Zhong et al., 2018, 2016). Similarly, lake surface temperature warming has been observed worldwide (O'Reilly et al., 2015). van Cleave et al. (2014) characterizes the recent decline in Great Lakes ice cover as having undergone a non-linear "regime shift" starting in 1998, which has yet to be fully understood or explained but coincided with a strong ENSO event. Zhong et al. (2016) outline the competing roles of decreasing ice cover: less ice cover 1) lowers the surface albedo and allows for greater absorption (i.e., raises the surface temperature), and 2) decreases the amount of insulation and allows greater heat loss (i.e., lowers the surface temperature). Each of these findings point to the complexity of lake-atmosphere interactions.

From the perspective of the global climate modeler, the effects of lakes are small, and the inclusion of lakes adds complexity and cost. The combination of small global effects and complexity costs often lower the priority of improved representation of lakes in glo-

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bal models. Lakes are, therefore, either completely absent from or simplified in their representation within global climate models. In early climate models the spatial resolution was so coarse that only the largest lakes might appear. Over time, lakes were included as a land type, sometimes only as wet soil or wetland. More recently, some global models simulate the thermal characteristics of lakes by representing heat transfer in a water column (1D lake models). To represent the regional lake-atmosphere interactions, there is a need for 3D modeling of hydrodynamic processes to represent a lake's physical characteristics, especially those of deep lakes (Gula and Peltier, 2012; Xue et al., 2017).

In our work, it is important to distinguish between grid spacing, resolution, and representation of the Great Lakes. Below, our criteria will include a requirement for a grid spacing that is 1- degree of latitude (order, 100 km), or finer, to represent the Great Lakes. At this grid spacing, the parameterizations of the model are designed to simulate bulk surface exchanges of heat, moisture, and momentum stress.

Though the grid spacing of a model is often referred to as the model resolution, the resolution of atmospheric and lake dynamics requires multiple grid cells. Thus, the effective resolution, the smallest spatial scale that is fully resolved, is up to an order of magnitude larger than the grid cell spacing; that is, a scale of 10 times the grid spacing (Kent et al., 2014). If one considers regional effects such as lake effect snow, great benefit in simulation is achieved at 3-km grid spacing (Fujisaki-Manome et al., 2020). However, one can argue that grid cells of considerably <1 km are required. Though some attributes of the physics are represented at a 1-degree grid spacing, neither atmospheric nor lake dynamics can be stated to be resolved. In none of the global models should the "representation" of lakes be confused with the "resolution" of lake processes.

Climate models have found an audience in those planning adaptation strategies; that is, practitioners (Barsugli et al., 2013). From our experiences as a regional climate information provider, practitioners are not necessarily aware of the challenges in representing large lakes in climate models, and they are surprised to learn that some models do not simulate lakes. This finding can impact their trust in the model information about the future when lakes and lake-effects are missing. The practitioners know how important the lakes are to regional and local weather patterns and variability; hence, the credibility of the model information becomes suspect. There is a need to communicate lake and lake-effect information about the models to practitioners during the process of selecting climate projections for adaptation planning.

Here, we focus on a widely used set of global climate models (GCMs), from the Coupled Model Intercomparison Project (CMIP) version 5 (Taylor et al., 2012). We focus on CMIP Version 5 because those data were available at the time of this research, but our methods also apply to Version 6 (CMIP6). CMIP6 data are currently being produced and distributed. In addition, many climate information products are currently built on CMIP5, so our results will remain valid for users relying on CMIP5 even after CMIP6 is released. We discuss the barriers we faced in uncovering the treatment of large lakes in the CMIP5 models and present the framework we developed for identifying how individual large lakes are represented in CMIP5. The Laurentian Great Lakes are used as an example throughout this paper, but the underlying principles, methods, recommendations, and conclusions apply to any large lake system.

Motivation for this work

The authors of this work are climate scientists in the Great Lakes Region and are connected formally to the National Oceanographic and Atmospheric Administration (NOAA) Regional Integrated Sciences and Assessments (RISA) program for the Great Lakes Region (The Great Lakes Integrated Sciences and Assessments, or GLISA). A large part of GLISA's work is communicating the limitations and uncertainty of climate data for informed decision making. Climate models are the primary source of quantitative future climate information GLISA provides. GLISA's Great Lakes Ensemble project (glisa.umich.edu/projects/great-lakes-ensemble) is focused on climate model evaluation and analysis for the region. GLISA leverages the expertise of a scientific advisory committee composed of regional climate modelers and a separate stakeholder working group to inform their evaluation and communication of model information. The investigation into the treatment of large lakes in climate models is a critical piece of model evaluation. Given the importance of the Great Lakes as a regional climate driver, there is a strong need to evaluate: 1) if the climate models we rely on include large lakes, 2) how well lake properties (e.g., surface temperatures, ice cover) and lake effects (e.g., lake-effect precipitation) are simulated, and 3) if the models capture historical climate-driven lake trends (e.g., ice cover declines). Here we focus on the first component—determining whether a model has large lakes. The other two components are part of GLISA's future work.

From the point of view of a climate scientist, we realize that the question of interest is, once identified, whether or not we can establish quantitative differences in the Great Lakes regional climate of CMIP5 models dependent on their representation of the lakes. This will be the subject of future studies. The question of interest here is about the usability of climate science in planning and management. Namely, in social science research on usability, it is necessary to establish trust with the practitioner community. Cash et al. (2003) maintain that there are three primary criteria at the foundation of usability: legitimacy, credibility, and salience. The presence or absence of a lake representation in the models is an indicator of scientific adequacy, i.e. credibility, and relevance to the application, i.e. salience. It is difficult to maintain credibility and salience to a regional expert who has the experience of managing in the presence of large, local lake effects. Hence, this paper addresses the science of the usability of climate projections, a central issue in our response to climate change (see also, Dilling and Lemos, 2011; Lemos and Rood, 2010).

Background

Global climate models (GCMs) are constructed by coupling together individual component models, for example, an atmosphere, land, ocean, and ice sheet model (e.g., Gettelman and Rood, 2016). These component models are made up of coupled sub-components. Lakes are often smaller than the spatial scales represented in models (except for very large lakes, like the Great Lakes), and only in the recent generations of CMIP climate models are efforts made to resolve lakes explicitly. Lakes, therefore, are often included as a sub-component of a component model. One possible configuration, where lakes are a sub-component of the land model, is represented in Fig. 1.

For our applications, credible lake representations should include accurate transfers of water, heat, and momentum at the interfaces of component models in correct geographical locations. Because most models do not have an explicit lake component, logically, lakes might appear as a water body within the ocean model or as a water surface type in the land model. Within the ocean model, lakes might be resolved explicitly, meaning that lake dynamics are represented. When lakes are contained within the land model, it is more likely that the bulk thermodynamics of surface exchanges are represented (Bonan et al., 2002).

To the authors' knowledge, there is no published work documenting the exact treatment of large lakes in specific CMIP5 GCMs.

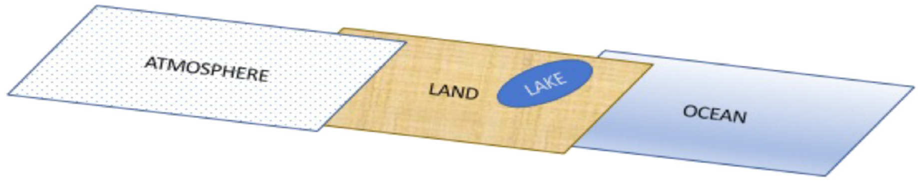


Fig. 1. Example depiction of climate model components where lakes are represented as a surface type within the land component.

Previous studies confirm the general difficulty of GCMs to represent the Great Lakes (Basile et al., 2017; Notaro et al., 2015a, 2014) because of low spatial resolution and missing lake dynamics, and in some cases specific models are critiqued. However, more detailed guidance is required for users wishing to hand select models based on specific lake criteria. Hence, we have undertaken the task of describing the treatment of the Great Lakes in more detail here. In addition to a lack of information on the scientific attributes of lakes in GCMs, there is not a complete and coherent representation of the treatment of lakes in metadata describing the models. Here we address this information gap by providing our methodology for identifying large lakes in GCMs. We applied our methodology to finding the Laurentian Great Lakes (Fig. 2).

Data

Our framework for finding large lakes in GCMs is applied to one of the largest, most widely used and publicly available GCM data sets, CMIP5 (released in 2011). CMIP is a global, coordinated effort to standardize the approach to climate model simulations, model output, and model metadata for research. The CMIP simulations have been widely adopted for real-world applications. There are 61 GCMs that make up the CMIP5 collection; however, the World Data Center for Climate (https://cera-www.dkrz.de/WDCC/ui/cera-search/) where we accessed the data had only 39 models with all of the output required for our analysis. Our results focus on these 39 models (Table 1).

Start-up barriers

Uncovering the treatment of large lakes in the CMIP5 models was not a straightforward or simple process. They are important to regional and local climate, but their specification and description are not central to global climate model performance. The first order question is whether or not lakes are represented in a particular model. If a model includes lakes, the follow-up question becomes whether or not the particular lake(s) of interest are present.

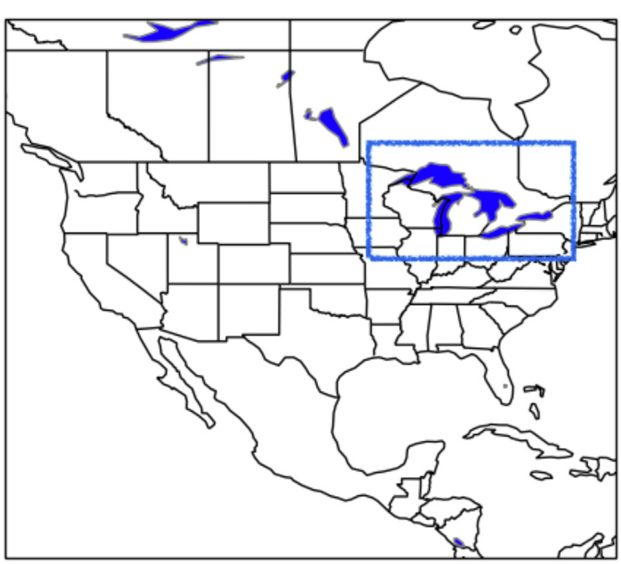


Fig. 2. Map of Laurentian Great Lakes (blue) inside blue rectangle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The most logical approach to learning about a model is to consult its documentation. In our efforts to find documentation for all 39 models, it became clear that this was going to be an arduous process. We learned there was a need to know the "language" of model developers, for example, that lakes are sometimes a type of "land". We consulted with experts, who provided valuable entry into the field (Rood and Edwards, 2014). However, to identify experts from each modeling group was not practical.

Once we knew that lake simulations were typically performed within the land component of each GCM, we searched each modeling group's website for descriptions of their land models. At best, a report documenting the model was available, but lake information was rarely mentioned. When documentation was not found, further literature searches were conducted to look for publications describing the model. This led to varying levels of success, with limited details about the treatment of lakes and minimal to no information about particular lakes.

One effort, Earth System Documentation (ES-DOC, https://www.earthsystemcog.org/projects/es-doc-models/), has the potential to eliminate these start-up barriers, but was designed primarily for experts who develop models or perform simulations using the models (Pascoe et al., 2020), not for the local decision makers who ultimately want to use the model data in their planning. ES-DOC is a collection of structured model metadata in one online location and offers the ability for users to quickly find details about specific components of a model, like lakes. Users still need to know to look within the "Land Surface" component to find lake information, but the list of component options is not too long to comb through. Basic lake properties, like lake dynamics (e.g., "vertical") and ice treatment (e.g., "No") offer a starting point but lack the level of detail required for a user who needs to verify the simulation credibility of specific lakes. In our use of ES-DOC, we found little helpful information about lake properties for the CMIP5 models. We do note that more thorough documentation is requested for lakes in CMIP6 (CMIP6 Specializations Viewer), but to date many models have not been added.

Altogether, this process of determining how large lakes are treated in the CMIP5 GCMs took over two years for us to complete as climate experts. This is arguably too lengthy of a process to receive timely information for real-world data selection in decision making. Taking lessons learned from this process, we developed the following approach that uses standardized model output as much as possible (because these data are typically accessible and easily compared across models) and cuts down on the need for extensive model documentation review. Using our approach, it is possible to categorize models into three main categories: 1) models that do not simulate large lakes; 2) models that simulate large lakes as oceans; and 3) models that simulate large lakes using a lake model.

Table 1
Treatment of the Laurentian Great Lakes in CMIP5 GCMs. Treatments include GCMs that simulate lake dynamics (blue), GCMs that crudely represent lakes (orange), and GCMs that do not simulate lakes by our credibility standard (red). Further description of these categories is available in the table.

Key: y = yes | n = no | NK = not known from the found documentation

Model	Atmos. Component Spatial Resolution (lat x lon)	All Five Great Lakes are Present	Lake/sea ice is simulated	Vertical lake dynamics are simulated	Land Component Name	Lake Classification Dataset/Notes	References
These models simulate lake-atmosphere feedbacks and vertical fluxes (horizontal fluxes vary by model). Further evaluation is required to know if the simulated lake dynamics are realistic for the Great Lakes. These models meet our first-order credibility requirement.							
BCC-CSM1-1m	1.12°x1.13°	y	y	y	Atmosphere-Vegetation Interaction Model based on NCAR's Community Land Model (CLM) version 3	Percent lake and wetland derived from Cogley's (1991) 1.0° by 1.0° data. - see Fig. 1 in Coe (2000) for Cogley's map - see Fig. 4 in Zheng et al (2002) for CLM lake fractions	Yu et al (2016) Oleson et al. (2004) Zeng et al. (2001)
CCSM4	0.94°x1.25°	y	y	y	CLM4	see CLM notes above	Kluzek (2010)
CESM1-BGC	0.94°x1.25°	y	y	y	CLM4	see CLM notes above	Kluzek (2010)
CESM1-CAM5	0.94°x1.25°	y	y	y	CLM4	see CLM notes above	Kluzek (2010)
CESM1(WAC-CM)	1.88°x2.5°	y	y	y	CLM4	see CLM notes above	Kluzek (2010)
CESM1(fast-chem)	0.94°x1.25°	y	y	y	CLM4	see CLM notes above	Kluzek (2010)
CSIRO-Mk3.6.0	1.87°x1.88°	y	y	NK	NK	see Fig. 45 in Gordon et al (2010) for map of 12 model grid cells that are Great Lakes	Gordon et al. (2010)
FGOALS-g2	2.79°x2.81°	y	y	y	CLM3	see CLM notes above	Oleson et al. (2004)
GFDL-CM3	2.00°x2.50°	y	y	y	Land Model (LM) 3	Lakes are defined by the "water body" classification in the U.S. Geological Survey (USGS) Global Land Cover Characteristics database (https://lta.cr.usgs.gov/GLCC)	Milly et a.l (2014)
GFDL-ESM2G	2.02°x2.50°	y	y	y	LM3	see LM3 notes above	Milly et al. (2014)
GFDL-ESM2M	2.02°x2.5°	y	y	y	LM3	see LM3 notes above	Milly et al. (2014)
GISS-E2-H	2.00°x2.50°	NK	y	y	SEA06	NK	Schmidt et al. (2006) Schmidt et al. (2014)
GISS-E2-H-CC	2°x2.5°	NK	y	y	SEA06	NK	Schmidt et al. (2006) Schmidt et al. (2014)
GISS-E2-R	2.00°x2.50°	NK	y	y	SEA06	NK	Schmidt et al. (2006) Schmidt et al. (2014)
MIROC5	1.40°x1.41°	NK	NK	y	Minimal Advanced Treatments of Surface Interaction and RunOff (MATSIRO)	NK	Takata et al. (2003)
MRI-CGCM3	1.12°x1.13°	NK	n	n	Hydrology, Atmosphere and Land (HAL) model	The Great Lakes are treated like a river system based on the 1° version of the Total River Integrated Pathway (TRIP)	Yokimoto et al. (2012) TRIP online: http://hydro.iis.u-tokyo.ac.jp/~taikan/T

							RIPDATA/TRIPDATA .html
NorESM1-M	1.89°x2.50°	y	y	y	CLM4	see CLM notes above	Kluzek (2010)
NorESM1-ME	1.89°x2.50°	y	y	y	CLM4	see CLM notes above	Kluzek (2010)
MIROC4h	0.56° x 0.56°	y	y	y	CCSR Ocean COmponent model (COCO)		
HadCM3	2.5°x3.75°	n	y	y	HadCM3 ocean component (HadOM3)		Gordon et al. (2000)
IPSL-CM5A-LR	1.89°x3.75°	n	y	y	Nucleus for European Modelling of the Ocean (NEMO)		Dufresne et al. (2013)
IPSL-CM5A-MR	1.27°x2.50°	n	y	y	NEMO		Dufresne et al. (2013)
IPSL-CM5B-LR	1.89°x3.75°	n	y	y	NEMO		Dufresne et al. (2013)
These models treat lakes as a water surface, but do not include lake dynamics. These models do not meet our credibility requirement.							
ACCESS 1.0	1.25°x1.88°	NK	n	n	MOSES		Collier and Uhe (2012) Rooney et al. (2006)
BNU-ESM	2.79°x2.81°	NK	n	n	Common Land Model (CoLM)		Ji et al. (2014)
HadGEM2 family	1.875°×1.25°	NK	NK	n	MOSESII		Essery (2003)
There are conflicts in these models over how the lakes are geographically defined in their land and ocean components (see Table 3). Inspection of the land and ocean components revealed the case where 1) both components claim 100% responsibility for simulating surface states/fluxes over at least one Great Lake and/or 2) neither component is responsible for simulations over at least one Great Lake. These models do not meet our credibility requirement. Model documentation was not reviewed since our Decision Tree identified major inconsistencies disqualifying models from further use.							
CMCC-CESM	3.44°x3.75°	n					
CMCC-CM	0.75°x0.75°	n					
CMCC-CMS	1.86°x1.88°	n					
INM-CM4	1.50°x2.00°	n					
CanESM2	2.79°x2.81°	n					
NCEP-CFSv2	1°x1°	n					
CNRM-CM5	1.40°x1.41°	n					
EC-Earth	1.12°x1.13°	n					
MPI-ESM-LR	1.86°x1.88°	n					
These models do simulate lakes based on what was found in their documentation. These models do not meet our credibility requirement.							
ACCESS 1.3	1.25°x1.88°	n	n	n	Community Atmosphere Biosphere Land Exchange (CABLE)		Law et al. (2012)
BCC-CSM1.1	2.79°x2.81°	n	n	n	BCC_AVIM 1.0		BCC Online Land Model Description
GFDL-CM2.1	2.79°x2.81°	n	n	n	Land Model (LM) 2		Delworth et al. (2006)
MIROC-ESM	2.79°x2.81°	n	n	n	MATSIRO		Takata et al. (2003)

Methods: A decision tree for characterizing large lakes in GCMs

Because model documentation was insufficient for determining how specific large lakes are treated in CMIP5, we developed a framework using the standardized CMIP5 model output to identify which models simulate lakes in their ocean components, land components, or by our standards, not at all (Fig. 3). In addition, this framework identifies lake representations that are dynamic (meaning lake fluxes are simulated in the vertical and, in some cases, the horizontal directions) and interactive (meaning lake fluxes are coupled to other components, like the atmosphere). In the remainder of this paper, this framework is referred to as the Decision Tree.

At the top of the Decision Tree, the first step is to identify if the land component is active, or turned "on" over the Great Lakes using the land area fraction (sftlf) variable. We mapped the land area fraction values (ranging from 0% to 100%) to show what percent of each grid cell was simulated by the land component. Grid cell values of 100% indicate the surface is simulated only using the land component, which may or may not include a water surface or more sophisticated sub-component lake model.

If the land fractions over the Great Lakes in Step 1 are < 100%, then the left branch is used to determine which models treat the Great Lakes (or a subset of them) as oceans. Step 2a checks for consistency in how the surface is defined between the ocean and land components. We mapped sea surface temperatures (tos) and ice cover (sic) data to show where the ocean component was "on." Then we compared where the ocean component was "on" to where the land component was "on" from Step 1. In theory, the ocean component should only be "on" where the land fraction is <100%. It is important to point out that the land and ocean components do not necessarily have the same spatial grid resolution. In fact, they typically do not, so one is not likely the complete inverse of another.

We found cases where the ocean and land components treated lake areas differently, which we outline in our results. We take the position that inconsistencies between components leads to an incomplete representation of the lake system, which decreases the credibility of the information for practitioners. For example, if the ocean component is only active over three of the five Great Lakes, the Great Lakes system as a whole (including energy and water cycles) is misrepresented. Where there are ocean data over the Great Lakes and the land component is "off," we say the lakes are treated as dynamic and interactive oceans, because ocean components simulate vertical ocean dynamics and are coupled to the land and atmosphere components.

Going back to the top of our Decision Tree, the right-hand branch is used when the land component is "on" over the lakes. We have a number of approaches for identifying and characterizing lakes that exist within the land component. Depending on the application, it may be helpful to employ a model spatial resolution requirement to filter out models that are too coarse to provide meaningful lake information. We recommend a surface grid cell size in the atmosphere component of 1-degree latitude or finer. This filters out models whose resolution is deemed too coarse to capture geographic placement and structuring of the lakes.

Continuing on to step 2b, we search for documentation describing the land component to learn more about its treatment of lakes. For some models, the Earth System Documentation (ES-DOC) provides

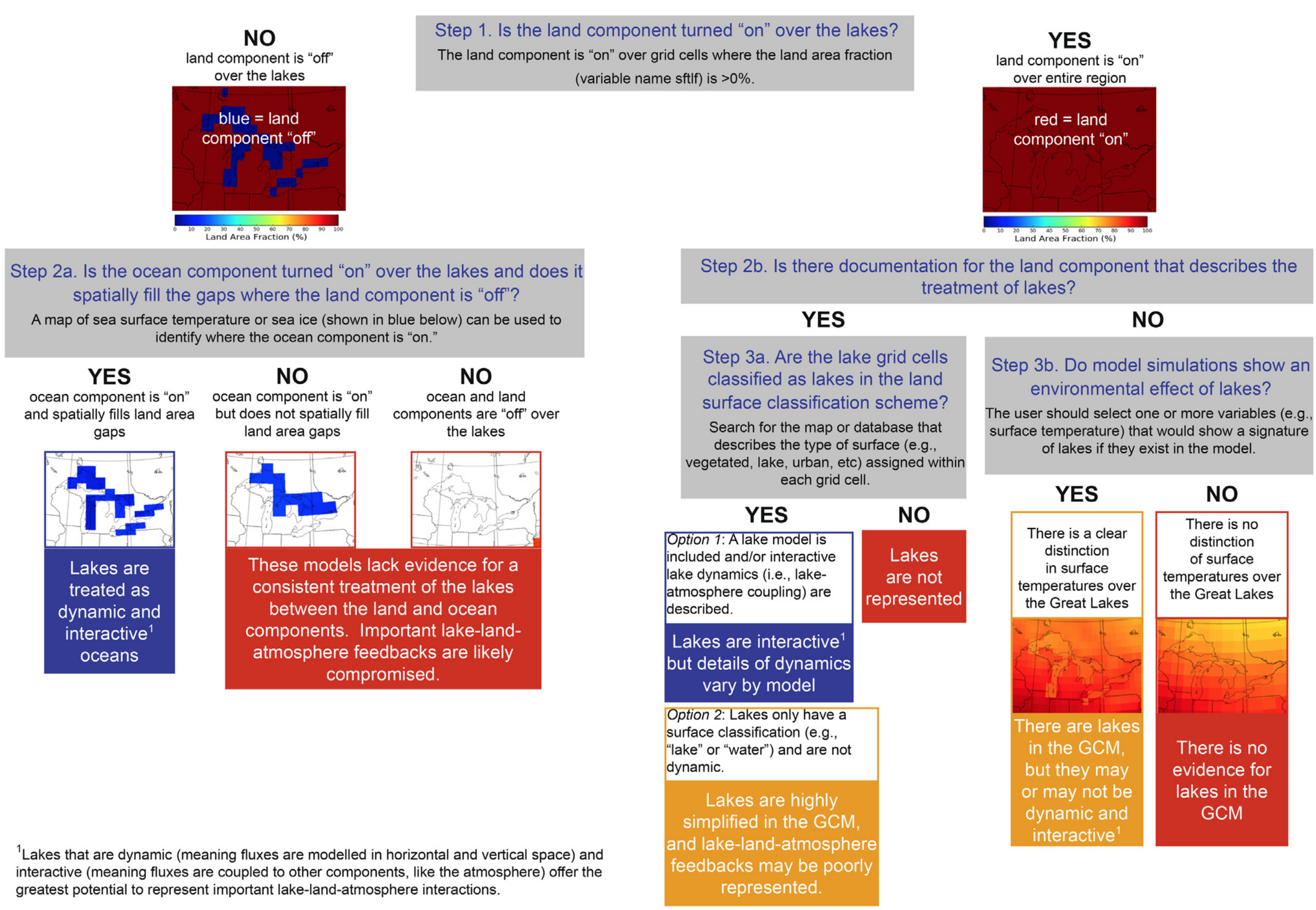


Fig. 3. A decision tree for characterizing large lakes in GCMs when their treatment is not known. Lakes may be simulated in a GCM using a lake model, the GCM's ocean component, a simplified water representation in the land component, or not at all. The Laurentian Great Lakes are used as an example throughout.

insights into lake simulations. In our search, we primarily relied on technical user guides, journal articles, and developer websites for the land component. Every source of documentation varied in the level of detail provided about the treatment of lakes, but the most important pieces of information we searched for included whether or not vertical lake dynamics were simulated and if lake ice was allowed to form in the model. Lake ice is critical for simulating important Great Lakes lake-atmosphere feedbacks, but the representation of lake ice in other regions, especially for more southern lakes, may not be an important criterion.

If a description of how lakes are simulated is found, the final step is to confirm that the land surface within specific lake grid cells are in fact classified as "lake." Each land component relies on an input land classification scheme (a map) that divides and classifies each grid cell's surface type as vegetated, lake, urban, etc. For example, lakes exist in the GFDL model where the U.S. Geological Survey Global Land Cover Characteristics database defines "water bodies." When a land component simulates lakes dynamically, the GCM is said to include interactive and dynamic lakes. When lakes in a land component are reduced to a non-dynamic nor interactive surface water body, the GCM cannot accurately represent lake-land–atmosphere feedbacks.

Returning to Step 2b of the Decision Tree, when documentation describing lakes is not available the next logical action is to look for an indicator of lakes in a map of the GCM's output. For example, we mapped surface temperatures because one would expect to see a distinction between over-lake and over-land values if lakes exist in the model. In the Great Lakes region, cooler surface temperatures exist over the lakes during summer compared to nearby land surfaces. There are other variables, for example, that could also be used as a proxy for identifying lakes, so this part of the methodology can be adjusted to whatever output makes the most sense for a particular region and application. The goal is to select a variable that would show a clear distinction over the lake versus over land where lakes exist in the model. If there is clear evidence for lakes in the GCM, additional investigation is required to know whether those lakes are dynamic and interactive. If there is no clear evidence for lakes, we conclude the GCM does not simulate lakes.

We do recognize there may be models whose documentation describes a dynamic lake representation, but model output does not show an indicator of its presence. From the practitioner's perspective, a model with a lake but no environmental effect (e.g., lake-effect) is equivalent to a model without a lake.

Results

We filtered 39 CMIP5 models through our Decision Tree in search of how the Great Lakes are represented. A summary of our results is in Table 1, and further discussion follows. Each of our findings is assessed in terms of our basic model credibility and usability standard; there is a dynamic lake representation within the model.

In our investigation of the lake models included in the global models, we did not investigate, deeply, the structure of the lake models. Most are one-dimensional and only represent heat transfer in the vertical dimension. Some are presented as part of the ocean component and will have horizontal transport of heat within the lakes. Strategies that couple lake, land, and atmosphere vary. As noted above, in none of these cases are the lakes and their coupling fully resolved.

The Great lakes are simulated as dynamic lakes in the model

A total of 18 GCMs incorporate dynamic lake simulations globally within their land components, but only 13 are confirmed (from their documentation) to simulate all five Great Lakes including lake ice cover (Table 1). These 13 models meet our first order credibility requirement that the model simulates the Great Lakes as dynamic lakes. However, only four models have spatial cells of 1°or less in at least one direction (latitude or longitude), and spatial resolution is a key factor in determining local lake-land–atmosphere feedbacks. Practitioners may find coarser GCMs with lakes, like these, unusable if they require site-specific lake-effect information.

The Great lakes are simulated as oceans in the model

Five GCMs treat the Great Lakes as oceans. The geography of the "oceans" is shown in Table 2 for both the land and ocean components to demonstrate how these GCMs have a consistent placement of the lakes in both components, although the ocean components have higher spatial resolutions. Only one of those GCM's (MIROC4h) captures all five Great "Oceans" with a relatively fine spatial representation. This model passes our first order credibility requirement and potentially offers usable information for the Great Lakes region. Additional evaluation of MIROC4h should be conducted to assess overall model performance for the region. The remaining four GCMs treat a *portion* of the Great Lakes as oceans, but those Great "Oceans" are spatially coarse and, in the HadCM3 model, much smaller than the actual area of the lakes.

The Great lakes are simulated like static water bodies

Three models (ACCESS 1.0, BNU-ESM, and the models in the HadGEM2 family) classify a type of land surface as "water," but vertical and horizontal lake dynamics are not simulated. Important lake-atmosphere feedbacks and the role of ice cover are not captured. This type of static lake representation does not meet our model credibility requirement.

The Great lakes are not simulated in the model

Our decision tree identified several GCMs that are inconsistent in their treatment of the Great Lakes (Table 3). These inconsistencies arise from competing or lacking spatial coverage between a model's land and ocean component for grid cells in the region of the Great Lakes. We would expect the ocean component to be "off" where the land component is "on" and vice versa. However, in some models both components are fully "on" for grid cells over one or more Great Lake(s). In other models both components are "off" for grid cells over one or more Great Lake(s). Each of these cases highlights uncertainty within the GCM for how surface fluxes of heat, momentum, and moisture are credibly simulated between components, especially when neither component is "on" for some model grid cells. We conclude that these GCMs do not meet our model credibility standard.

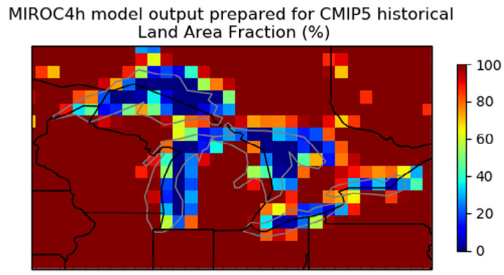
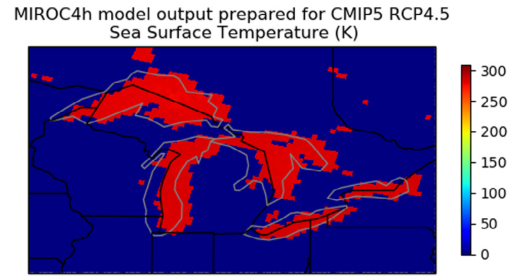
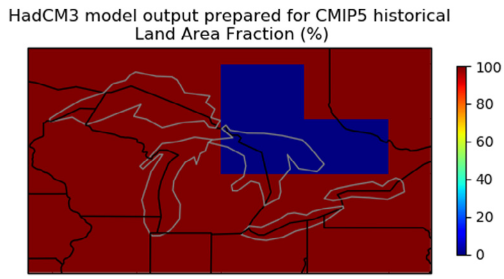
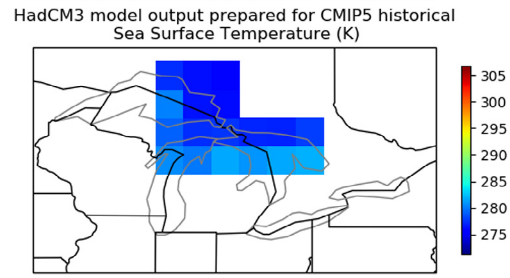
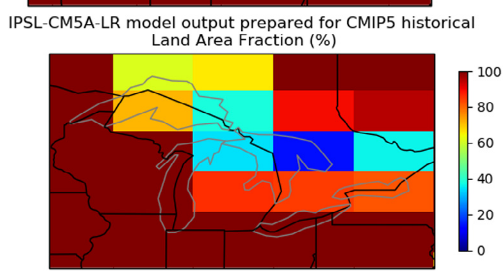
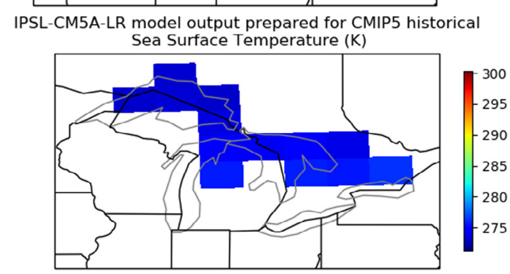
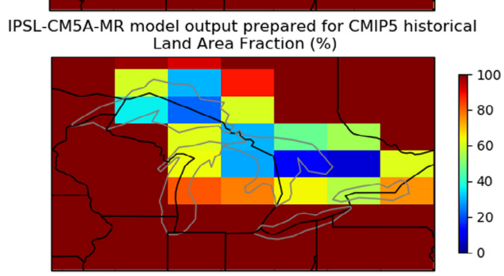
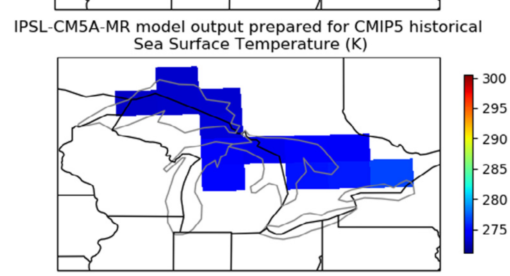
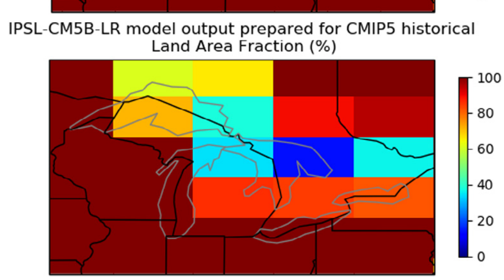
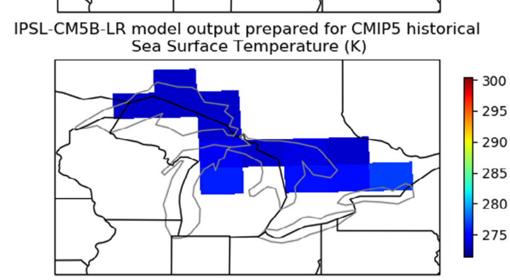
Finally, there are four models (ACCESS 1.3, BCC-CSM1.1, GFDL-CM2.1, and MIROC-ESM) that do not document the treatment of water surfaces or dynamic lakes nor is there an environmental effect of the Great Lakes in their model output. Based on our standards, these models do not simulate the Great Lakes.

GCMs classified as having no lakes by our standards may in fact have dynamic lakes, but descriptions of them could not be found within their documentation. As a double check, we applied Decision Tree Step 3b to search for evidence of the Great Lakes in maps of each GCM's surface temperature but found no clear indicator for lakes.

Other large lake systems

Wherever possible, we cite references in Table 1 for each GCM's land component documentation and surface classification schemes so that users interested in lakes other than the Laurentian Great Lakes can consult the documentation more easily. Several of the GCMs rely on the same land component and surface classification

Table 2
CMIP5 GCMs that represent the Great Lakes as dynamic oceans are shown. Maps of each GCM's land area fraction (0 to 100%) and ocean component output (sea surface temperatures are used) demonstrate that the land component is "off" over grid cells where the ocean component is "on." These models offer a consistent treatment of the Great Lakes as oceans.

Model	Land Component Map Blue (0%) = land component "off"	Ocean Component Map Ocean component "on" where colored or not 0
MIROC4h		
HadCM3		
IPSL-CM5A-LR		
IPSL-CM5A-MR		
IPSL- CM5B-LR		

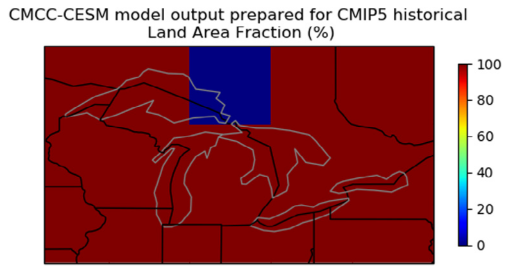
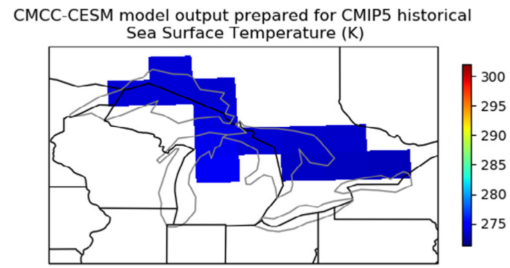
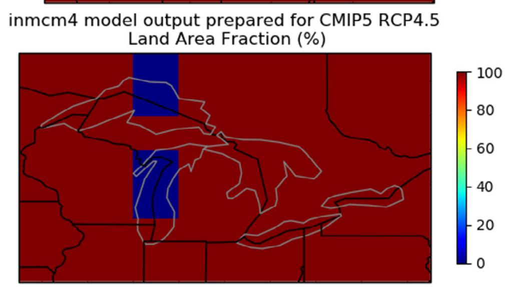
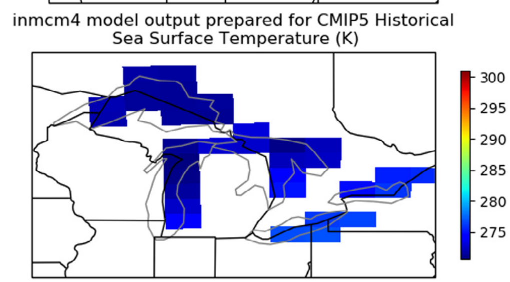
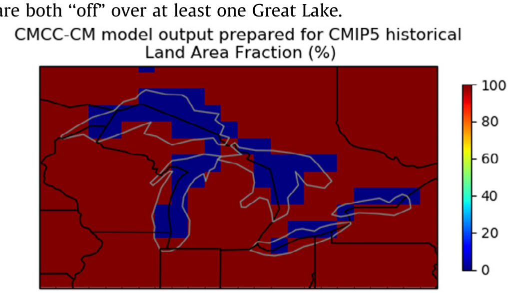
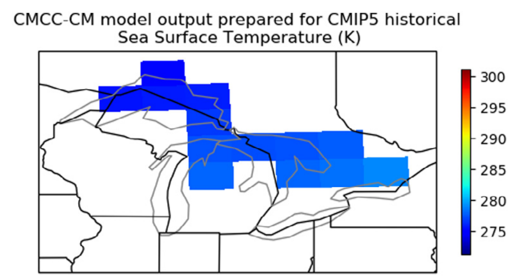
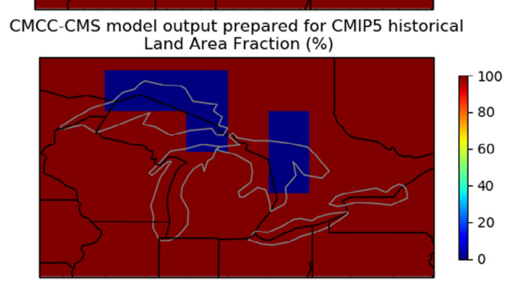
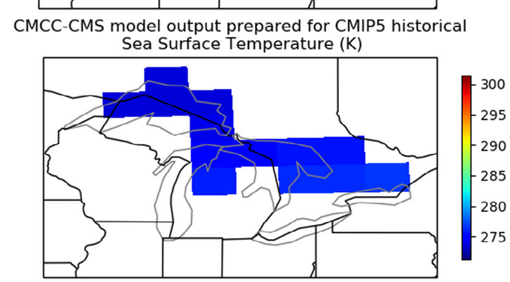
schemes, so their treatment of lakes is identical to one another. Documentation for GCMs with conflicts between their land and ocean components was not investigated because we already knew those models failed our credibility requirement.

Discussion

GCMs are valuable tools for investigating global climate responses, but they often lack important regional details; for example, the representation of large lakes and lake effects. It should be noted, however, the presence of large lakes in a GCM does not necessarily mean the model produces more realistic simulations of, say, surface temperatures (including lake surface temperatures) or precipitation. Further analysis is required to investigate the quality of simulated lake-effects.

The CMIP5 models we found that represent large lakes do so at relatively coarse spatial resolutions that are less than ideal for many practitioners' uses. This mismatch between the spatial resolution of GCM output and the spatial scales practitioners operate

Table 3
CMIP5 GCMs that inconsistently represent the Great Lakes between their land and ocean components are shown. Maps of each GCM's land area fraction (0 to 100%) and ocean component output (sea surface temperatures are used) demonstrate cases where 1) the land and ocean components are both "on" for some lake grid cells or 2) neither the land nor ocean component is "on" for some lake grid cells. These models do not offer a consistent treatment of the Great Lakes between their land and ocean component and therefore do not meet our credibility standard.

Model	Land Component Map Blue (0%) = land component "off"	Ocean Component Map Ocean component "on" where colored or not 0	Notes
The land and ocean components are both "on" over at least one Great Lake.			
CMCC-C5ESM			Both components are "on" for grid cells in the regions of Lakes Superior, Huron, and Ontario.
INM-CM4			Both components are "on" for grid cells in the regions of Lakes Huron, Erie, and Ontario and smaller portions of Lake Superior.
The land and ocean components are both "off" over at least one Great Lake.			
CMCC-CM			Both components are "off" for grid cells over Lake Erie.
CMCC-CMS			Both components are "off" for grid cells over Lake Erie.

(*continued on next page*)

Table 3 (*continued*)

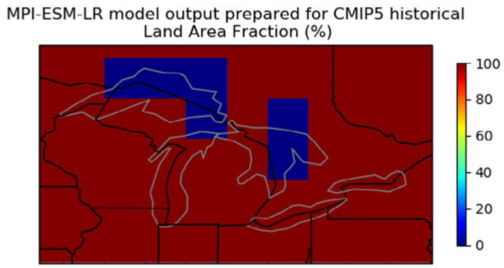
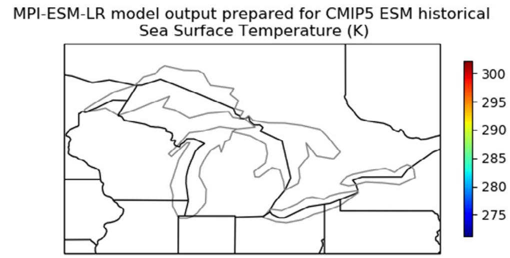
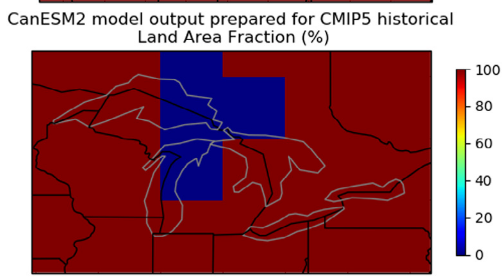
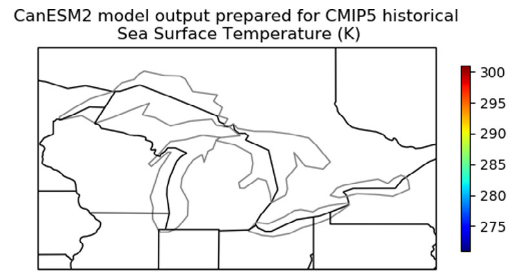
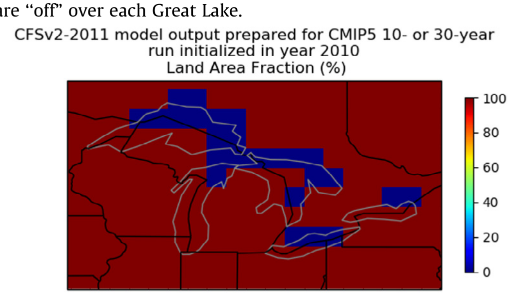
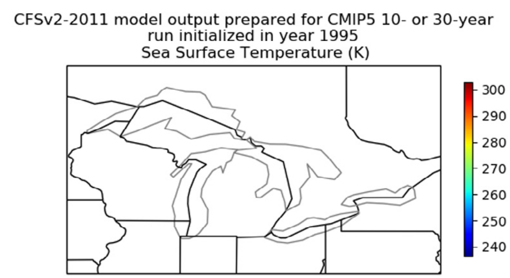
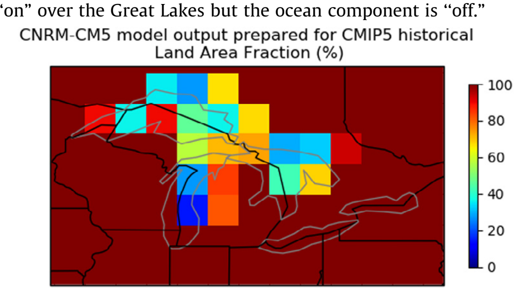
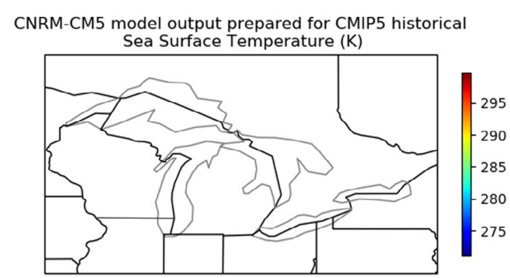
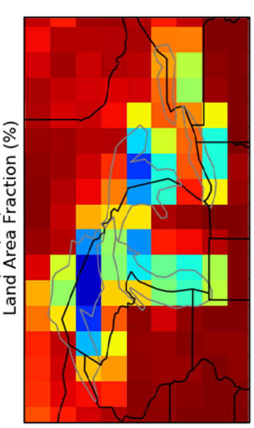
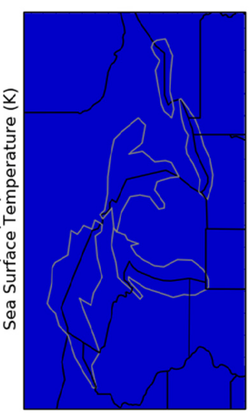
Model	Land Component Map Blue (0%) = land component "off"	Ocean Component Map Ocean component "on" where colored or not 0	Notes
The land component is "off" over some lakes and the ocean component is "off" over all lakes.			
MPI-ESM-LR			The land component is "off" for grid cells over Lakes Superior and Huron.
CanESM2			The land component is "off" for grid cells over parts of Lakes Superior, Michigan, and Huron.
The land and ocean components are "off" over each Great Lake.			
NCEP-CFSv2			The land and ocean components are "off" for grid cells over each Great Lake.
The land component is partially "on" over the Great Lakes but the ocean component is "off."			
CNRM-CM5			Grid cells near Lakes Superior, Michigan, and Huron are partially simulated (<100%) by the land component, but the ocean component is "off" over the entire region.

Table 3 (*continued*)

Model	Land Component Map Blue (0%) = land component "off"	Ocean Component Map Ocean component "on" where colored or not 0	Notes
EC-Earth	EC-Earth model output prepared for CMIP5 historical Land Area Fraction (%)  	EC-EARTH model output prepared for CMIP5 historical Sea Surface Temperature (K)  	Grid cells near each Great Lake are partially simulated (<100%) by the land component, but the ocean component is "off" for the entire region.

on has led to the development of several techniques that increase, or "downscale," the spatial detail of GCM output. The remainder of this section is devoted to discussing alternatives to GCM simulations that practitioners may be inclined to use, primarily to meet spatial resolution requirements. We present a basic overview of GCM downscaling and bias-correction techniques and drawbacks of these methods practitioners should be aware of in regions where lake-atmosphere dynamics are important.

Broadly speaking, downscaling methods fall into two primary categories: statistical and dynamical downscaling. Each of these forms of downscaling has its own advantages and disadvantages (Winkler et al., 2011), and several different downscaled forms of the CMIP5 models are available to end users. These downscaled data are typically more attractive to end users because of their finer spatial detail; however, users are not always aware of the underlying assumptions inherent in the downscaling procedure. There is an additional data processing technique, called bias correction, which also introduces its own set of assumptions. We assert that in regions where regional climate drivers (i.e., large lakes) are non-stationary, or changing, the common assumptions of statistical downscaling and bias correction are invalidated.

In statistical downscaling, it is commonly assumed that observed relationships in the current climate will stay the same in the future (i.e., stationarity is assumed). This assumption is necessary for the technique, because the local observed (historical) spatial pattern of say, precipitation, is used to define statistical relationships between the larger-scale model output and downscaled precipitation data. One area that statistical downscaling can add value to GCM output is in mountainous regions, because the relationship of local precipitation to large orographic features does not change over time. In regions with large lakes, if lake-atmosphere processes are changing, as is the case in the Great Lakes, then assumptions of stationarity do not hold. Briley et al. (2017) present an example of how the role of reduced lake ice cover on the Great Lakes has fundamentally changed the source of atmospheric moisture, which has led to increases in lake-effect snowfall.

Bias-correction procedures are another statistical technique applied to climate model data to adjust for differences between the model's historical simulation and the observed climate. Without this adjustment, the model data may be biased, or inaccurate, compared to observations. There are several bias-correction techniques, but in general the model's historical simulation is compared to observations in an overlapping time period to calculate the amount of model bias, which is then the amount of "correction" that is applied. Emphasis should be made that the "correction" is purely statistical and does not actually improve the physical representation of climate processes in the model. The amount of bias correction necessary to match the model to the past is then applied to its future projection and requires the assumption that the amount of correction is constant over time. Briley et al. (2017) present how bias corrections based on past climates will not be the same as what is required for the future in the Great Lakes region, because the timing of the seasonal transition and lake-atmosphere interactions governing lake-effect snowfall are already changing.

Bias correction is commonly applied to both statistically and dynamically downscaled GCM output. As Great Lakes regional climate experts, we do not recommend using bias-corrected data for the reasons mentioned earlier, but other tools exist for practitioners to explore and manage high uncertainty in the future. For example, scenario planning is a process where practitioners explore future climate predictions, among other pieces of information, to increase their capacity to manage uncertainty in the future (Flynn et al., 2018; Weeks et al., 2011).

We are not naive to the fact that there will be applications that require bias-corrected data, like hydrological modeling, where time series of modeled data must realistically capture the statistics of the past. In cases like these, we recommend integrating information about the underlying models' bias in the assessment of future climate uncertainty. Such information may come from publications on a particular model's evaluation or, if available, calculated from uncorrected model output.

Our primary recommendation for users interested in high-resolution future climate projections in large lake regions is to consider dynamically downscaled climate models. Dynamical downscaling is achieved through the use of regional climate models (RCMs), which simulate smaller-scale climate processes at finer resolutions over a specific geographic area. RCMs rely on the output from GCMs at that area's boundary in order to ensure that all necessary physical equations are balanced and that the climate system as a whole is accurately represented. For regions with large lakes, there is also the option to couple RCMs to a lake sub-model. Several different types of lake models exist, which aim to more accurately simulate lake processes and improve the representation of lake-atmosphere interactions (Leon et al., 2007; Subin et al., 2012; Xue et al., 2017). There are several regional climate modeling efforts in the Great Lakes Region (Mallard et al., 2014; Gula and Peltier, 2012; Xue et al., 2017), but we are only aware of one that has made its data publicly available (Notaro et al., 2015a, 2015b, 2016). Limited access to regional climate projections is one of the reasons why users are still relying on global climate projections, like CMIP.

When regional projections are available, a good approach may be to compare the RCM projections to data in: 1) the CMIP models that simulate large lakes and 2) widely recognized climate synthesis products, like the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports or U.S. National Climate Assessments. The goal would be to show if/how the regional climate projections differ from the other types of data sets. If the regional climate projections are significantly different from the other sources, then there is reason to believe the RCM is simulating dynamics (maybe well, maybe poorly) that the other data sets do not have in their underlying models. Depending on evaluations of the RCMs, there may be evidence for the added value of using RCM information. If the regional climate projections are not significantly different from the other sources, the user may want to question 1) the significance of the role of large lakes in their regional climate and 2) the quality of the RCM before deciding the RCM does not provide added value to their application.

More broadly speaking, we recommend placing greater emphasis on the importance of lakes in climate models for practitioner audiences. One suggestion is to form a lake working group that would continue a similar style assessment to what we have done here with future GCMs coming online, as well as engage regional modelers who are producing new regional climate data sets. In particular for the U.S., we recommend better framing of existing climate projections in the National Climate Assessments, or the incorporation of regional model projections, so that practitioners in the Great Lakes region have higher quality information for their planning. Lastly, better documentation of lakes in model metadata, especially metadata that is standardized across all modeling groups, would greatly reduce the amount of effort required to assess models in the future.

Conclusion

We have presented a framework for extracting the treatment of large lakes in climate models and demonstrated its use with the CMIP5 climate models over the Great Lakes region. Our goal is to provide information on lakes to the community of end-users of model information interested in planning and management; that is, practitioners. We showed that many CMIP5 models do not include credible representations of large lakes; and, of those that do, model spatial resolutions are too coarse (>1°latitude/longitude) for practitioner audiences. Only four GCMs are available that simulate dynamic lakes at relatively fine spatial grid cells (<1°latitude/longitude), and these GCMs offer potentially more credible information for practitioners in regions where lakes play a significant role in modifying the regional climate.

Given the very few GCMs that are sufficient for practitioners in large lake regions, we conclude that the multi-model approach to analyzing climate information may not be very useful when model selection is limited to CMIP GCMs. Instead, practitioners should seek out regional climate projections that were designed to better represent lake-land–atmosphere processes. Where regional climate projections are not available or are in limited supply (and even when they are available), we suggest practitioners explore future climate uncertainty using scenario planning informed by multi-model ensembles but not limited to the model information.

Our efforts to determine, simply, the presence of lakes in the CMIP5 models lead to several observations on usability in practice. First, we have established a substantial barrier in the application of the models. Namely, the amount of time spent in determining the presence or absence of lakes in a large set of CMIP models was two years. This is with a team trained in climate science and climate data analysis, who worked closely with both metadata experts and model developers. At the end of that time, there is another lengthy process to establish, whether or not, the presence or absence of lakes influences the salience of the model projections to the Great Lakes applications. This barrier is long, whether compared to the length of time of a Masters student or the budgets that a practitioner might have to answer a specific adaptation question.

We realize that the original intent of the CMIP simulations was not directed at regional application as we have pursued (Jones et al., 2017; Taylor et al., 2012; Xie et al., 2015). However, the CMIP archive has emerged as the foundational dataset used in assessments and applications. There have been enormous efforts to define and improve the metadata of the CMIP models. However, both the complexity of the models and the complexity of the applications community offer daunting challenges to providing complete and accurate metadata. This is made more challenging by the fact that metadata accuracy requires self-reporting in a field where neither methods nor language is fully standardized. We suggest that in addition to the dynamical downscaling recommended above, it is time for the development of a class of models specifically designed for the purpose of adaptation on decadal scales. Not only for their regional applications such as ours, but the demands of, for example, regional characterization of sea level rise will be growing rapidly.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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