Reviewer2:

RC2: ['Comment on gmd-2021-440'](), Anonymous Referee #2, 06 Feb 2022

This study demonstrates the use of a two-way coupling of regional climate models with a 3-D hydrodynamic model (GLARM) of the US Great Lakes based on three selected CMIP5 AOGCMS and two spatial domains. The authors first evaluate the degree of skill of the models and then examine two climate scenarios (RCP 4.5, 8.5) and evaluate their impact on the Great Lakes Basin during the mid and late 21st century. They show the spatial and temporal variability in expected precipitation, ice cover and LST for all the great lakes.

General

I found the paper to be very well written and timely. It represents one of the only cases (if not the only one) in which two-way coupling of a lake 3D hydrodynamic model and regional climate model have been use to examine the potential impacts of project climate change under various climate scenarios.

Nevertheless a number of questions come to mind. Were the lake models driven with inflows and outflows and do the models account in any way the likely increase in inflows especially during the rainy spring period as projected by the results of simulations? If the inflows and outflows are neglected in the simulation, this should be mentioned and discussed as I assume they will have an impact on water temperature.

Response: Thanks for the question! The hydrological cycle is not simulated in this paper for two reasons. First, surface hydrology requires great effort and needs to be studied separately. 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, and minus lake evaporation), in a combination with the Great Lakes regulation plan as well as inter-lake flows to describe a complete water budget. This requires a suite of models to be properly integrated to project water level changes. In fact, we have done it in our recent study of the Great Lakes water level, which has been submitted to *Journal of Hydrology*, "Future Rise of the Great Lakes Water Levels under Climate Change" by Miraj B. Kayastha, Xinyu Ye, Chenfu Huang, Pengfei Xue* (corresponding author) (in revision). In that paper, we integrated GLRM (for over lake precipitation, evaporation), LBRM(Large Basin Runoff Model for river runoff into each lake), CGLRRM (Coordinated Great Lakes Regulation and Routing Model for inter-lake flow and regulation plans) to project the changes in surface hydrology and the Great Lakes water level change in the future. Given the complexity and importance of this topic, it is beyond the scope of this study. Second, the water level fluctuation (1-2 m) does not impact the surface area of the Great Lakes (considering the depth and size of these lakes); therefore, water level change (which is certianly critical for coastal erosion, navigation) does not play an important role in influencing lake-air heat fluxes and climate change, that's why we simulate the over lake evaporation (latent heat flux) but did not simulate complete surface hydrological cycle in this study. In addition, the heat transport between lakes associated with inter-lake flows is secondary. It falls in the uncertainty of surface heat fluxes (i.e. the primary cause of lake thermal change) in the GLARM.

These are now explicitly mentioned in the discussion section as "*We note that this study does not directly simulate the surface hydrological cycle for three reasons. First, the water levels of the Great Lakes are primarily governed by the net basin supply (NBS) of each lake (over-lake precipitation, river runoff, and lake evaporation), in combination with natural and regulated inter-lake flows. The projection of water level changes requires the integration of a suite of models. Such integration is documented in our separate study, in which we use GLARM (for over-lake precipitation, lake evaporation), LBRM (Large Basin Runoff Model) for river runoffs into each lake, CGLRRM (Coordinated Great Lakes Regulation and Routing Mode) for inter-lake flows. Given the complexity of the projection of the surface hydrological cycle, it is beyond the scope of this study. Second, the impact of water level change on the surface area of the Great Lakes is negligible; therefore, water level change does not play a critical role in influencing lake-air heat fluxes and climate change. Third, compared to the primary factor (surface heat fluxes) of lake thermal change, the heat transport between lakes associated with inter-lake flows is secondary on the lake basin-wide scale. It falls in the uncertainty of surface heat fluxes in the GLARM projections.* "

The authors mention two key physical processes in the lakes but don't present any data or model output for the two processes. The first is the possible change in stratification which as the authors quite correctly point out in the introduction can greatly impact the ecosystem. The second is the mention of the possible effect of the mixing of heat from the surface to bottom. It would be very interesting to see what the projected change in the duration in stratification is expected to be (as expected by the authors, lines 436-437) and whether there is any clear increase in bottom water temperature to support the mechanism suggested by the authors (e.g. line 437-439). I would also have liked to see a brief discussion as to the quality of the 3d lake model results in relation to other models and where the weaknesses may be.

Response: Good question! This question was asked by other reviewers too! In the revised version, one of the major changes we made is to address this question. We have dedicated a thorough discussion from lines 279-302 and new figure 12 (projected thermal structure change) to this. Here I try to make a short summary: It is related to the strong early stratification in the deep lakes that cause a significant increase in spring LST. And the higher ice cover in Lake Erie (which leads to a relatively lower increase in LST during winter), and relatively lower ice in deep lakes. This is because deep lakes are, by nature, large heat reservoirs that can transfer heat from a deep lake layer to the surface to reduce ice formation. The best example is the observed ice coverage of the shallowest lake (Erie) and the second deepest lake (Ontario). Both lakes have small surface areas but significantly different water depths (mean water depths are 19 m and 86 m, respectively, Fig. 1, panel b), resulting in high (low) winter ice cover in Lake Erie (Ontario) (Fig. 4).

Here is new figure 12 (screenshot) for the projected change in the duration in stratification is expected to be and clear increase in bottom water temperature to support the mechanism suggested by the authors.

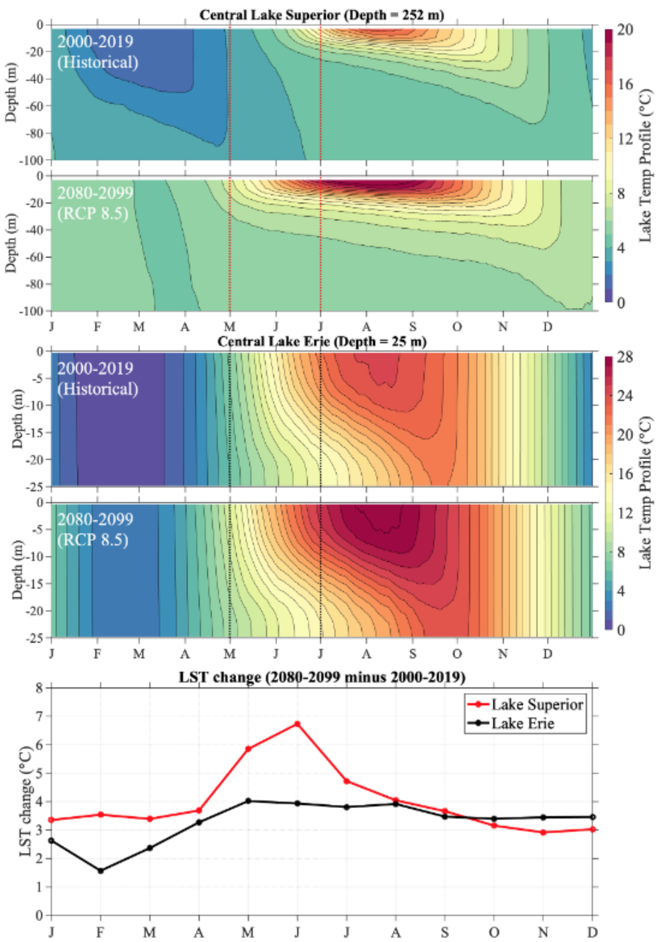

Figure 12. The lake thermal structures in the central Lake Superior (upper panel) and Lake Erie (middle panel) in the present-day climate (2000-2019) and the late century (2080-2099). Bottom panel:The comparison of projected changes in monthly LST in Lakes Superior and Erie in the late century (2080-2099) in RCP 8.5, relative to the present-day climate (2000-2019).

What are the important 3-D lake processes that 1-D lake models fail to resolve and impact lake thermal structure and ice cover? We have a separate manuscript (*Importance of Coupling a 3D Lake Model to the Regional Climate Model in Simulating the Great Lakes System by Xue P, Notaro M., Huang C., Zhong Y., Peters-Lidard, C., Cruz, C., Kemp, E., Kristovich, D., Kulie, M., Wang, J., Huang, C., Vavrus, S* to be submitted to Journal of Hydrometeorology, which specifically addresses this. As you may notice, this is a study with a separate group of collaborators and we don't steal the main message from that study. So we prefer not to discuss it in this manuscript (thank you for your understanding). However, We are happy to share our findings here below.

We have done a set of process-oriented numerical experiments in the aforementioned study and results show that the most important lake process that impact LST and ice is the turbulent mixing process, which is controlled by turbulent kinetic energy calculated by shear production, buoyancy production, rate of dissipation, and advective and turbulent transport. Many of these processes require 3-D fields to be correctly estimated. In the 1-D model, these estimations have to be simplified with 2 m wind speed, the Brunt-Väisälä frequency, the latitude-dependent Ekman decay, and often with an empirical modification factor to find a lumped eddy diffusivity coefficient. This is the most important process that the 3-D lake model outperforms 1-D lake models in simulating lake thermal structure.

Also, our previous publication (Ye, X., Anderson, E. J., Chu, P. Y., Huang, C., & *Xue, P.[Corresponding author] (2018). Impact of Water Mixing and Ice Formation on the Warming of Lake Superior: A Model-guided Mechanism Study. Limnology and Oceanography) studies the impact of strong and weak winter mixing on the lake heat content and lake surface temperature and ice. During wintertime, stronger mixing causes a warm surface layer by allowing the heat transport to the surface from the warmer deep layer, causing less ice and stronger evaporation. Weaker mixing results in a strong winter stratification, and cold surface with extensive ice cover.

There are other important 3-D processes that can only be resolved in 3-D lake model, including heat transport associated with large-scale circulation, and density-driven two-layer baroclince flow, upwelling, and ice drifting, which significantly affect the spatial pattern ice coverage (we have done simulations with and without ice drifting).

Specific comments:

Line 28- % of what

Response: the sentence is revised as “Correspondingly, the highest monthly mean ice cover is projected to be reduced to 3-15\% and 10-40\% across the lakes by the end of the century in RCP 8.5 and RCP 4.5, respectively.”

Line 97- remove the word in

Response: removed.

Line 101- FVCOM not yet defined

Response: Corrected. Finite Volume Community Ocean Model (FVCOM)

Line 116- add space between ice and atmosphere

Response: added.

Line 145-149- how accurate are these data compared to actual measurements? Is a correction required before using to validate the model?

These data have been used in many studies in the Great Lakes region. It is appropriate to use the dataset for a basin-wide assessment (but not the best choice for site-specific validation if in-situ data is available). The GLSEA LST has a very good representation of the LST spatial pattern (based on our studies with three NOAA-funded data assimilation projects for the Great Lakes); however the GLSEA LST data quality is much lower during the wintertime because of the quality and availability of satellite data and ice cover. That's why we focused on ice cover data to validate the model performance during winter.

Eq 1- over what time and spatial resolution is this calculated? Is there a reference to the use of this type of equation?

Response: We conducted the model reliability analysis using model-simulated NA-averaged temperature in the historical periods (1901-2005) and the future period (2006-2100) in RCP 8.5 scenario. The three GCMs with the highest reliability scores are selected to drive GLARM for the present-day and two future periods in each scenario.

As we cited in our paper, this method including the equation is documented in (Giorgi and Mearns, 2002, Journal of Climate: Calculation of Average, Uncertainty Range, and Reliability of Regional Climate Changes from AOGCM Simulations via the "Reliability Ensemble Averaging" (REA) Method). This is equation (4) in their paper.

The equation is also shown as equation 2 in Miao, C., Duan, Q., Sun, Q., Huang, Y., Kong, D., Yang, T., Ye, A., Di, Z., and Gong, W.: Assessment of CMIP5 climate models and projected temperature changes over Northern Eurasia, Environmental Research Letters, 9, 055 007, 2014. (this citation is also added in the revision)

After the three GCMs are selected using reliability analysis, we then used taylor diagrams (RMSD, correlation, Std; figure 2 upper panel) and warming trend analysis (figure 2, lower panel) to check (validate) if our GCM selection is appropriate. The four statistic metrics are for independent validation of our GCM selection.

Table 2- change RMSE in the legend to RMSD

Response: corrected.

Figure 3- would be nice to have lake names on this and the other figures, especially for those not familiar with the Great Lakes.

Response: we've added lake names to all applicable figures.

Figure 4- legend- there is a mistake in the seasons and figures. A1,a2 for example are the winter and not spring.

Response: Corrected.

Figure 8 legend- word missing from last line.

Response: Corrected.

Table 3- what is ΔT2 in column title?

Response: We replaced ΔT2 with "T2 change", along with more clear table title: The projected changes in monthly, seasonal, and annual surface air temperature over land, lake, and the Great Lakes basin in the mid-century and the late century in RCP 4.5 and RCP 8.5 scenarios, relative to the present-day climate (2000-2019).

Line 343- "particularly in Aril and May" this is correct only for the end of century results

Response: corrected.

Line 361- Figure 12 should be Table 5

Response: corrected.

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A note:

Finally, we want to let you know that in response to other reviewer's question and our (Co-PI) internal discussion (also in consulting with a senior climate scientist at MIT) on the concern of whether or not (and how) we should combine these 3 GLARM-large domain model results and 3 GLARM-small domain model results. We agreed that a simple ensemble average seems questionable because these results are from two sampling groups that can possess different uncertainty distributions. We decided just to use one of the domains. We selected the small domain GLARM, which is similar to other RCM configurations for the Great Lakes climate studies, to represent the uncertainty inherited from different GCMs and enhance the computational efficiency. Nonetheless, please note that the results (GLARM-EA3) are similar to our previous 6-member ensemble results (GLARM-EA6), and all conclusions remain unchanged. Still, we did update the results (like numbers and tables) throughout the manuscript.

Thank you again for your questions and suggestions. I hope we have addressed your concerns and questions satisfactorily.