Reviewer 1:

General comments

This paper describes model improvements when using a fully 3-dimensional hydrodynamic model within a regional climate model. The authors describe the simulation improvements with the 3D model as compared with a 1D model, and explore the physical processes that lead to this improvement. As the authors acknowledge, this coupling has been performed before and several other papers have highlighted the importance of improving deep lake representation. The novelty in this paper is that they explore the physical reasons as to why these improvements occur. The results in the latter half of the paper are interesting, and the authors do a thorough job explaining the physical processes underlying the model improvement.

My main comments are surrounding the paper organization, figure clarity, and being sure to accurately acknowledge prior work in this space. These revisions are relatively minor, and I recommend publication with this minor changes.

Thank you for your thoughtful comments and suggestions to help improve our manuscript. We have carefully considered your feedback and incorporated the suggested revisions into the updated manuscript, along with a detailed point-by-point response to facilitate your evaluation. For your convenience, we have also included a version of the manuscript with tracked changes.

Process description

> The process-level description that the authors are highlighting isn't explained with equations until much later in the paper (5.2 for the heat transport, 5.3 for the vertical mixing). It would have helped if the authors had used a more traditional framework and described the important component models upfront (e.g., in Section 2.2) to make all the processes clear before getting to the results
> In the same way, there is one paragraph on the 1D model in Section 2.2 that is out of place. Given that the paper focuses on how the results are so different, more time to clarify the key difference of the model (in equations) would have set up the paper better.
> This would be helpful for later interpretation, e.g., Section 5.1 – line 523-4 states "Instead, only ice thermal dynamics are simulated as in the 1D lake model." Something that describes this 1D process would be helpful for the reader.

Response: As suggested, we have revised the manuscript structure to follow a more traditional framework and now describe the key component models up front in Section 2.2. We have also added a new Section 2.3 to describe the 1D lake model (including equations) to provide readers with the necessary background information.

Figure consolidation – Many of the figures have redundant information in them, e.g.,

> Figures 4/10/13 (vertical T profiles at the Spectacle Reef Site): Many duplicate panels in these three figures. While I understand the intention to step through the different experiments, I often wanted to see these figures side by side. I think these panels could be effectively combined to make one comprehensive figure.
>
> Figure 5/8/14 (spatial distribution of ice cover): Same as above – lots of redundant information on these figures, and it would help the reader to see some consolidation here.

Response: Thank you for your suggestion regarding Figures 4, 10, and 13 (vertical temperature profiles at the Spectacle Reef site) and Figures 5, 8, and 14 (spatial distribution of ice cover). We understand your preference for a consolidated view to facilitate side-by-side comparison across experiments.

To address this helpful suggestion, we have compiled the relevant figures into **Supplementary Figures S4 and S5**, enabling direct visual comparison of results across the different experimental setups.

We have chosen to retain **original Figure 4** and have combined **Figures 10 and 13 into a new Figure 10, as you suggested,** in the main manuscript, as this structure provides a step-by-step narrative aligned with the logical progression of our analysis. This sequential approach helps guide the reader through the key hydrodynamic processes and their individual impacts at each stage of the study.

Since **Figures 5, 8, and 14** each represent different phases of the experimental analysis, we feel it is not ideal to present them together early in the manuscript without discussion until much later. Maintaining their original structure supports a clearer, more coherent progression for the reader. We also simplified **Figure 14** (now **Figure 13**) to remove redundant information.

That said, for readers interested in **side-by-side comparisons** of thermal structure and ice cover across model cases, we provide a consolidated view in **Supplementary S4 and S5**, as you suggested.

We believe this approach—maintaining a logically structured main figure layout while offering a complementary, reformatted comparison in the supplementary materials—offer an optimal balance between clarity, readability, and comparative utility.

> All figure panels could use some additional labeling on rows/columns, as they change from figure to figure (e.g., sometimes the different months are the rows, sometimes

they are the columns). Also, many of the fonts and legends are *extremely* small and hard to read (e.g. Figures 9, 11, 12). Some sublabels (e.g., labeling the panels a, b, c, etc.) would help to connect specific figures to the text.

Response: Regarding figure quality, labeling, and readability, we have carefully reviewed and revised all figures based on your suggestions. These adjustments improve clarity and visual coherence across the manuscript, ensuring a more accessible and effective presentation of the data. We appreciate your suggestions, which helped us improve the clarity and accessibility of our visual materials.

References to prior work: The authors do acknowledge that some work has been done in this space before, but I don't think that they have fully acknowledged all that has been done in the regional climate community, e.g.a few key ones that are missing include

1. Leon et al. 2007 ELCOM in the Canadian regional model (CRCM)
2. Turuncoglu et al. 2013 ROMS in the Regional climate model (RegCM)
3. Bryan et al. 2015, showing the impacts of 1D lakes in RegCM

Response: Thank you for bringing to our attention the omission of several key studies. We have now incorporated additional references in the Introduction to reflect important prior work by the regional climate modeling community.

Leon, L. F., Lam, D., Schertzer, W., and Swayne, D. (2005): Lake and climate models linkage: a 3-D hydrodynamic contribution, Adv. Geosci., 4, 57–62, https://doi.org/10.5194/adgeo-4-57-2005, 2005.

Leon, L. F., Lam, D. C. L., Schertzer, W. M., Swayne, D. A., & Imberger, J. (2007). Towards coupling a 3D hydrodynamic lake model with the Canadian regional climate model: simulation on Great Slave Lake. Environmental Modelling & Software, 22(6), 787-796.

Turuncoglu, U. U., Giuliani, G., Elguindi, N., and Giorgi, F.(2013): Modelling the Caspian Sea and its catchment area using a coupled regional atmosphere-ocean model (RegCM4-ROMS): model design and preliminary results, Geosci. Model Dev., 6, 283–299, https://doi.org/10.5194/gmd-6-283-2013, 2013.

Bryan A. M., A. L. Steiner, and D. J. Posselt (2015), Regional modeling of surface-atmosphere interactions and their impact on Great Lakes hydroclimate, *J. Geophys. Res. Atmos.*, 120, 1044–1064, doi:10.1002/2014JD022316.

Minor editorial:

1. Line 35-36: change to "…. this study identified the key processes influencing…."

Response: Changed.

2. Lines 153-160: This is a long list of possible obstacles followed by a long list of references. Could the authors parse this out more so there is more clarity in which studies were investigating specific components?

Response: Good suggestion, revised as "*The lack of fully resolved lake hydrodynamics in models (Xue et al., 2017; Sharma et al., 2018), including lake circulation (Song et al., 2004), upwelling and downwelling, thermal bar formation (Martynov et al., 2010, 2012), explicit horizontal mixing, and ice motion, along with overly simplified stratification processes (Bennington et al., 2014), unrealistic treatment of eddy diffusivity (Stepanenko et al., 2010; Gu et al., 2015; Mallard et al., 2015) has been the main obstacle in further improving climate simulations for the Great Lakes Basin.*"

3. Line 179: LISSS, first use of acronym with no description.

Response: Added.

4. Suggest to remove Table 1 as this information is all in the text

Response: We believe that Table 1 plays a crucial role in providing a clear and concise overview of our experimental design, particularly given the large number of sensitivity experiments conducted. The table enables readers to quickly understand the structure, variations, and purpose of each experiment without having to extract this information from the main text. Given its importance in improving the clarity and accessibility of our methodology, we respectfully request to retain Table 1 in the manuscript.

5. Figure 2 – why not include the 1D model on here as well for comparison?

Response: We see your point—this information has now been added to Supplementary Figure S1. In Figure 2, we focus specifically on evaluating the performance of the 3D lake model against observations.

6. Line 460 – can you show these observation locations on one of the spatial figures? Also, you note they are selected because of the highest ice coverage – what about observations on Lake Erie? That usually tends to be the most ice covered.

Response: We have included the observation locations in Figure 1b.

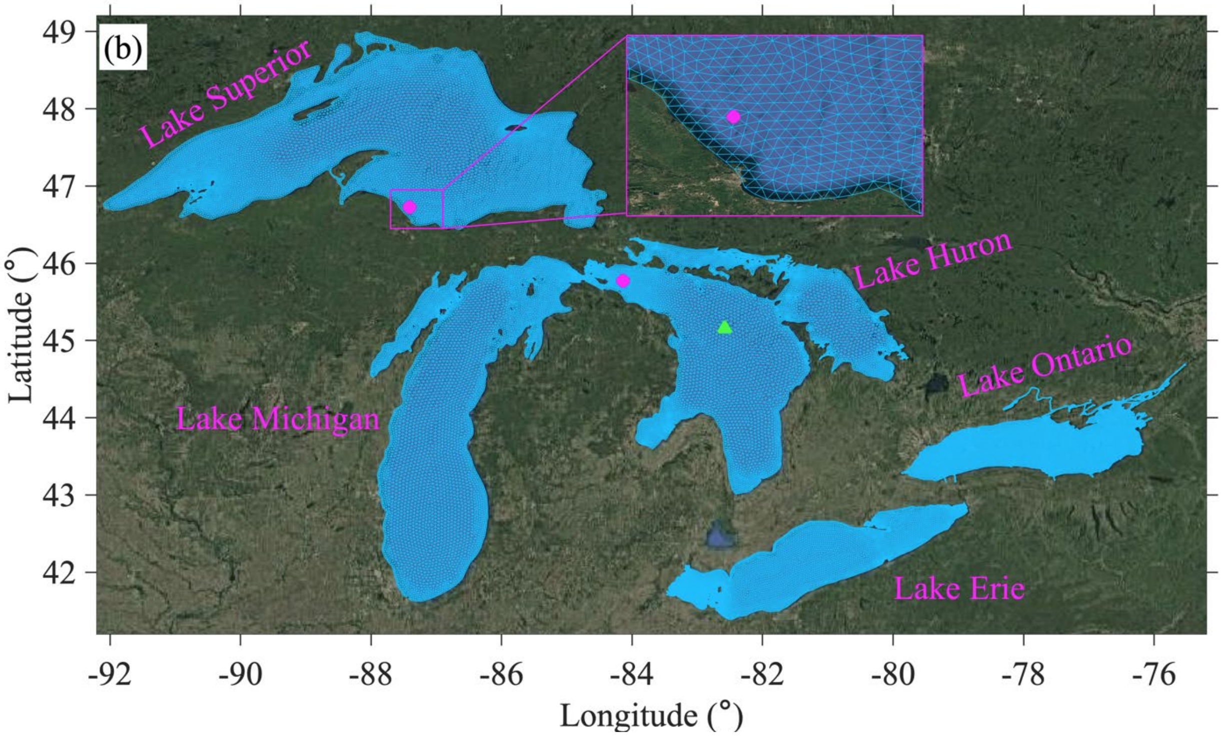

Fig 1b in the manuscript: The two dots denote the locations of Granite Island (87.4°W, 46.7°N) on Lake Superior and Spectacle Reef (84.1°W, 45.7°N) on Lake Huron. The triangle marker denotes the location (82.58°W,45.16°N) of thermistor observation in deep, central Lake Huron, where the water depth is 220 meters.

We appreciate the opportunity to clarify our methodology and selection criteria. The original text was imprecise, and we have revised it to read:

"Lake Superior and Lake Huron were selected for demonstration because studies have shown that deeper, larger Great Lakes present more complex hydrodynamic challenges that 1D models consistently fail to represent accurately, often resulting in substantial errors."

While Lake Erie does experience significant ice coverage, it is relatively shallow (with an average depth of approximately 19 meters). The performance of 1D lake models in Lake Erie has been mixed, with reasonable accuracy achievable in some cases through empirical tuning and careful configuration. This has been demonstrated in several studies (Martynov et al., 2010; Subin et al., 2012; Bennington et al., 2014; Gu et al., 2015). In contrast, numerous studies have shown that deeper, larger Great Lakes—such as Lake Superior and Lake Huron—pose greater hydrodynamic complexity, which 1D models consistently struggle to capture, often leading to substantial simulation errors.

Therefore, we focused our comparative analysis on Lake Superior and Lake Huron, where the limitations of 1D lake models are more clearly expressed and consistently observed. We believe the revision helps to clarify our rationale and better align our site selection with the study's objectives.

7. Figure 7 – These line plots are very hard to read. Could it have the observations on one y axis, and the two model versions bias on a second y axis?

Response: We appreciate your suggestion and have generated the revised figure as recommended. After comparison, we find that both the original and revised versions have their respective strengths and limitations. The original figure is more effective at illustrating how the model tracks observed variability—particularly for air temperature—though it is somewhat harder to interpret for wind speed. In contrast, the revised figure presents model biases relative to observations more clearly, but it lacks a direct visualization of the model's ability to capture temporal variability, as it only shows the biases.

To address this, we have decided to include both versions. The original Figure 7 has been refined with improved resolution, and the revised bias-focused plot has been included as Supplementary Figure S3.

Both figures are provided here for your convenience.

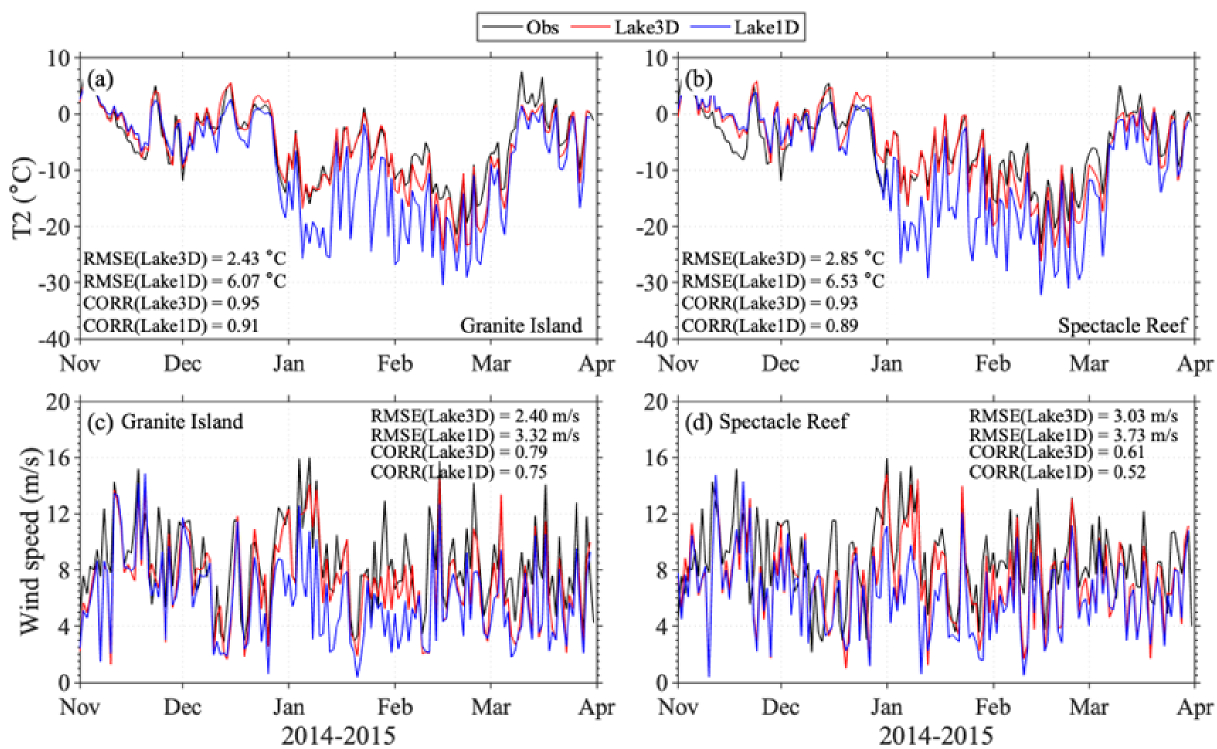

Figure 7 in the manuscript. Time series of daily air temperature (°C, upper panels; a, b) at 2-m height (T2) and wind speed (m/s, lower panels; c, d) from GLEN observations (black lines), NU-WRF/FVCOM 3D lake model simulations (red lines), and NU-WRF/LISSSS 1D lake model simulations (blue lines) at Granite Island on Lake

Superior and Spectacle Reef on Lake Huron during November 2014-March 2015. The RMSE and temporal correlations between the simulations and GLEN observations are provided in each panel.

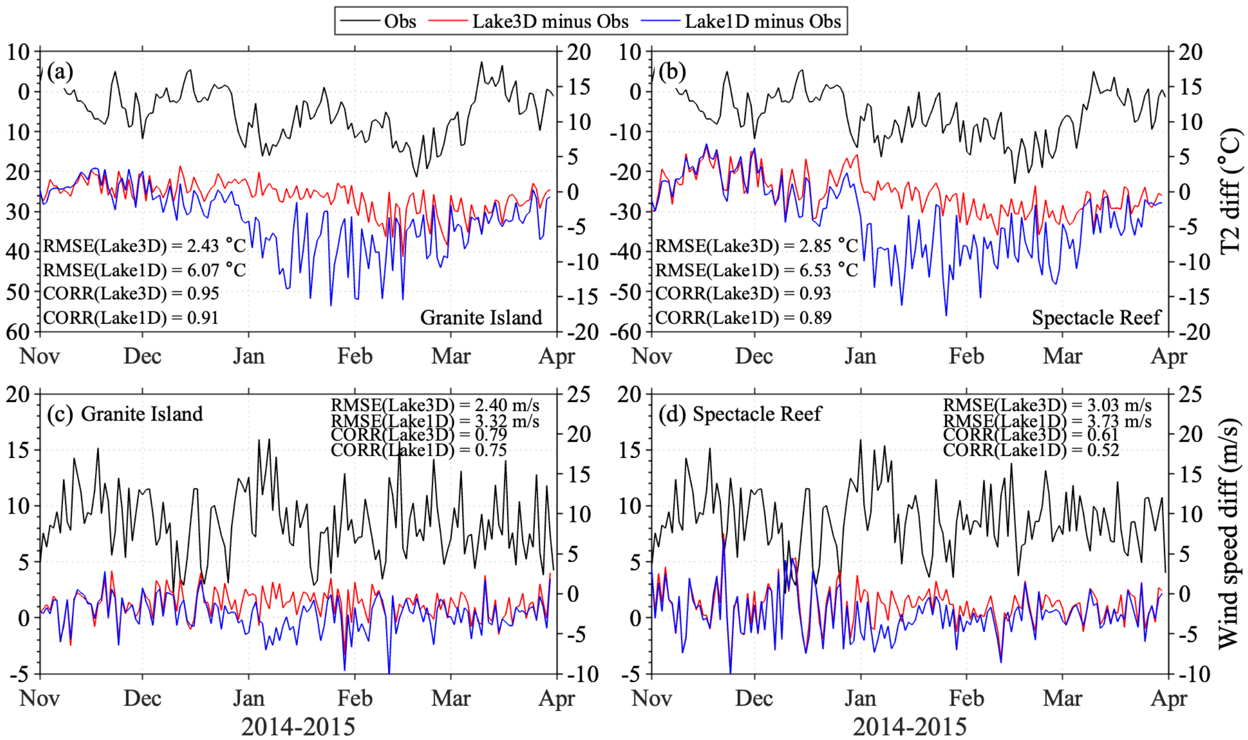

Figure S3. Time series of daily 2-meter air temperature (°C; upper panels: a, b) and wind speed (m/s; lower panels: c, d) from GLEN observations (black lines, left y-axis) at Granite Island (Lake Superior) and Spectacle Reef (Lake Huron) during November 2014 to March 2015. Model biases relative to observations are shown on the right y-axis for the NU-WRF/FVCOM simulation with the 3D lake model (red lines) and the NU-WRF/LISSS simulation with the 1D lake model (blue lines).

8. Line 574 – change "… GLSEA is not able to well capture…." to "…. GLSE cannot capture…"

Response: The sentence has bee removed.

9. Figure 11 – this figure is so hard to read, yet seems to be a very important one. Note that dT/dt is the black line in the caption. It is very hard to see the difference between the black and the purple line, so perhaps dash one of them.

Response: Thank you for the suggestion. We have revised the figure accordingly, and it is now much clearer. The updated figure is provided here for your convenience.

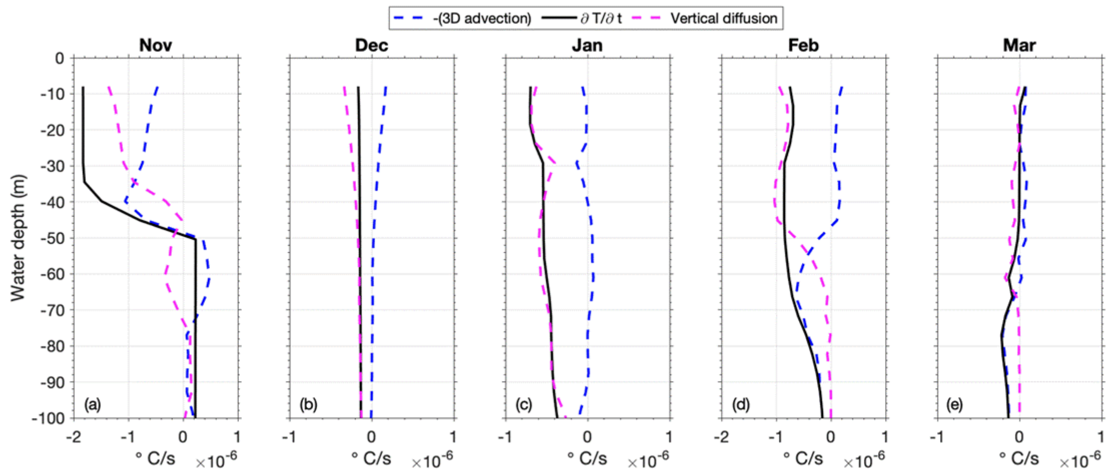

Figure 11 in the manuscript. Monthly-averaged vertical profiles of key terms in the temperature equation in the C1-1 (Lake3D) simulation at the deep-water thermistor site (220 m) in central Lake Huron (site location is on Fig. 1) from November 2014 through March 2015. The black line represents the temperature change rate (∂T/∂t), while the dashed blue and magenta lines represent the contributions from 3D advection and vertical diffusion, respectively. Horizontal diffusion is omitted here due to its negligible contribution throughout the winter season.

10. Lines 620-623: Can you comment more on the importance and implications of this issue?

Response: The entire paragraph has been rewritten to more clearly elaborate the role of advective heat transport, with coherent reference to Figures 10 and 11.

11. Line 632: what specifically is meant by "sophisticated"? At this point, most readers would want to know specifically which model is used (with a reference).

Response: As you previously suggested, we have moved the model description to Section 2.2. Specifically, we now clarify that the simulation utilizes the **Mellor–Yamada Level 2.5 turbulence closure scheme**, a widely used approach for geophysical fluid dynamics (Mellor and Yamada, 1982).

Reference: Mellor, G. L., & Yamada, T. (1982). Development of a turbulence closure model for geophysical fluid problems. *Reviews of Geophysics*, 20(4), 851–875.

12. Figure 12 – there are six terms in equation 3, yet only five are shown in the plot. Is there a reason why the horizonal diffusion is not plotted? If too small, then this should be included in the caption or the text.

Response: Thank you for your observation. The horizontal diffusion term, along with a few other terms, is indeed also small, making them difficult to visualize separately in the plot. To improve clarity, we have revised the figure (included below for your convenience) and represented these terms using a dashed line for better visibility and have explicitly noted its small magnitude in the figure caption to ensure transparency.

We note that the primary purpose of this figure is to highlight the dominant terms in the temperature tendency and turbulence kinetic energy (TKE) budget. In particular, we emphasize that shear production, a key source term for TKE, is largely balanced by eddy dissipation, the primary sink term. This balance underscores the importance of resolving realistic flow conditions, which directly govern shear-driven mixing.

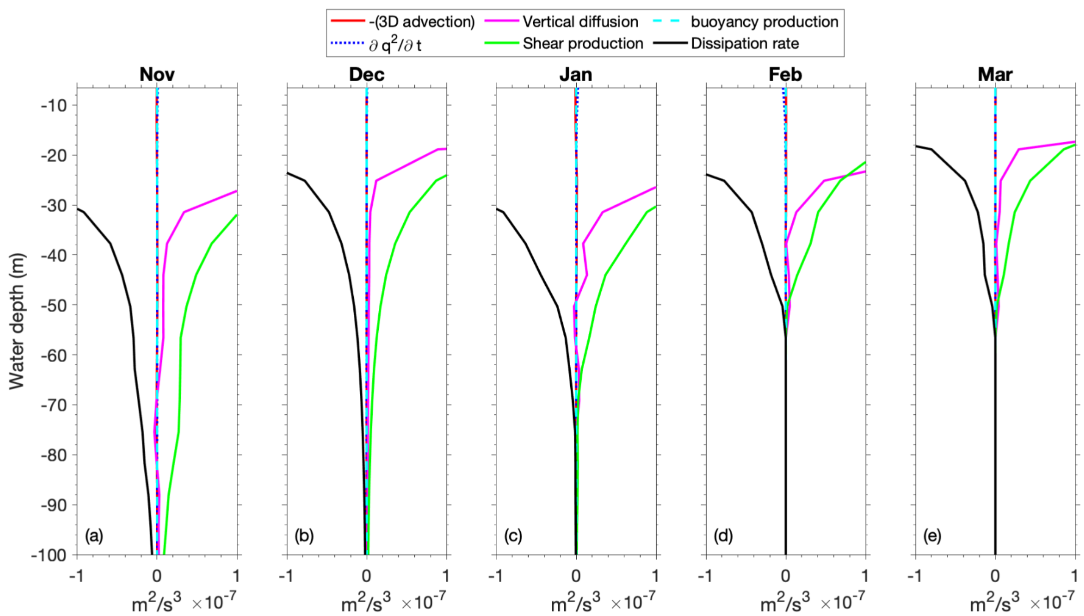

Figure 12. in the manuscript. Monthly averaged vertical profile of each term of the turbulence kinetic equation in the C1-1 (Lake3D) simulation at the deep-water thermistor site (220 m) in central Lake Huron (site location is on Fig. 1) from November 2014 through March 2015. The profiles include shear production (green), buoyancy production (cyan dashed), vertical diffusion of TKE (magenta), dissipation rate (black), 3D advection of TKE (red dashed), and the TKE change rate term $\partial q^2/\partial t$ (blue dotted). Shear production is the dominant source term balancing the dissipation rate (sink), while the other terms—buoyancy production, 3D advection—are comparatively smaller in magnitude. The dominance of shear-driven mixing emphasizes the importance of resolving realistic current structures.

Thank you for your time and effort in helping us improve the manuscript. We hope that our responses and revisions have satisfactorily addressed your concerns.