Reviewer1:

RC1: 'Comment on gmd-2021-440', Anonymous Referee #1, 04 Feb 2022
The paper presents climate projections of the Great Lakes region based on a regional climate model (GLARM) coupled with an ocean model (FVCOM) applied to the Great lakes. Climate projections derived from 3 ESMs and for two RCP scenarios have been used. The predictions for the mid and late 21st century are discussed. The results show the increased lake surface temperature and reduced ice cover at annual and seasonal scales with strongest changes over the Lake Superior.

Overall comments:
The paper is interesting and well written. The results are reasonable and well discussed. My main concern is the use of an ocean model to simulate the lake processes and the fact that the processes which are represented are not really described. It seems that only the energy transfers are represented and that there are no coupling with the surface model hydrology. I would like to know how the water volume of the lake is constrained, are they some glaciers melting water and lateral runoff inputs, water table exchanges ? how these contributions are impacted by climate warming? And how can they modify lake temperatures in addition to the direct exchanges with the atmosphere?

Response: Thanks for your question. The use of community ocean models to simulate the Great Lakes has been widely applied in an appropriate way. Because of their sealike characteristics (including distant horizons, great depths, steep bathymetric gradients, strong Coriolis-influenced currents, and large thermal variability), the Great Lakes have long been referred to as ‘‘inland seas’. All-natural water bodies (lakes and oceans) are physically described by the same set of primitive equations that are used in nearly all community ocean models. The major difference is that the Great Lakes is a freshwater system (no salinity simulation is needed, which is a standard option to turn on and off in all ocean models) and that’s why it can be well handled by ocean models.

In fact, the NOAA official Great Lakes Operational Forecast System (GLOFS:https://tidesandcurrents.noaa.gov/ofs/glofs.html) utilizes FVCOM (Finite Volume Community Ocean Model) for the Great Lake hydrodynamic operational forecast. Note that FVCOM is also the hydrodynamic model we used in GLARM. The use of ocean models (more precisely, they are all 3-D hydrodynamic models originally developed for ocean application but are also suitable for the Great Lakes) in the Great Lakes has been for decades. Popular ocean models used for the Great Lakes include POM (Princeton Ocean Model), FVCOM (Finite Volume Community Ocean Model), NEMO (Nucleus for European Modelling of the Ocean), etc. However, these models were applied to the Great Lakes in a standalone fashion. The importance of this study is the two-way coupling of the RCM (RegCM4) and 3-D hydrodynamic model (FVCOM) to resolve lake-air interactions to better represent the system for climate change projection, To date, no studies exist applying a 3-D hydrodynamic model (only 1-D column lake models were used) two-way coupled with RCM to resolve the air-lake-ice interactions in projecting the evolution of the Great Lakes themselves interacting with regional climate changes.

Because there are plenty of applications and publications on the standalone hydrodynamic model (ocean model) simulations of the Great Lakes. We feel redundant to re-introduce and discuss them. FVCOM has gained popularity in research and applications to the Great Lakes (Anderson and Schwab, 2013; Bai et al., 2013; Beardsley et al., 2013; Xue et al. 2015; Anderson et al. 2018; Ye et al. 2020 and many more). There are other coastal hydrodynamic models (e.g., Beletsky et al., 2006; Fujisaki et al., 2013; Dupont et al., 2012; White et al., 2012 and others.) with similar characteristics to FVCOM, but we chose the FVCOM model because it is currently being used by NOAA for operational forecasting in the Great Lakes.

You are right, 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 is 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 which, we integrated GALRM (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 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.

These are now explicitly mentioned in the discussion section “*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 (Kayastha et al., under review), 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.*"

Anderson, E. J., Fujisaki-Manome, A., Kessler, J., Lang, G. A., Chu, P. Y., Kelley, J. G., ... & Wang, J. (2018). Ice forecasting in the next-generation great lakes operational forecast system (GLOFS). *Journal of Marine Science and Engineering*, *6*(4), 123.

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

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

Beardsley, R. C., Chen, C., & Xu, Q. (2013). Coastal flooding in Scituate (MA): A FVCOM study of the 27 December 2010 nor'easter. *Journal of Geophysical Research: Oceans*, *118*(11), 6030-6045.

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

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

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

White, B., Austin, J., & Matsumoto, K. (2012). A three-dimensional model of Lake Superior with ice and biogeochemistry. *Journal of Great Lakes Research*, *38*(1), 61-71.

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

Ye, X., Chu, P. Y., Anderson, E. J., Huang, C., Lang, G. A., & Xue, P. (2020). Improved thermal structure simulation and optimized sampling strategy for Lake Erie using a data assimilative model. *Journal of Great Lakes Research*, *46*(1), 144-158.

Specific comments:

- Equation 1, P7: I am not familiar with these scores, is there a justification to have this form of combination of the metrics? I am wondering if the exponent should be 1/(m+n) instead of 1/(mxn)? Is there a reference to this equation that could be added?

Response: It is 1/(mxn), 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)

-P12, Table 2 , REA is not defined, how did you combined the 3 statistical metrics ?

Response: REA is defined in line 188 in the original manuscript, but we noticed that the description was not clear. We have revised the description of GCM selection (i.e. the description of equations 1 and 2 for reliability analysis) in line 135-145 in the revised manuscript, it should be clear. Regarding table 2, we shouldn’t put “REA” there, it should be “normalized reliability score” (which has caused your confusion), this has been corrected in the revision.

Notice that the reliability analysis was used to select the three GCM models. AFTER the three GCMs are selected, 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 reliability analysis for GCM selection does not (should not) combine the 3 statistical metrics. The three statistic metrics are for independent validation of our GCM selection.

-P14, line 263, evaporation and latent heat flux are the same variable (in different units) please modify your sentence.

Response: Within the Great Lakes, LST and ice cover are the two most important physical lake variables that influence the lake-atmosphere heat and water fluxes by affecting solar radiation, longwave radiation, and sensible and **latent (evaporation) heat**.

- Figure 4: it would be more clear to map the differences mod/obs in the right column

Response: We (co-authors) have discussed this comment internally. We feel that, for the present-day simulation, we prefer to show the model simulated patterns to give readers an intuitive feeling of the model performance. In addition, we discussed modeled patterns (not only differences) in the later sections, so showing the observed and model pattern rather than the differences is better. We prefer to retain the current plot. Thanks for your understanding.

-Figure 5: the names of the lakes need to be added on the plots,

Response: added.

-Figure 6: the legend is not clear, is it annual mean of the differences that are plotted, what about seasonal variations?

Response: Thanks, it is the annual mean of the differences. We changed the caption into "*The projected changes in the annual mean surface air temperature over the Great Lakes basin during the mid-century (2030-2049) and the late century (2080-2099) in RCP 4.5 and RCP 8.5 scenarios, relative to the present-day climate (2000-2019).*" And the legend has also been revised as "T2 change" instead of "T2", this should avoid any potential confusion. The seasonal variations are presented and discussed in Figure 7 and Table 3. Notice that we have had results for 2 scenarios and 2 periods and we already have 16 figures (we added more important information on lake thermal structure) and 5 tables. We also try to pick the most important information for readers and avoid overwhelming them.

-Figure9: Total precipitation changes are plotted, how is it shared between rainfall and snowfall? How rainfall is treated when it falls over the lake? Can it freeze/melt when the lake is ice covered?

Response: This study doesn't distinguish between rainfall and snowfall and doesn't include its impact on water level change (please see our response to the general comment).

- Figure 13 and text related: do you have explanations concerning the lower warming of the Erie lake? The lake is the shallowest, it should be more impacted by the atmosphere warming, did I miss something?

Response: Good question! 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 is 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).

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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 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. We have updated the results (like numbers, figures, and tables) throughout the manuscript, please see track change version that marks all updates and changes.

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