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Future rise of the Great Lakes water levels under climate change

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ABSTRACT

The Great Lakes of North America are the largest unfrozen surface freshwater system in the world and many ecosystems, industries, and coastal processes are sensitive to the changes in their water levels. The water levels of the Great Lakes are primarily governed by the net basin supplies (NBS) of each lake which are the sum of over-lake precipitation and basin runoff minus lake evaporation. Recent studies projected the future NBS of the Great Lakes by dynamically downscaling General Circulation Models (GCMs) using Regional Climate Models (RCMs). However, their RCMs had been coupled to one-dimensional (1D) lake column models which lack the ability to accurately simulate the Great Lakes' hydrodynamics and thermal structure. In this study, an ensemble of three dynamical downscalings based on the Great Lakes-Atmosphere Regional Model (GLARM) is used to project the future NBS and water level of the Great Lakes. GLARM is a three-dimensional (3D) regional climate modeling system for the Great Lakes region that two-way couples an RCM to a 3D hydrodynamic lake and ice model, making this the first study to use such an advanced model for water level projection of the Great Lakes. For the present-day climate, over-lake precipitation and lake evaporation simulated by GLARM, along with the basin runoff simulated by the GLARM-driven Large Basin Runoff Model (LBRM), track the mean seasonal cycle of the NBS components remarkably well. In particular, compared to previous studies, the most significant improvements are made in estimating the lake evaporation. For future hydroclimate, the ensemble average projects an increase in annual NBS and average annual water level for each lake. The projected NBS increase is mostly due to an increase in over-lake precipitation and basin runoff combined with a relatively smaller increase in lake evaporation. According to the ensemble average, by 2040–2049, the average annual water levels of Lake Superior, Michigan-Huron, and Erie are projected to increase by +0.19, +0.44, and +0.28 m, respectively, relative to 2010–2019. The individual downscaling cases highlight the uncertainty in climate projection, showing both increases and decreases in annual NBS and water level projection. The projected changes in the average annual water levels by 2040–2049 relative to 2010–2019 range from −0.01 to +0.32 m in Lake Superior, −0.13 to +0.80 m in Lake Michigan-Huron and −0.09 to +0.54 m in Lake Erie.

1. Introduction

The Great Lakes of North America — Superior, Michigan, Huron, Erie, and Ontario — form the largest surface freshwater system in the world. Collectively they have a surface area of about 244,000 km^2 and contain around 23,000 km^3 of water which accounts for 18% of the world's freshwater supply (U.S. Environmental Protection Agency and Government of Canada, 1995). The Great Lakes exert a significant influence on the regional climate, especially on air temperature and precipitation, due to their large size, large thermal inertia, low surface roughness, and low albedo (Changnon and Jones, 1972; Scott and Huff, 1996; Notaro et al., 2013). The large thermal inertia of the lakes decreases the variability of near-surface air temperature and the amplitude of its diurnal, seasonal, and annual cycles (Scott and Huff, 1996; Notaro et al., 2013). The lakes also support greater atmospheric instability (stability) during the cold (warm) seasons which results in increased (decreased) sensible and latent heat fluxes, lake evaporation, convective clouds, and precipitation (Scott and Huff, 1996; Notaro et al., 2013).

In recent decades, climate change has affected the Great Lakes Basin with noticeable changes such as higher air temperatures and lake

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temperatures (Zhong et al., 2016), decreased ice cover over the lakes (Wang et al., 2012), increased over-lake wind speeds (Desai et al., 2009) and fluctuating water levels (Gronewold et al., 2013, 2016, 2021). A substantial decrease in ice cover over the lakes due to warmer winters (Wang et al., 2012) has strengthened the ice-albedo feedback and has caused a rapid increase in the summertime water temperatures of the Great Lakes (Austin and Colman, 2007). Decreased ice cover and warmer waters have also led to increased lake-effect snowfall in specific areas of the Great Lakes region (Burnett et al., 2003; Kunkel et al., 2009).

Water levels of the Great Lakes have fluctuated dramatically by more than 2 m over the past decades due to climate-induced changes in the three major components of the lakes' water budget: over-lake precipitation, lake evaporation, and basin runoff (Gronewold et al., 2016). These three components are collectively referred to as the net basin supply (NBS), calculated as over-lake precipitation plus basin runoff minus lake evaporation. In the early 1970s and early 1980s, an increase in precipitation led to water level rise, while unusually high air and water surface temperatures during the late 1990s — coincident with one of the strongest El Nino events on record — led to high lake evaporation, low basin runoff, and ultimately low water levels from 1998 to 2013 (Assel et al., 2004; Gronewold and Stow, 2014). After this period of low water levels, a rapid decline in lake evaporation due to colder winters triggered a record-setting water level rise in 2013–2014, and persistent above-average precipitation further sustained the water level rise, leading to record highs in 2019–2020 (Gronewold et al., 2016, 2021).

Such large fluctuations in water levels, which are much more significant than that of marine systems, have forced communities to adapt and have highlighted the need for incorporating climate change-induced water level changes into water level management (Gronewold et al., 2013). High water levels have led to severe flooding in the past (Gronewold and Rood, 2019), while low and fluctuating water levels affect hydropower production (Hartmann, 1990; Shlozberg et al., 2014) and coastal bluff erosion (Theuerkauf et al., 2019; Krueger et al., 2020; Volpano et al., 2020). Therefore, improving our understanding and projection of the Great Lakes water levels have been a priority for the Great Lakes scientific community in recent years (Sharma et al., 2018; Delaney and Milner, 2019).

Numerous studies have projected the water levels of the Great Lakes on a climate timescale by adopting a common and straightforward approach — project the NBS (i.e., project the three components of NBS) and translate it into future water levels using a lake-to-lake routing model that incorporates inter-lake flows with regulation rules/logic such as the Coordinated Great Lakes Regulating and Routing Model (CGLRRM) (Quinn, 1978; Clites and Lee, 1998). Early studies (e.g., Croley, 1990; Chao, 1999; Mortsch et al., 2000; Lofgren et al., 2002; Angel and Kunkel, 2010) projected the basin runoff and lake evaporation by driving a pair of models from the Great Lakes Environmental Research Laboratory (GLERL) with future climate variables (e.g., air temperature, precipitation, and wind speed) that were created by perturbing historical data with the changes projected by General Circulation Models (GCMs). The pair of GLERL models consisted of the Large Basin Runoff Model (LBRM) to simulate future basin runoff and the Large Lake Thermodynamic Model (LLTM) to simulate future lake evaporation. The future over-lake precipitation, on the other hand, was estimated by simply perturbing the historical over-lake precipitation data with the changes projected by GCMs.

These studies projected both increases and decreases in water levels with a high degree of uncertainty due to the coarse spatial resolution of the GCMs, lack of representation of the Great Lakes in the GCMs, and the one-way coupling of GCMs with LBRM and LLTM that did not allow for any feedback mechanisms between the land/lake processes and the atmosphere (MacKay and Seglenieks, 2013). Furthermore, the use of air temperature to calculate the potential evapotranspiration (PET) in LBRM was later found to violate the conservation of energy and consequently result in an unnaturally large future PET (Lofgren et al., 2011), putting the basin runoff and water level projections from these GCM-based studies into question. It should be mentioned that this issue in LBRM has since been addressed with an update to the PET formula in the LBRM code to ensure the PET follows the Clausius-Clapeyron relationship (this modified version of LBRM is hereafter referred to as LBRM-CC).

To mitigate the limitations and shortcomings of the early GCM-based studies, more recent studies (e.g., MacKay and Seglenieks, 2013; Notaro et al., 2015a) opted to dynamically downscale GCMs using Regional Climate Models (RCMs) to project the NBS components. But, similar to the GCM-based studies, these RCM-based projections also showed some contradictory results due to the uncertainties in climate modeling. MacKay and Seglenieks (2013) performed a cascading sequence of dynamical downscaling on Environment Canada's GCM (CGCM3) and projected decreases in the Great Lakes water levels, while Notaro et al. (2015a) dynamically downscaled two different GCMs using the same RCM and projected both increases and decreases in the water levels. Nevertheless, RCMs provided significant improvements over the use of GCMs and GLERL models, partly because RCMs have a much higher spatial resolution and were coupled to lake models that capture the influence of the Great Lakes on the local climate (including lake-induced phenomena such as lake-effect storms) by resolving lake-atmosphere interactions (MacKay and Seglenieks, 2013).

However, to date, the RCMs used to project the future NBS on a climate timescale have been two-way coupled to one-dimensional (1D) lake column models. 1D lake models have been shown to produce large biases in lake surface temperature (LST), ice cover, and thermal structure due to their inability to resolve three-dimensional (3D) lake circulation and the associated turbulent mixing processes (Bennington et al., 2014). These biases lead to higher uncertainties in the projected precipitation (Notaro et al., 2015b; Shi and Xue, 2019) and lake evaporation (Notaro et al., 2015a; Xue et al., 2017, 2022) and undermine the credibility of the NBS projections. Thus, multiple studies (e.g., Bennington et al., 2014; Notaro et al., 2015a, Notaro et al., 2015b; Sharma et al., 2018) have highlighted the two-way coupling of RCMs to 3D lake models to properly resolve the complex dynamics and lake-atmosphere interaction of the Great Lakes as a necessary step to ultimately improve the long-term water level projections.

3D lake models have been developed for the Great Lakes but until recently extremely limited progress was made in terms of two-way coupling them to RCMs (Sharma et al., 2018; Xue et al., 2022). Xue et al. (2017) were the first to two-way couple an RCM, the International Center for Theoretical Physics (ICTP) Regional Climate Model version 4 (RegCM4) (Giorgi et al., 2012) with a 3D hydrodynamic lake and ice model based on the Finite Volume Coastal Ocean Model (FVCOM) (Chen et al., 2006, 2013). Their coupled system, called the Great Lakes-Atmosphere Regional Model (GLARM), showed significant improvements over the RCMs coupled to built-in 1D lake and ice models in simulating the Great Lakes' ice and thermal structure. Sun et al. (2020) likewise demonstrated the benefits of a 3D hydrodynamic model by two-way coupling the Climate-Weather Research and Forecasting (CWRF) RCM to an FVCOM-based 3D lake and ice model. They also simulated the historical water levels of the Great Lakes by using CWRF-FVCOM to calculate the historical NBS and running the NBS through a stage-fall discharge equation within the FVCOM model. However, they made no efforts in projecting the future water level changes of the Great Lakes. Durnford et al. (2018) developed an operational water level forecasting system for the Great Lakes by two-way coupling an RCM with a 3D lake model, but their forecasts were on a 7-day short-term timescale with data assimilation. In fact, at the time of writing this paper, no study has projected the water levels of the Great Lakes on a climate timescale by utilizing an RCM with a two-way coupled 3D lake model.

Therefore, the primary goal of this study is to use a two-way coupled 3D regional climate modeling system (GLARM) in conjunction with LBRM and CGLRRM to better resolve land-lake-atmosphere interactive processes and project the water level changes of the Great Lakes on a climate timescale. Here, three GCMs from the Coupled Model

Intercomparison Project Phase 5 (CMIP5) are dynamically downscaled using GLARM for the early twenty-first (2000–2019) and mid-twenty-first (2030–2049) centuries under the Representative Concentration Pathway (RCP) 8.5 scenario. The changes in the NBS components by the mid-twenty-first century — i.e., the modeled changes between the early and mid-twenty-first century in GLARM and LBRM simulations — are applied to the observed early twenty-first century NBS to derive the future NBS, which is then used to drive CGLRRM to project the mid-twenty-first century water levels.

2. Methodology

2.1. Models

2.1.1. Great Lakes-Atmosphere Regional Model (GLARM)

GLARM (Xue et al., 2017) is a regional climate modeling system for the Great Lakes that two-way couples RegCM4 and an FVCOM-based 3D hydrodynamic lake and ice model. It has been recently updated to GLARM version 2 (Xue et al., 2022), which is the version used in this study. RegCM4 is a 3D, hydrostatic, compressible, σ-coordinate regional climate model whose atmospheric dynamics and radiative transfer scheme are based on the hydrostatic version of the Pennsylvania State University– National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) (Grell et al., 1994) and NCAR Community Climate Model, version 3 (CCM3) (Kiehl et al., 1996) respectively. RegCM4 has several improvements over its older version (RegCM3) such as multiple schemes for representing cumulus convection, planetary boundary layer processes, and land surface processes (Giorgi et al., 2012). Here, the cumulus convection is represented using the Grell parametrization (Grell, 1993; Grell et al., 1994), and the planetary boundary layer processes are described using the Holtslag et al., (1990) scheme. The version of RegCM4 in GLARM is based on Wang et al. (2016), so the land surface processes are described using the Community Land Model, version 4 (CLM4). The spatial modeling domain of GLARM (Fig. 1) encompasses the Great Lakes Basin along with parts of the Midwest and Northeast regions of the US and the Ontario and Quebec provinces of Canada. The RegCM4 module in GLARM covers this modeling domain with 18-km spaced grids and 18 vertical sigma layers.

The 3D hydrodynamic model in GLARM is based on FVCOM, a prognostic, free-surface, 3D primitive equation coastal ocean circulation model that is numerically solved over an unstructured grid using the finite-volume method (Chen et al., 2006, 2013; Xue et al., 2020). The ice-water interaction processes are simulated by a computationally efficient version of the Los Alamos Community Ice Code (CICE) within the FVCOM framework (Xue et al., 2017). The horizontal resolution of the hydrodynamic model ranges from ~1 to 2 km near the coast to ~2–4 km in the lake's offshore region, and the vertical resolution ranges from <1 m in nearshore waters to ~2–4 m in the lake's offshore region. In GLARM, LST and ice coverage calculated by FVCOM are provided to RegCM4 for the over-lake surface boundary conditions, and the surface meteorological forcing fields calculated by RegCM4 are provided to FVCOM. This two-way coupling is employed through the OASIS3-MCT coupler (Craig et al., 2017).

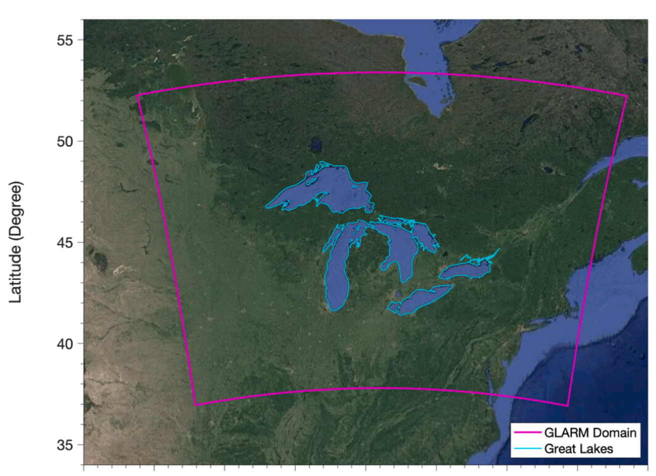

Fig. 1. GLARM's Great Lakes domain (magenta), along with the outline of the Great Lakes (cyan). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1.2. Large Basin Runoff Model – Clausius Clapeyron (LBRM-CC)

LBRM, developed by GLERL, is a physically-based conceptual model that utilizes an interdependent tank cascade model to simulate basin runoff from all 121 subbasins of the Great Lakes (Croley, 1983a, 1983b). The model represents the land as a cascade of four layers: upper soil zone, lower soil zone, groundwater storage, and surface storage, and describes the flows within these layers using the linear reservoir concept. The basin runoff, along with all fluxes between the layers (including evaporation and evapotranspiration), is calculated by solving a set of one-dimensional mass continuity equations.

LBRM requires limited input data, which is quite useful for working within the Great Lakes basin where observational data are sparse (Croley, 2002). LBRM has been successfully calibrated and used by multiple studies for simulating the historical basin runoff within the Great Lakes region (e.g., Croley, 2002; Anderson et al., 2010; Gaborit et al., 2016). Additionally, as mentioned in section 1, the LBRM code has been revised to improve its performance in future basin runoff projection and climate change studies by incorporating the Clausius-Clapeyron relationship (CC). The inputs to LBRM-CC, aside from the calibrated parameters (Hunter, personal communication, 2020), are the daily precipitation and daily minimum and maximum air temperature over a subbasin. These daily inputs for the historical and future simulations are obtained directly from GLARM.

2.1.3. Coordinated Great Lakes Regulation and Routing Model (CGLRRM)

CGLRRM is a hydrologic routing model developed by the Coordinating Committee for Great Lakes Basic Hydraulic and Hydrologic Data, hereafter referred to as the "Coordinating Committee", that uses NBS to compute the water levels and the flows in the connecting channels for Lake Superior, Michigan-Huron, St. Clair, Erie, and Ontario. Besides NBS, it also considers the major diversions in the Great Lakes like the Ogoki and Long Lac Diversion, the Chicago Diversion, and the Welland Canal.

The model consists of three linked modules: the Lake Superior module, the middle lakes module, and the Lake Ontario module. The Lake Superior module computes the water level and outflow via the St. Mary's River of Lake Superior under the pre-project relationship, the Plan 1977-A regulation plan, and the Plan 2012 regulation plan. In this study, the 1977-A regulation plan was used as it required the fewest initial conditions and performs very similarly to Plan 2012. The middle lakes module, initially developed by Quinn (1978) and Clites and Lee (1998), computes the water level and the outflow of the middle lakes (Michigan-Huron, St. Clair, and Erie). Since the middle lakes' outflows via their connecting channels (St. Clair River, Detroit River, and Niagara River) are all unregulated and interdependent, the module calculates the water levels and outflows using continuity equations and stage-fall discharge relationships. Lastly, the Lake Ontario module computes the water level and outflow of Lake Ontario. However, at the time of this study, this module was not operational, so the water levels of Lake Ontario are not projected in this study.

2.2. Dynamical downscaling

In this study, three CMIP5 GCMs are dynamically downscaled using GLARM, namely GISS-E2-H, IPSL-CM5A-HR, and MPI-ESM-MR. These three GCMs were chosen due to their high reliability factor when simulating the mean surface air temperature over North America under the Reliability Ensemble Averaging (REA) method as shown by Xue et al. (2022). The downscalings are performed for the early twenty-first (2000–2019) and mid-twenty-first (2030–2049) centuries under the RCP 8.5 scenario. RCP 8.5 was chosen because, out of all the RCP scenarios, its total CO_2 emission for 2005–2020 is the closest (within 1%) to the observed total emission (Schwalm et al., 2020). It is the most suitable pathway for assessing the impact of climate change by 2050 under the current and stated policies (Schwalm et al., 2020). RCP 8.5 has the highest greenhouse gas emission within the RCP set, leading to an additional radiative forcing greater than 8.5 W/m^2 by 2100 (Moss et al., 2010; Riahi et al., 2011). Hereafter, GISS, IPSL, and MPI refer to GISS-E2-H, IPSL-CM5A-HR, and MPI-ESM-MR, respectively, while GISS-GL, IPSL-GL, and MPI-GL refer to their downscaled simulations using GLARM. Additionally, the mean of these three downscaling cases is hereafter referred to as the ensemble average.

2.3. Developing NBS and water level projections

GLARM (estimating over-lake precipitation and evaporation) and LBRM (estimating basin runoff) simulate the NBS components for both the early twenty-first century and mid-twenty-first century. The future NBS could have directly been used as an input to CGLRRM to estimate the future water level change; however, driving CGLRRM directly with the future NBS would introduce the inherent biases in GLARM and LBRM projections into the water level estimation. One common way to minimize the introduction of bias is to estimate the future NBS based on the observed historical NBS and the model-projected changes in the NBS components (i.e., the difference between the mid- and early twenty-first century simulations).

The following paragraphs describe the specific procedure that was developed to calculate: (1) the projected changes in the NBS components and (2) the future NBS. The procedure to calculate the projected changes is the same for each NBS component, so X is hereafter used to denote the three NBS components (over-lake precipitation, lake evaporation, and basin runoff).

First, the monthly climatology mean and standard deviation of X for historical ($\overline{X_m^{his}}$ and $\sigma_{X_m^{his}}$) and future simulations ($\overline{X_m^{fut}}$ and $\sigma_{X_m^{fut}}$) were calculated. Then, the monthly climatology mean and the standard deviation of the projected changes between the future and present-day climate in X ($\overline{\Delta X_m}$ and $\sigma_{\Delta X_m}$) were calculated based on Equation (1) and Equation (2) respectively.

$$\overline{\Delta X_m} = \overline{X_m^{fut}} - \overline{X_m^{his}}\ ,\ \forall m = 1\ to\ 12 \quad (1)$$

$$\sigma_{\Delta X_m} = \sqrt{\left(\sigma_{X_m^{his}}\right)^2 + \left(\sigma_{X_m^{fut}}\right)^2 - 2cov\left(X_m^{his}, X_m^{fut}\right)}\ ,\ \forall m = 1\ to\ 12 \quad (2)$$

where

X_m^{his} = values of X for month m during the early twenty-first century.

X_m^{fut} = values of X for month m during the mid-twenty-first century.

$\overline{X_m^{his}}$ = climatology mean of X for month m during the early twenty-first century.

$\overline{X_m^{fut}}$ = climatology mean of X for month m during the mid-twenty-first century.

$\sigma_{X_m^{his}}$ = standard deviation of X for month m during the early twenty-first century.

$\sigma_{X_m^{fut}}$ = standard deviation of X for month m during the mid-twenty-first century.

$cov\left(X_m^{his}, X_m^{fut}\right)$ = covariance between X_m^{his} and X_m^{fut} for month m

$\overline{\Delta X_m}$ = climatology mean of the projected changes in X for month m

$\sigma_{\Delta X_m}$ = standard deviation of the projected changes in X for month m

Next, a 20-member ensemble was randomly generated, where every member was a 20-yr monthly time series of the projected changes in X. Each time series was generated by randomly drawing 20 values from the normal distribution $N(\overline{\Delta X_m}, \sigma_{\Delta X_m})$ for each month m. Additionally, to avoid large changes in X, the time series was constrained to contain the changes within $\pm 1\sigma_{\Delta X_m}$. These aforementioned steps were performed for each NBS component to obtain a 20-member ensemble for each NBS component.

The ensembles of each NBS component were then combined to produce a 20-member ensemble of projected changes in NBS (Equation (3)). Finally, an ensemble of future NBS time series was created by applying the projected NBS changes to the observed historical NBS from the Coordinating Committee (Equation (4)). This ensemble of future NBS was used to drive CGLRRM to produce a 20-member ensemble of mid-twenty-first century water levels.

The historical NBS from the Coordinating Committee is termed as residual NBS (NBS^{res}) as it is inferred as a residual term between the observed water level of the Great Lakes, the inter-lake flows, and the flow in the major Great Lakes diversions. This is considered as the most accurate estimate of historical NBS. The Coordinating Committee's NBS data are coordinated by the US Army Corps of Engineers (USACE) and Environment and Climate Change Canada (ECCC), although data from 2009 onward remain provisional at the time of the writing of this paper.

$$\Delta NBS_i = \Delta P_i + \Delta R_i - \Delta E_i,\ \forall i = 1\ to\ 20 \quad (3)$$

$$NBS_i^{fut} = NBS^{res} + \Delta NBS_i,\ \forall i = 1\ to\ 20 \quad (4)$$

where

subscript $i = i^{th}$ member of the 20-member ensemble.

ΔP = time series of the projected changes in over-lake precipitation by the mid-twenty-first century relative to the early twenty-first century.

ΔR = time series of the projected changes in basin runoff by the mid-twenty-first century relative to the early twenty-first century.

ΔE = time series of the projected changes in lake evaporation by the mid-twenty-first century relative to the early twenty-first century.

ΔNBS = time series of the projected changes in NBS by the mid-twenty-first century relative to the early twenty-first century.

NBS^{res} = time series of the residual NBS from the Coordinating Committee for the early twenty-first century.

NBS^{fut} = time series of the projected mid-twenty-first century NBS.

This entire procedure (visually represented in Fig. 2) was repeatedly performed for each of the five lakes and each of the three downscaling cases. The projected water level changes were derived by comparing the projected future water levels with the early twenty-first century water levels which were simulated by forcing CGLRRM with the early twenty-first century residual NBS.

Note that although we only used the projected changes in NBS components rather than directly using the projected future NBS component values, we conducted a detailed validation (section 3.1) of the GLARM and LBRM performances in simulating the present-day NBS components to provide confidence in our projected changes.

The projected changes in the NBS components, NBS, and water levels presented in this paper are the average of the 20-member ensemble. Additionally, for the water level projections, the simulation period is 2040–2049, as the first 10 years of the simulation (2030–2039) is used as a spin-up time for CGLRRM to ensure the model results are not affected by the model initialization (section 3.2).

3. Results

3.1. Evaluation of the simulated historical NBS and its components

The estimates from the Great Lakes Hydrometeorological Database (GLERL-HMD) (Hunter et al., 2015), maintained by GLERL, are used to evaluate GLARM's performance in simulating the historical mean seasonal cycles of the NBS components (Fig. 3). GLERL-HMD is a monthly hydrometeorological database that provides historical estimates for all

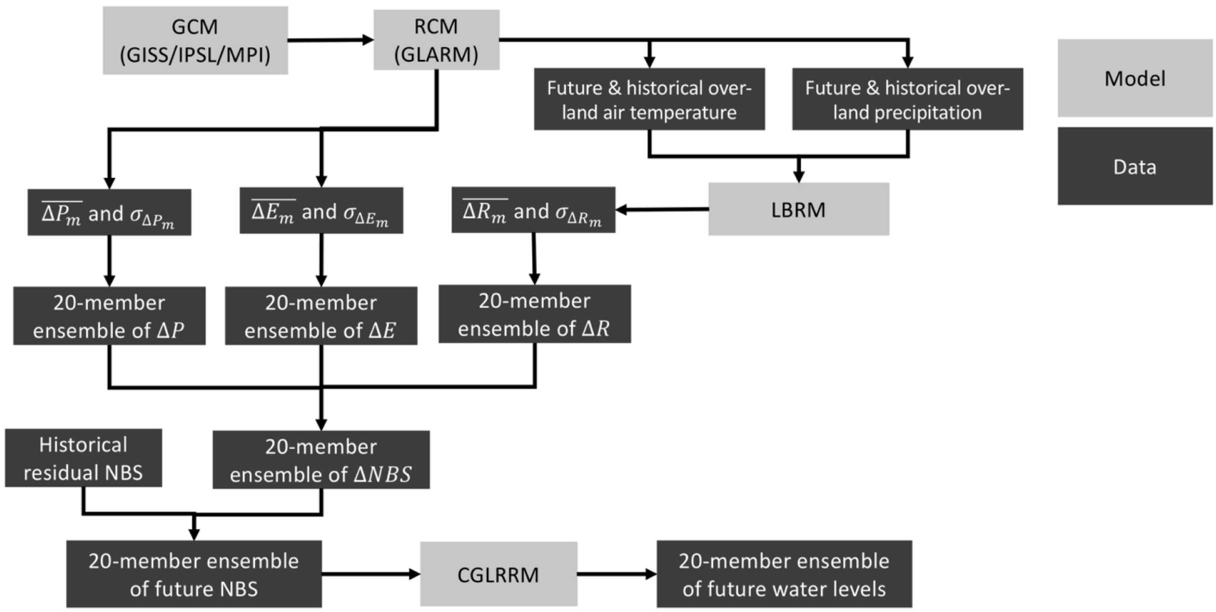

Fig. 2. Modeling framework of this study. P, E, and R represent over-lake precipitation, lake evaporation, and basin runoff respectively.

the major components of the Great Lakes' water budget, including the three NBS components. The over-lake precipitation and basin runoff estimates are derived almost exclusively from land-based station measurements, whereas the lake evaporation estimates are produced directly from LLTM simulations (Hunter et al., 2015). It should be noted that due to sparse land-based stations in some regions and the lack of lake-based stations in the Great Lakes, there are biases and uncertainties in the GLERL-HMD estimates (Hunter et al., 2015). So, although it is the most comprehensive dataset for the Great Lakes' water budget components, we should be mindful of its potential biases when comparing it to the GLARM simulations.

The ensemble average of GLARM's over-lake precipitation has a good agreement with GLERL-HMD in terms of the seasonality and magnitude. It captures the diminished winter precipitation and rising spring precipitation reasonably well. A comparison between GLERL-HMD and the GLARM ensemble average shows that the mean monthly over-lake precipitation from the ensemble average is larger by 8 (10%) and 9 mm (10%) for Lake Michigan-Huron and Erie respectively and smaller by only 0.2 (0.3%) and 3 mm (3%) for Lake Superior and Ontario respectively. These results are particularly encouraging considering that the lateral boundary conditions (LBCs) for the dynamical downscalings are from GCMs instead of reanalysis data. This provides us with confidence regarding our selection of GCMs.

Furthermore, the ensemble simulation represents uncertainties in climate modeling which are partly inherited from the driving GCMs in downscaling. The individual downscaling cases span a wide range of values, with MPI-GL and GISS-GL producing the largest and smallest estimates of mean monthly over-lake precipitation respectively. Relative to the ensemble average, the mean monthly estimates from MPI-GL are larger by up to 40% in Lake Erie while the mean monthly estimates from GISS-GL are smaller by up to 49% in Lake Erie.

The lake evaporation from GLARM is very consistent and all three downscaling cases closely follow the seasonality and magnitude of GLERL-HMD (Fig. 3, second column). Compared to precipitation, GLARM's evaporation is affected to a lesser extent by the LBCs from GCMs. The evaporation minima during spring and early summer and maxima during the late fall and winter are well captured by GLARM. Noticeable discrepancies in evaporation between the GLARM ensemble average and GLERL-HMD are mostly limited to Lake Superior and Erie only. The ensemble average simulates smaller evaporation during September-March and October-December in Lake Superior and Erie respectively. Overall, compared to GLERL-HMD, the mean monthly lake evaporation from the ensemble average is smaller by 13 (24%), 0.1 (0.3%), 1 (1%), and 3 mm (6%) for Lake Superior, Michigan-Huron, Erie, and Ontario respectively.

More importantly, upon comparing GLARM's historical evaporation with those simulated by RCMs that were coupled to 1D lake models in Notaro et al. (2015a), Music et al. (2015), and Mailhot et al. (2019), it is evident that GLARM reproduces historical lake evaporation significantly better. The RCM-based evaporation presented in those three studies exhibited larger monthly biases and early seasonal peaks due to their rudimentary derivation of lake surface conditions via GCM lake/ocean grids or 1D lake models (see Fig. 6 in Notaro et al. (2015a), Fig. 2 in Music et al. (2015), and Fig. 2 in Mailhot et al. (2019)). This again highlights the importance and advantage of two-way coupling an RCM with a 3D lake model.

With respect to the basin runoff validation, the GLARM-driven LBRM-CC ensemble average also reproduces the seasonality of monthly basin runoff very well (Fig. 3, third column). The timings of the peaks are well captured in all lakes while the most noticeable discrepancy is that the LBMR-CC slightly underestimates the winter runoff and overestimates the snowmelt-fed spring peak and summer decline, particularly for Lake Michigan-Huron and Erie. Compared to GLERL-HMD, the mean monthly basin runoff from the ensemble average is larger by 6 (12%), 13 (19%), and 21 mm (26%) for Lake Superior, Michigan-Huron, and Erie respectively, and smaller by 12 mm (7%) for Lake Ontario.

Again, similar to over-lake precipitation, the individual downscaling cases illustrate the inherent uncertainties in climate impact modeling by spanning a wide range of values for basin runoff. MPI-GL (GISS-GL) produces the largest (smallest) mean monthly basin runoff primarily due to its larger (smaller) estimate for over-land precipitation, which is consistent with its large (small) estimate for over-lake precipitation.

The last column of Fig. 3 compares the simulated NBS (which is calculated by combining the simulated NBS components) with the residual NBS from the Coordinating Committee. The ensemble average reasonably captures the magnitude and seasonality of NBS because each NBS component is already well reproduced by the ensemble average. The NBS peak during spring and the subsided period during late summer and early fall are closely tracked by the ensemble average, albeit with a slightly higher magnitude for Lake Michigan-Huron and Erie due to the larger simulated basin runoff. Compared to the Coordinating

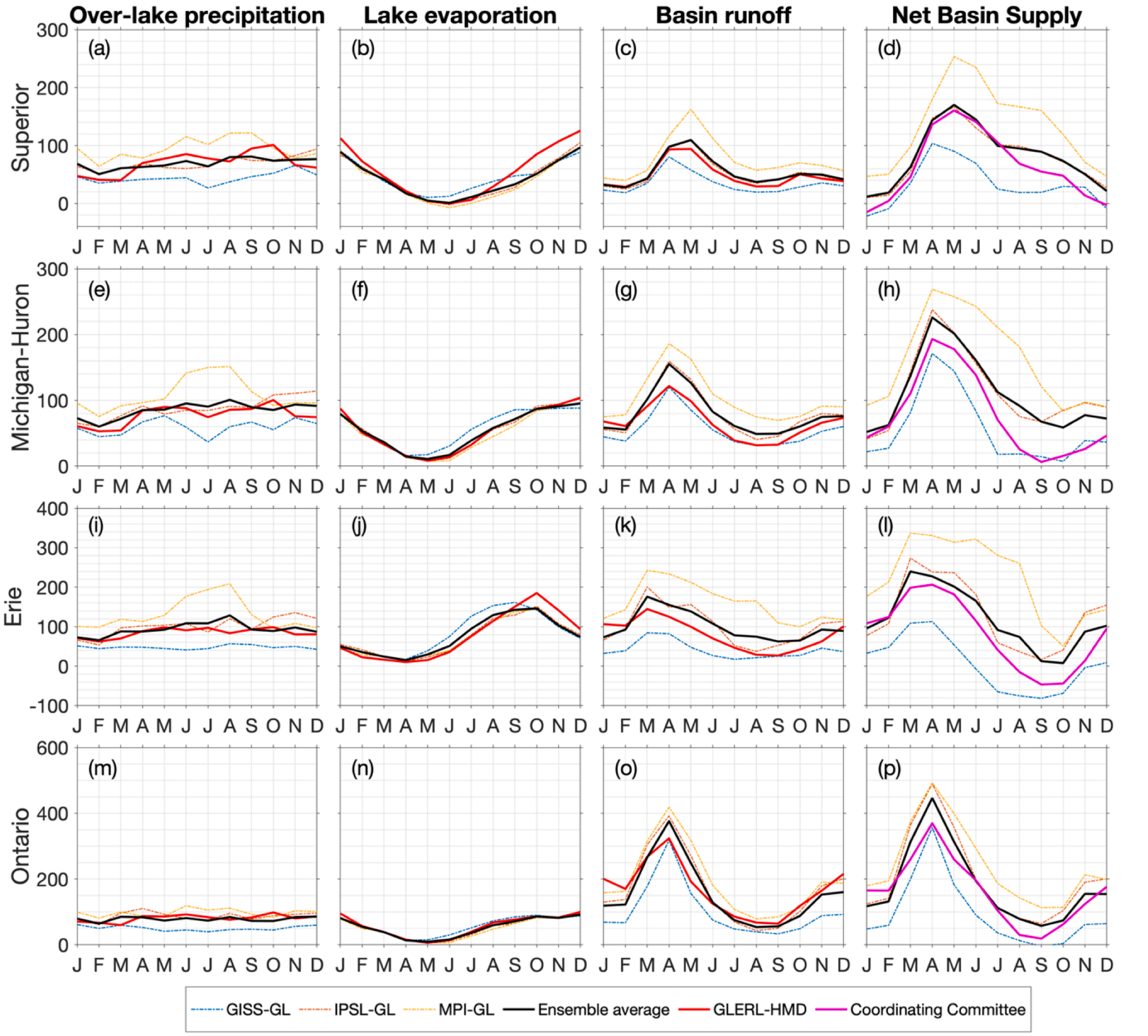

Fig. 3. Mean seasonal cycles of over-lake precipitation (a, e, i, m), lake evaporation (b, f, j, n), basin runoff (c, g, k, o), and NBS (d, h, l, p) for the early twenty-first century (2000–2019) in millimeters per month over the respective lake areas. The dotted lines represent the downscaling cases while the solid black, red, and magenta lines represent the ensemble average, GLERL-HMD, and the Coordinating Committee respectively. Results are shown for Lake Superior (a-d), Michigan-Huron (e-h), Erie (i-l), and Ontario (m-p). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Committee, the mean monthly NBS from GLARM is larger by 18, 34, 37, and 18 mm for Lake Superior, Michigan-Huron, Erie, and Ontario respectively. Since NBS is the combination of its components, the simulated NBS also reflects the differences between individual downscaling cases. For example, since MPI-GL (GISS-GL) estimates the largest (smallest) over-lake precipitation and basin runoff, it estimates the largest (smallest) mean monthly NBS as well.

Overall, the ensemble average reproduces the historical NBS and its three components remarkably well and justifies our selection of GCMs and the use of GLARM for future climate projections.

3.2. Assessing the impact of NBS biases on the long-term projection of water level change

The validation results show that the model performs well in simulating the climatological monthly values of over-lake precipitation, lake evaporation, basin runoff, and NBS. However, even though the biases are small in the climatological comparisons, one important question is whether and to which extent these biases can accumulate over time and result in the long-term projection drifting away from the true state over several decades, especially in the context of climate change impacts. In this section, we address this question with a set of CGLRRM simulations and quantify the cumulative impact of these so-called chronic biases on the long-term water level projection.

Four CGLRRM simulations were performed to examine the error accumulation in simulated water levels over time. Each simulation was driven by an NBS time series (1950–2019) with a perturbation, where the perturbations represented the levels of climatological biases. The perturbed NBS time series were created by applying four constant perturbations to the observed residual NBS time series of each lake: +10%, −10%, +20%, and −20% of the 1950–2019 NBS average. The four CGLRRM simulations are hereafter referred to as the perturbed runs. A fifth run in which CGLRRM is driven by the observed residual NBS was also performed and is hereafter referred to as the unperturbed run. By comparing the perturbed runs with the unperturbed run over a 70-year simulation, we examine whether the NBS biases quantified at the climatological level would accumulate over time in the long-term water level projection.

Fig. 4 shows the results from the perturbed and unperturbed runs for Lake Michigan-Huron (the other lakes produce similar results). It is evident from the lower panel of Fig. 4 that the perturbation in NBS result in a bias in the water level. However, note that the biases increase in a quasi-linear fashion only for the first five years and eventually transition to an asymptote where the bias level nearly reaches an equilibrium after the first 10 years. In other words, the errors in the water levels from the perturbed runs do not continue to grow with time after the first decade. It shows that the lake system has a memory of 10 years (it takes 10 years for the lakes to adjust to NBS changes through changes in inter-lake flows to reach a new equilibrium state). That is to say, it is appropriate to use the climatological error after the model spinup of the first decade to represent the level of climate projection’s uncertainty.

More importantly, the relative evolution in water level in all these simulations remains similar. This is quantified in Table 1 which, for example, shows that the difference between the January water level of 2000 and 2019 from the perturbed runs is similar to the difference from the unperturbed run. The relative magnitude of water levels between two periods is more or less conserved after the first decade. So, since the first decade of water level is already ignored for this study (described in section 2.3), the projected future water level changes from this study do not suffer from increasing errors/uncertainties that we were concerned of being amplified due to the climatological biases in NBS.

Table 1
Difference between the January water levels of 2000 and 2019 for different NBS perturbations.

Applied perturbation	Water level difference between 01/2000 and 01/2019 (m)		
	Superior	Michigan-Huron	Erie
Unperturbed	0.46	0.92	0.77
+10%	0.44	0.92	0.77
−10%	0.42	0.94	0.77
+20%	0.50	0.93	0.77
−20%	0.45	0.94	0.78

3.3. Projected changes in NBS and its components

The projected annual and monthly changes in NBS and its components are shown in Fig. 5 and Fig. 6 respectively. The ensemble average projects an increase in annual over-lake precipitation for all the lakes: +55, +54, +66, and +27 mm for Lake Superior, Michigan-Huron, Erie, and Ontario respectively by the mid-twenty-first century relative to the early twenty-first century. The biggest increases are projected for May-September with decreases or minimal changes projected for December-March.

Although the ensemble average projects an increase in annual over-lake precipitation, there is a large variability among the individual downscaling cases. The projections from the three downscaling cases range from +28 to +72 mm in Lake Superior, −11 to +92 mm in Lake Michigan-Huron, −4 to +138 mm in Lake Erie, and −25 to +64 mm in Lake Ontario; thus, illustrating the uncertainty in future climate

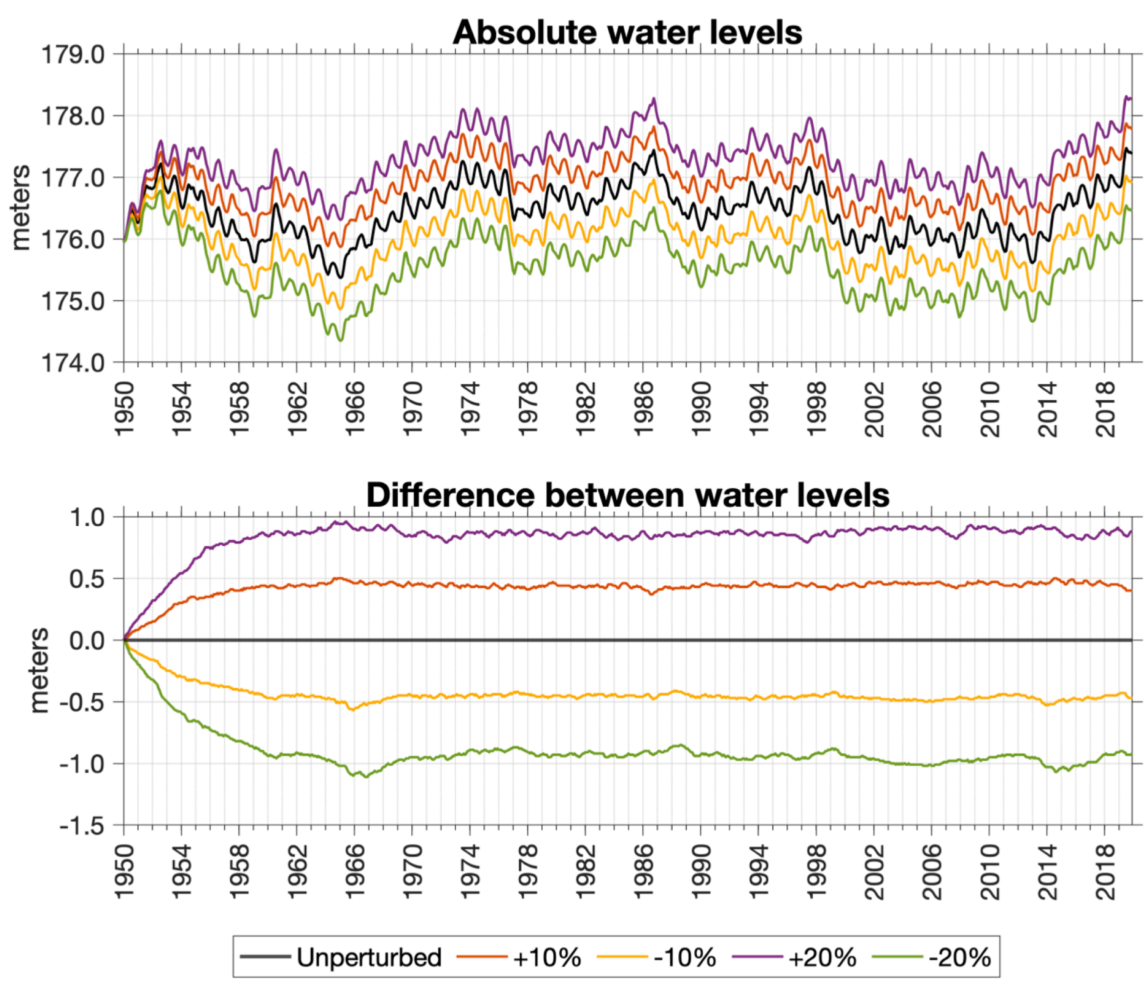

Fig. 4. Water levels of Lake Michigan-Huron for the unperturbed and perturbed runs (upper panel). The difference in water levels of Lake Michigan-Huron between the perturbed runs and the unperturbed run (lower panel).

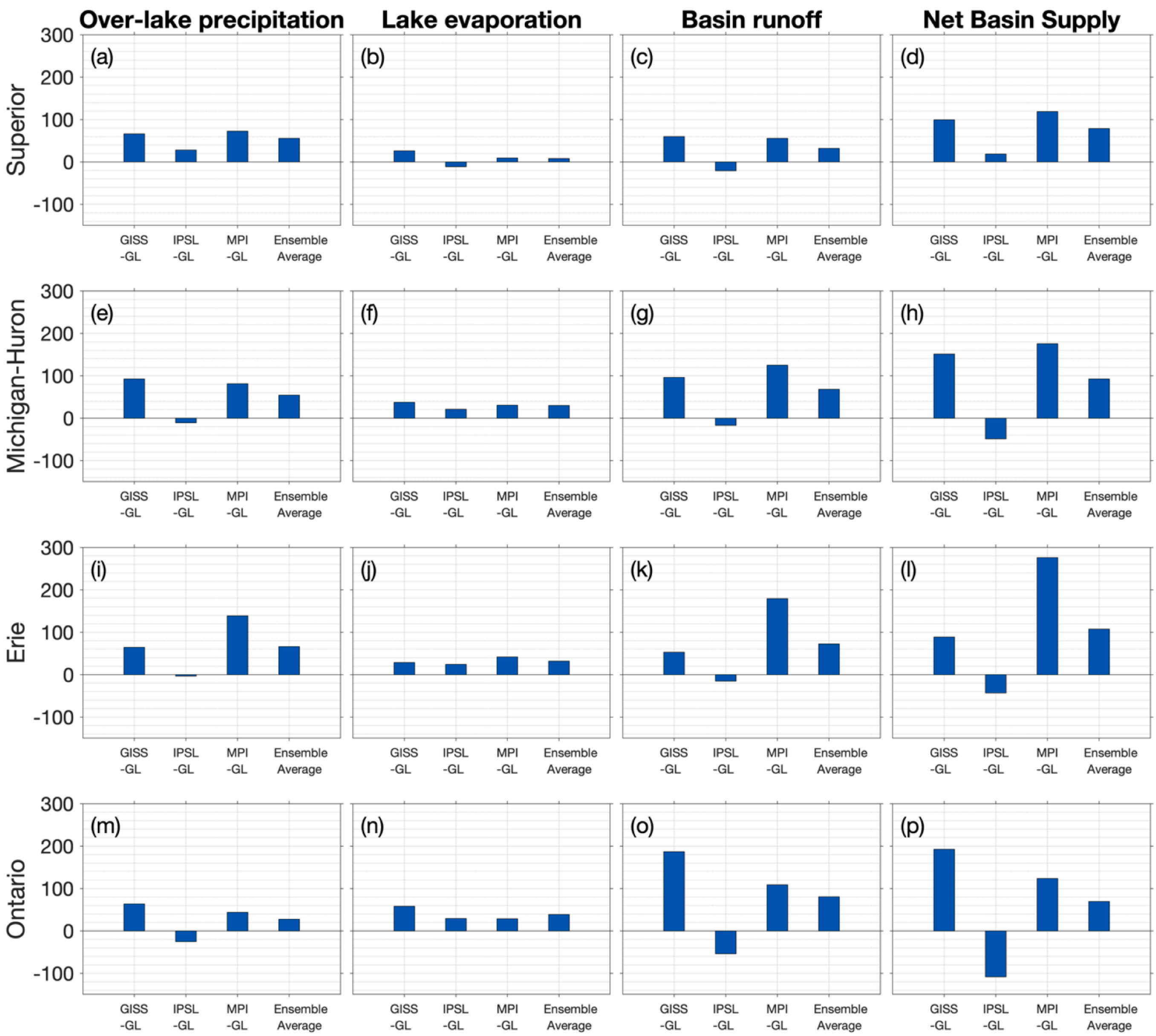

Fig. 5. Projected changes in annual over-lake precipitation (a, e, i, m), lake evaporation (b, f, j, n), basin runoff (c, g, k, o), and NBS (d, h, l, p) for each lake and downscaling case by the mid-twenty-first century (2030–2049) relative to the early twenty-first century (2000–2019). The changes are represented in millimeters per year over the respective lake area.

projections. IPSL-GL is the only downscaling case to project either decreases or the smallest increase in annual precipitation over the lakes. Such contrasting projections show that, in addition to affecting historical simulations as shown in the validation (section 3.1), the driving GCM also affects the future changes.

Similar to over-lake precipitation, the ensemble average projects an increase in annual basin runoff for all the lakes, and the individual downscaling cases project both increases and decreases. The ensemble average projects annual runoff increases of +31, +68, +72, and +80 mm for Lake Superior, Michigan-Huron, Erie, and Ontario respectively. The biggest projected increases such as +187 mm from GISS-GL for Lake Ontario are primarily due to the large projected increases in over-land precipitation. The projected decreases, on the other hand, are projected solely by IPSL-GL and are a result of a warmer and drier future climate. The projections from the three downscaling cases range from −21 to +59 mm in Lake Superior, −17 to +125 mm in Lake Michigan-Huron, −15 to +179 mm in Lake Erie, and −54 to +187 mm in Lake Ontario. As for the monthly changes, basin runoff is projected to increase in winter and early spring due to the increased snowmelt and precipitation and decrease in late spring due to the reduced snowpack following the increased snowmelt.

Compared to the over-lake precipitation and basin runoff changes, the projected changes in annual lake evaporation are smaller in magnitude. Lake Superior's annual evaporation is projected to undergo the smallest changes with IPSL-GL projecting a decrease in annual evaporation. In all the remaining lakes, all three downscaling cases project increases in annual evaporation. The changes projected by the ensemble average for the annual evaporation in Lake Superior, Michigan-Huron, Erie, and Ontario are +8, +30, +31, and +38 mm respectively. Evaporation is projected to increase during spring and summer with minimal changes during fall and winter, except in Lake Superior, where there is a clear decrease in evaporation during fall and early winter.

Compared to over-lake precipitation and basin runoff, the evaporation projections from the individual downscaling cases for a particular lake span a smaller range. This is consistent with the validation efforts

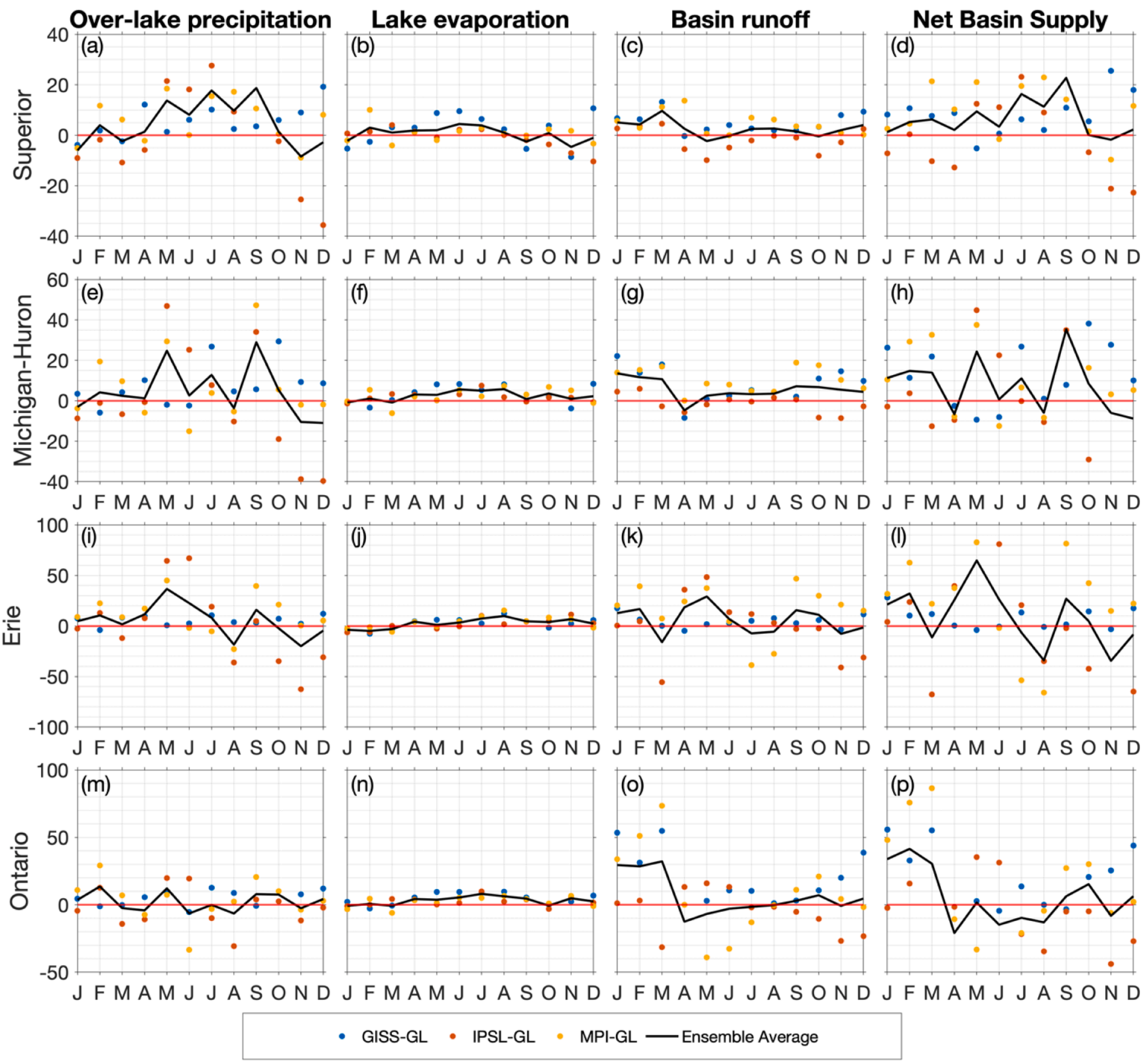

Fig. 6. Projected changes in monthly over-lake precipitation (a, e, i, m), lake evaporation (b, f, j, n), basin runoff (c, g, k, o), and NBS (d, h, l, p) for each lake and downscaling case by the mid-twenty-first century (2030–2049) relative to the early twenty-first century (2000–2019). The changes are represented in millimeters per month over the respective lake area.

for evaporation shown in Fig. 3. The projections from the three downscaling cases range from −11 to +26 mm in Lake Superior, +21 to +37 mm in Lake Michigan-Huron, +24 to +42 mm in Lake Erie, and +28 to +58 mm in Lake Ontario.

As for the NBS, the ensemble average projects an increase in annual NBS for all the lakes since, for most downscaling cases, the projected changes in the NBS components create an influx of water into the lake. The ensemble average projects the annual NBS to increase by +79, +92, +107, and +69 mm in Lake Superior, Michigan-Huron, Erie, and Ontario respectively. Peaks in NBS increases are scattered throughout the year with most of them coinciding unsurprisingly with the peaks in the projected over-lake precipitation and basin runoff increases. Peaks in the projected NBS increases are most common during May and September while November and December usually exhibit decreases or relatively minimal changes in NBS.

The projected changes in annual NBS from the three downscaling cases range from +18 to +119 mm in Lake Superior, −49 to +175 mm in Lake Michigan-Huron, −43 to +276 mm in Lake Erie, and −109 to +192 mm in Lake Ontario. IPSL-GL is the only downscaling case to project a decrease in NBS, mainly due to the projected decrease in precipitation and basin runoff.

3.4. Projected changes in water level

The ensemble average projects an increase in average annual water level for all the lakes: +0.19, +0.44, and +0.28 m for Lake Superior, Michigan-Huron, and Erie respectively (Fig. 7 and Figure S1). From the individual downscaling cases, the projections range from −0.01 to +0.32 m in Lake Superior, −0.13 to +0.80 m in Lake Michigan-Huron, and −0.09 to +0.54 m in Lake Erie. The projected increases are significantly larger than the projected decreases, hence the positive ensemble average. Additionally, no major changes are projected for the

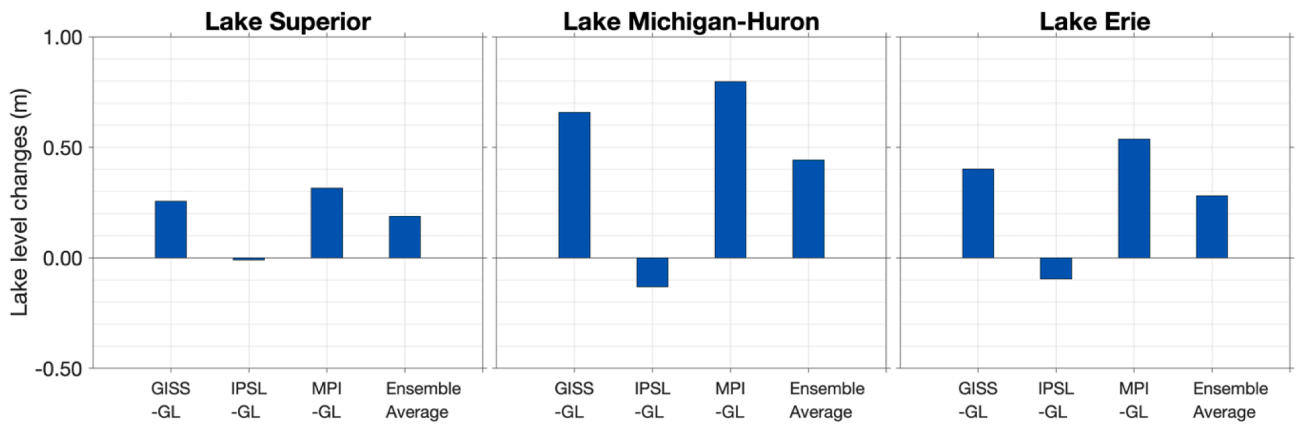

Fig. 7. Projected changes in average annual water level by the mid-twenty-first century (2040–2049) relative to the early twenty-first century (2010–2019).

seasonality of the water levels.

Changes in NBS are the primary drivers behind water level changes; however, since the Great Lakes are connected by rivers whose flows are mainly governed by the hydraulic head, the water level of a lake is also affected by the water level changes in the upstream and downstream lakes. So, the projected changes in water levels reflect the projected

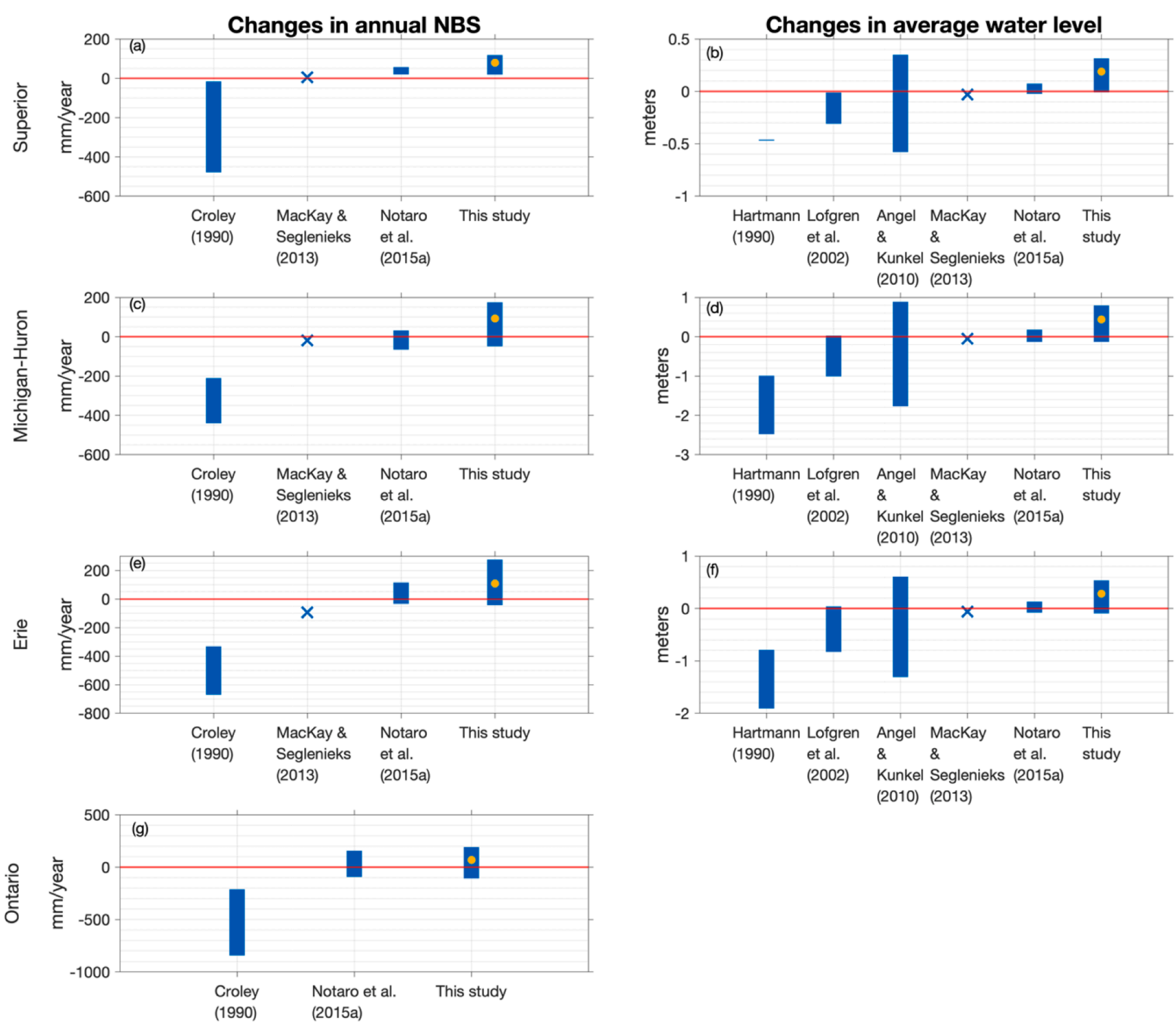

Fig. 8. Range of the changes in annual NBS (a, c, e, g) and water level (b, d, f) projected by this and previous studies. The change in NBS is represented in millimeters per year over the respective lake area. The projection from MacKay and Seglenieks (2013) is a single value (denoted by a cross) instead of a range because they projected the changes using a single GCM while the other studies used at least 2 GCMs. The projections from Croley (1990) and Hartmann (1990) are for the steady-state 2xCO_2 scenario. The projections from Lofgren et al. (2002) are for the 20-yr future time period centered in 2050. The projections from Angel and Kunkel (2010) are for the 2080–2094 period under the A2 emission scenario. The projections from Notaro et al. (2015a) are for 2040–2059 under RCP 8.5. The yellow dot represents the ensemble average of this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

changes in NBS as well as the projected water level changes in the upstream and downstream lakes. For example, even though IPSL-GL projects an increase in Lake Superior's NBS, the water level in Lake Superior decreases because the projected decrease in Lake Michigan-Huron's water level increases the outflow of water from Lake Superior through St. Mary's River. Therefore, the water level change of a particular lake is not an exact reflection of the lake's NBS change; rather, it is a reflection of the NBS changes across the whole Great Lakes system.

4. Discussion

4.1. Importance of a two-way coupled 3D lake model in simulating NBS

Xue et al. (2017) conclusively presented evidence of GLARM's superiority over RCM coupled with 1D lake model systems in simulating the thermal structure, surface water fluxes (e.g., precipitation and evaporation), and ice coverage of the Great Lakes. The exceptional historical simulation of NBS and its components by GLARM, presented in section 3.1, further supports Xue et al. (2017)'s conclusion. The accuracy of lake evaporation, which is the NBS component that is most affected by the lake modeling, has been significantly improved by GLARM when compared to the previous studies (e.g., Music et al., 2015; Notaro et al., 2015a; Mailhot et al., 2019) which used 1-D lake models to represent the Great Lakes. Lake evaporation was clearly impacted by their simplified lake model since, in their validation, their simulated evaporation had an almost different climatology pattern to the observation, as discussed in section 3.1. The ensemble averages of the historical NBS presented in this study are also better than those from the aforementioned studies due to the much-improved evaporation. Additionally, Xue et al. (2022) recently showcased GLARM's ability to significantly improve the driving GCM's air temperature, precipitation, LST, and ice cover for the Great Lakes. Therefore, GLARM, by properly representing the complexity of hydrodynamics and lake-atmosphere interaction, contributes to a more advanced modeling framework necessary for improving the Great Lakes' hydroclimate projections. This is particularly evident through the markedly improved simulation of one NBS component, lake evaporation.

4.2. Comparison of NBS and water level projection with previous studies

The range of the projected NBS and water level changes from this and previous studies are shown in Fig. 8. Upon comparison, the early GCM-based studies of Croley (1990), Hartmann (1990), Lofgren et al. (2002), and Angel and Kunkel (2010) projected significant decreases in NBS and water levels, partly due to the faulty LBRM that projected larger increases in evapotranspiration and subsequently larger decreases in basin runoff. GCM's inability to capture the moisture recycling within the Great Lakes (i.e., evaporated water returning to the lake as over-lake precipitation or basin runoff) also contributed to the large projected decreases in NBS and water levels (MacKay and Seglenieks, 2013).

RCM-based studies, including this one, do not project drastic decreases in NBS and water level due to the projected increase in over-lake precipitation and basin runoff. While the NBS and water level increases projected by our ensemble average are closer to the increases projected by the RCM-based studies, the upper bound of our projected water level increases is in fact closer to the increases projected by the GCM-based study of Angel and Kunkel (2010). It should be noted that all these previous studies considered different time periods and emission scenarios for their projections, but a comparison is nevertheless useful as it illustrates the challenges and uncertainties in projecting the water level of the Great Lakes. These comparisons also suggest that as there are many methodological differences and associated sources of errors and uncertainties that may be accumulated or offset in all these studies, it is difficult to assert that the current study has the most accurate projection of the water level change. However, we highlight that the current study does provide the more appropriate and the most advanced modeling framework which is a critical step towards a better understanding and projection of the Great Lakes water level changes. Also, a future rise rather than a decline of the Great Lakes water levels is more likely based on the most up-to-date climate projection.

4.3. Challenges in water level projection

This paper marks one of the more notable advances in water level projection of the Great Lakes by using a two-way coupled RCM and 3D lake model to project NBS. However, apart from the mostly unavoidable uncertainties in future climate modeling which Giorgi (2010) calls the intrinsic uncertainties (those related to future climate policies and internal variability in climate), there are some limitations stemming from our applied models that could be addressed in future complementary studies.

One focus of future studies should be developing water level projections using a two-way coupled land-lake-atmosphere modeling system that can more accurately represent the complete hydrological cycle of the Great Lakes. The modeling framework used in this study is also a land-lake-atmosphere coupled modeling system but the basin runoff and inter-lake flows/water levels in this study were simulated offline using LBRM-CC and CGLRRM respectively. An integrated two-way coupled land-lake-atmosphere modeling system, with a more advanced representation of land hydrology processes, would provide a better estimation of basin runoff in the Great Lakes. For example, the direct contribution of groundwater to the Great Lakes is considered to be negligible in magnitude when compared to the NBS components and therefore was ignored or lumped into the error term in almost all studies relating to the Great Lakes water budget (Lee, 1992; Lenters, 2001, 2004; Fortin and Gronewold, 2012). However, groundwater has a big impact on basin runoff and therefore has a significant indirect contribution to the lakes' water balance. LBRM-CC has a simplified representation of land surface processes as described in section 2.1.2. In addition, although LBRM-CC considers the contribution of groundwater to basin runoff, it does not account for the lateral exchange of groundwater between subbasins. Using a modeling system that resolves land–atmosphere interaction and vertical/lateral movement of surface and subsurface water to calculate basin runoff would be an improvement upon this study. A modeling system like the NCAR Weather Research Forecasting (WRF) hydrological modeling system (WRF-Hydro) (Gochis et al., 2020) is a possible future substitute for LBRM-CC. The integration of WRF-Hydro into GLARM would offer a more realistic representation of land surface processes on both temporal and spatial scales, which has a profound impact on the soil thermal and moisture states, surface energy fluxes, and consequently on the entire coupled land-lake-atmosphere processes.

Future studies can also complement this study by downscaling a larger and more advanced ensemble of GCMs. The GCMs for this study were chosen from CMIP5 based on the REA method. So GCMs from the latest phase of the Coupled Model Intercomparison Project, CMIP6, along with other GCM ensembles and selection methods that have been prescribed for use in the Great Lakes region (Delaney and Milner, 2019), can help improve upon this study. The use of new integrated modeling systems and a larger ensemble of projections will help improve our understanding of the role of climate change in Great Lakes' water levels and ultimately help water resource managers better prepare for the future.

5. Summary

The changes in the Great Lakes' NBS components, NBS, and water levels by the mid-twenty-first century relative to the early twenty-first century are projected using an ensemble of three GLARM-based dynamical downscalings. Unlike the widely used RCMs that are two-way coupled to 1D lake models, GLARM two-way couples the RegCM4 RCM to an FVCOM-based 3D lake model. The modeling system reproduces the present-day NBS remarkably well, with a significantly improved simulation accuracy of lake evaporation, reinforcing the importance of this new modeling system for hydroclimate simulation. The ensemble average of the simulated NBS and its components closely follow the estimates from GLERL-HMD and the Coordinating Committee, with the span of individual downscaling cases representing the uncertainty present in GCMs.

For future hydroclimate, the ensemble average projects an increase in annual NBS and average annual water level for each lake. Increases in over-lake precipitation are projected in May-September with minimal changes during winter, while increases in basin runoff are the most significant during the winter and early spring due to increased snowmelt. As for annual lake evaporation, compared to over-lake precipitation and basin runoff, the ensemble average projects relatively smaller increases, with slight increases for spring and summer followed by decreases or minimal increases during the fall and winter months.

The projected changes in the NBS components result in an increase in the average annual water level. According to the ensemble average, by 2040–2049, the average annual water levels of Lake Superior, Michigan-Huron, and Erie are projected to increase by +0.19, +0.44, and +0.28 m, respectively, relative to 2010–2019. The individual downscaling cases highlight the uncertainty in climate projection, showing both increases and decreases in annual NBS and average annual water level projection. For GISS-GL and MPI-GL, the projected changes in the NBS components result in an increase in average annual water level by 2040–2049 relative to 2010–2019. However, IPSL-GL project decreases in average annual water level, thus leading to projections ranging from −0.01 to +0.32 m in Lake Superior, −0.13 to +0.80 m in Lake Michigan-Huron, and −0.09 to +0.54 m in Lake Erie. Water level projections highlight the complexity of the Great Lakes hydroclimate system and the need for an integrated modeling framework as a critical element toward better understanding and projections of the Great Lakes water levels.

CRediT authorship contribution statement

Miraj B. Kayastha: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Xinyu Ye:** Methodology, Software, Writing – review & editing. **Chenfu Huang:** Methodology, Software, Writing – review & editing. **Pengfei Xue:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.128205.

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