Reviewer 2:

Review Comments

Xue et al. developed a coupled lake-ice-atmosphere modeling system of NU-WRF/FVCOM. The new model demonstrates clear advantages over the 1D lake model (LISSS). The authors also address a crucial question regarding the key processes influencing lake thermal structure and ice cover in 3D lake models through well-designed numerical experiments. The overall work is strong, and the process analysis is comprehensive. The manuscript requires adjustments to its structure and presentation for clarity and consistency. Below are specific comments and suggestions for improvement:

Response: Thank you for your constructive comments and suggestions to improve our manuscript. We have carefully revised the manuscript, taking all of your feedback into full consideration. A point-by-point response is provided below to facilitate your evaluation. For your convenience, we have also included a tracked-changes version of the revised manuscript.

We recognized the need to communicate and emphasize the purpose of the study and the research questions more clearly to a broader audience. To facilitate your evaluation, we appreciate the opportunity to elaborate on the subject further here for your reference.

Background: There has been *a well-established consensus* in the Great Lakes regional modeling community that climate models used in this region should incorporate lake simulations—particularly three-dimensional (3D) lake models when available (Briley & Jorns, 2021). Numerous studies, dating back to the early 2010s have acknowledged the limitations of such models when applied to large, deep lakes like those in the Great Lakes system. These limitations, primarily due to the simplified representation of lake hydrodynamics, have led many researchers (e.g., Martynov et al., 2010, 2012; Stepanenko et al., 2010; Bennington et al., 2014; Gu et al., 2015; Mallard et al., 2015) to advocate for the use of 3D lake models in future coupled RCM applications.

In alignment with this, more recent studies employing RCMs coupled with 3D lake models have consistently shown improved performance and predictive skill in the Great Lakes. These advancements have been documented in the peer-reviewed literature (Xue et al., 2017; Sun et al., 2020) and the Great Lakes Climate Modeling Workshop reports (Briley & Jorns, 2021).

Therefore, it is neither our intention to reiterate an already well-established consensus. This study is not driven by an effort to improve 1D lake models or to refine 3D lake models further. **Rather, our focus is on understanding the fundamental hydrodynamic processes absent in 1D models and how they are resolved in 3D frameworks.**

We clarify this in the revised text in the new Discussion Section line 800-807: "*Within this context, the core contribution of this research lies in advancing our understanding of a central* *question in Great Lakes regional climate modeling: What are the key* ***hydrodynamic processes missing*** *from one-dimensional (1D) lake models—processes that are critical for simulating lake thermal structure and ice cover during the cold season—and how are these processes resolved in three-dimensional (3D) lake models? Our findings provide* ***generalized insights that are not dependent*** *on specific model configurations, tuning strategies, or the reproduction of individual observed events, making them broadly applicable across different modeling systems and lake conditions*."

To answer this, we structured the study in two stages:

- **C-1: Foundational Evaluation of the Coupled System** In this component, we conduct benchmark simulations using NUWRF coupled with FVCOM (3D Lake) and NUWRF coupled with a LISSS (1D lake model). The results aim to verify the skill of our coupled modeling NUWRF-FVCOM system in reproducing observed lake surface temperatures (LST) and ice cover. This foundational experiment serves ***not*** to rehash the well-known limitations of 1D models, but to **establish confidence in the coupled NUWRF-FVCOM framework** and justify its application for process-level investigation in the next stage (C-2 experiments).

- **C-2: Diagnosing the Hydrodynamic Processes Missing in 1D Lake Models** This represents the core contribution of our study and distinguishes it from previous work, including our own earlier efforts using coupled RCM–3D lake models. We systematically identify three key hydrodynamic processes that are absent in 1D lake models but are resolved in 3D models, which account for the improved cold-season performance in simulating LST and ice cover: 1) Lateral ice transport; 2) Advective heat transport; 3) Shear-induced turbulence. Critically, all three of these processes are dynamically linked to water currents—spatially and temporally evolving flow fields that are fundamentally unresolved or crudely simplified in 1D lake models. This represents the key scientific insight of our study: these dominant hydrodynamic processes responsible for realistic wintertime lake thermal structure and ice cover are current-driven, and thus structurally absent in 1D models. This finding constitutes the key contribution of our work and, we believe, offers an important step forward in understanding why 3D models perform better—not merely that they do.

So we structured and revised our manuscript centered on the following key criteria: (1) Does the study pose a meaningful central scientific question that benefits the broader research community? (2) Does the manuscript present robust evidence in support of its conclusions? (3) Are the conclusions well-supported and persuasive to readers?

Thank you again for your time and effort in providing comments and suggestions and for evaluating our revision. Below is our point-by-point response, guided by the revision principles and criteria we outlined and your suggestions.

1. On Line 30, add the full name of “LSTs” (presumably “lake surface temperatures”) upon first mention for clarity.

Response: Thanks, the missing full name is added.

2. In Figure 1, the blue line for “FVCOM mesh” does not appear to be visible in panel (a). Consider using blue in panel (b) instead of red to clearly show the FVCOM mesh. Additionally, add the names of the lakes to panel (b) for better context.

Response: Figure 1 has been revised as you suggested to enhance clarity and improve visibility. We include it here for your convenience.

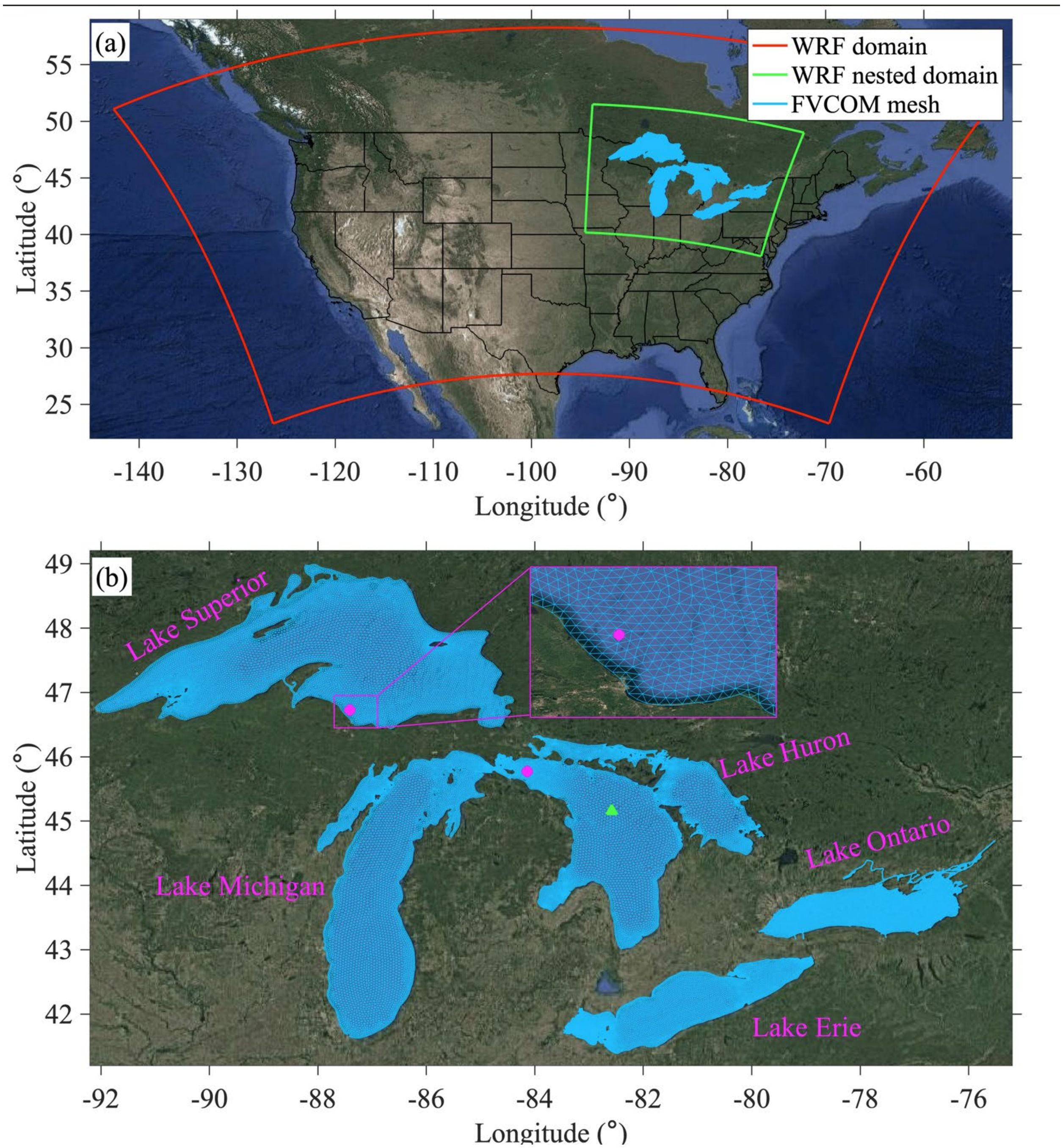

Figure 1 in the manuscript. NU-WRF nested domains (upper panel) and unstructured mesh used in FVCOM to represent the Great Lakes in FVCOM (lower panel). The two dots denote the locations of Granite Island (87.4°W, 46.7°N) on Lake Superior and Spectacle Reef (84.1°W, 45.7°N) on Lake Huron. The triangle 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.

3. For all figures, it is standard practice to label subplots with (a), (b), (c), etc. Please add these labels to improve readability.
Response: We have now added labels to all subplots across the figures, as recommended.

4. In Section 3.2, clarify whether the NU-WRF/LISSS configuration uses the same lake mesh as shown in Figure 1b (like NU-WRF/FVCOM). This will help readers understand the setup differences between the two models.

Response: No, LISSS and FVCOM do not use the same mesh, as their integration with the atmospheric model (NUWRF) differs fundamentally—both in terms of architecture and representation of lake dynamics.In short, LISSS has to operate on the NUWRF atmospheric model grid, whereas FVCOM uses its own unstructured grid that is independent of the NUWRF grid.

This has now been explicitly explained and clarified in section 3 in revision as "*FVCOM is a complex, fully prognostic 3D hydrodynamic model. It operates on its own unstructured mesh, which is independent of the NUWRF atmospheric grid, and is well-suited to resolving complex lake geometry, shorelines, and bathymetry. Therefore, coupling between NUWRF and FVCOM must be achieved through an external coupler, which facilitates end-to-end, two-way exchange of information at any desired interval. NU-WRF and FVCOM are run simultaneously, exchanging information bidirectionally at 1-hour intervals through the OASIS3-MCT coupler. FVCOM dynamically calculates the LST and ice cover, providing these as overlake surface boundary conditions to NU-WRF. Meanwhile, NU-WRF calculates and supplies the atmospheric forcings required by FVCOM, including surface air temperature, surface air pressure, relative and specific humidity, total cloud cover, surface winds, and downward shortwave and longwave radiation. No tuning was applied to FVCOM in the coupled configuration to improve consistency with observations, as the default FVCOM configuration was applied.*

In contrast, 1D lake models, including LISSS, are simplified, column-based lake models directly embedded within NUWRF without using a coupler. Each NUWRF atmospheric grid cell over a lake surface contains one corresponding vertical water column 1D model, which simulates thermal processes in the vertical direction. Collectively, these columns provide a pseudo-3D representation of the lake but do not simulate horizontal processes such as advection, circulation, or lateral ice transport. As a result, LISSS must use the same horizontal resolution as the NUWRF grid."

5. In Figure 2, observations from GLSEA show some spikes in temperature and ice cover time series (e.g., Lake Ontario's low-temperature spike in February and ice cover spike in February), but the simulations appear smoother. Could the authors explain this discrepancy? Is it due to model limitations or data processing?

Response: Thank you for your comments. We address Comments 5 and 6 together in the response below.

6. In Figure 3, while Lake3D performs much better than Lake1D, the spatial pattern in GLSEA observational data is still more heterogeneous compared to the Lake3D simulation. What are the potential reasons for this? Additionally, were any parameters tuned, or initial conditions adjusted to improve the Lake3D simulation compared to Lake1D? If so, please clarify.

Response: We appreciate the reviewer's observation. Indeed, Figure 3 shows that while the Lake3D simulation captures the large-scale thermal structure of the Great Lakes with good fidelity—particularly when compared to the 1D model—there is a noticeable difference in the degree of spatial heterogeneity when compared to the GLSEA (Great Lakes Surface Environmental Analysis) observational product. We have now explicitly acknowledged these model limitations in the revised text in line 454-459 as "*While the model successfully reproduces the overall seasonal evolution, it misses some episodic fluctuations. For example, observational data from GLSEA show short-term spikes in both temperature and ice cover—such as the notable low-temperature and ice cover spikes in Lake Ontario during February—that are not fully captured in the simulation. The modeled LST and ice cover time series tend to appear smoother than the observations (Fig 2. a4, b4) ..... Also, the spatial pattern in GLSEA observational data appears more heterogeneous on a finer scale compared to the 3D Lake simulation.*"

There are several factors contributing to this discrepancy:

Resolution Differences: The GLSEA product is generated from satellite-derived data with a horizontal resolution of approximately 1.3 km, providing fine-scale spatial detail in open-water areas. In contrast, while FVCOM's unstructured grid allows for flexible mesh refinement, the configuration used in this study employed a coarser horizontal resolution of up to 4 km in open lake regions. This coarser resolution may smooth out finer-scale spatial variability, reducing the ability of the model to replicate small-scale thermal features present in the observations.

Model Limitations: While the 3D lake model substantially improves the representation of physical processes compared to the 1D model, it is not without limitations. Like all process-based models, both NUWRF and FVCOM are subject to uncertainties in boundary conditions and internal dynamics, subgrid parameterizations, which can limit its ability to fully capture observed spatial variability. These limitations are also relevant to the issue raised in Comment #5, where we believe that the coupled model may not have adequately resolved the episodic events responsible for the observed temperature spikes.

That said, these small-scale spatial mismatches are not central to the main objective of this study, *as elaborated at the beginning of our response.* Our primary focus is to **identify the key hydrodynamic mechanisms absent from 1D lake models that contribute to their cold-season temperature biases and excessive ice cover**. The Lake3D simulation's demonstrated ability to reproduce large-scale spatial and temporal patterns provides a robust foundation for the mechanistic analysis and conclusions presented in this work.

We have also explicitly clarified in lines 361-363 as "*No tuning was applied to FVCOM in the coupled configuration to improve consistency with observations, as the default FVCOM configuration was applied.*" The FVCOM component used in this study employed a standard parameter configuration that has been widely applied and documented in prior publications. This configuration has been fully archived and made publicly accessible via Zenodo to ensure transparency and reproducibility. As we noted in the original manuscript, the initial lake conditions of November 2014 were obtained from FVCOM standalone simulations driven by Climate Forecast System Reanalysis (CFSR) forcing.

For the 1D lake model, we used LISSS in its optimal configuration, as determined by Notaro et al. (2023), who conducted a comprehensive sensitivity analysis across more than 20 configurations. We adopted the best-performing setup reported in their study to ensure a fair and representative comparison between the 1D and 3D models. However, as explained in the beginning, we acknowledge that 1D lake models can be tuned to better match observational data (e.g., through lumped eddy diffusivity; Xiao et al., 2016; Bennington et al., 2014), yet this is directly related to our central research question.

Importantly, our central conclusion is that the performance differences arise from the ***presence or absence of key physical processes*** *as generalized insights that are not dependent on specific model configurations, tuning strategies, or the reproduction of individual observed events, making them broadly applicable across different modeling systems and lake conditions*

We hope this clarifies both our methodology and the core scientific contribution of the study.

7. In Figure 6, what are the potential reasons for the underestimation of latent heat flux by Lake3D over Spectacle Reef? Please discuss possible causes.

Response: Good question. We have specifically discussed this in the revised manuscript in lines 557-569 with supplementary Fig S2 as "*Latent heat in Spectacle Reef is the only exception, where NU-WRF/FVCOM struggles to capture the magnitude of the upward latent heat flux due to the overestimated ice cover at the site (Fig. S2). Ice cover plays a critical role in modulating latent heat exchange: in the bulk aerodynamic formulation, latent heat flux is scaled by the open water fraction, as ice acts as a physical barrier to evaporation and moisture transfer. A higher modeled ice fraction reduces the effective evaporation area, resulting in suppressed moisture exchange and, consequently, underestimation of latent heat flux. As shown in Fig. S2, the model substantially overestimates ice cover at this site in January and maintains high ice concentration through February. This persistent overestimation directly reduces the open water fraction, contributing to low latent heat. Interestingly, the observed latent heat flux remains elevated in February despite observed ice cover approaching 90%. This apparent discrepancy suggests potential uncertainty in either the observed ice cover, the latent heat flux measurements, or both, and warrants further investigation.*"

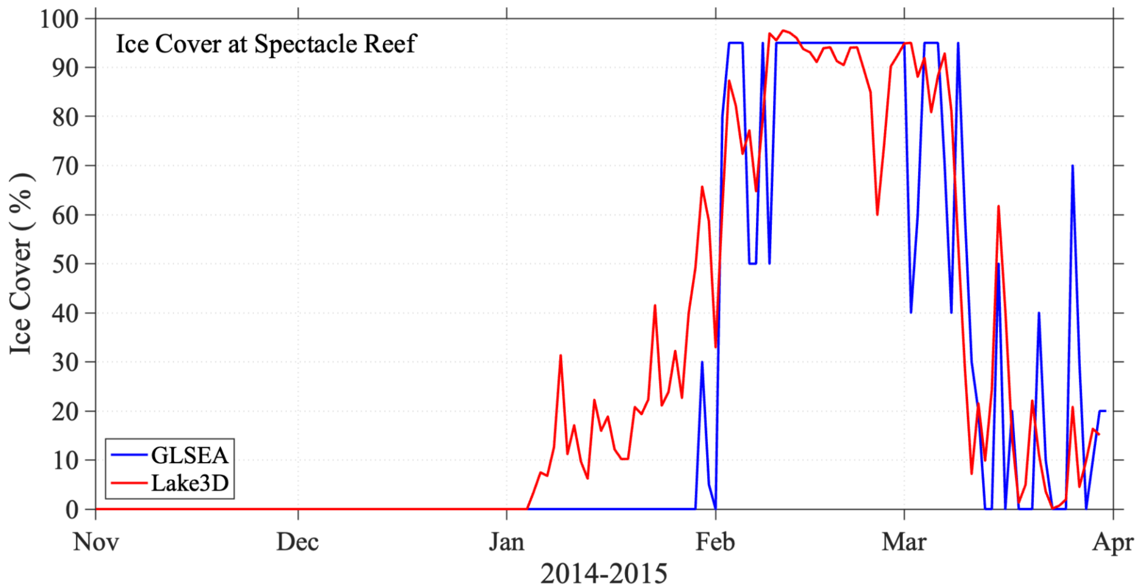

Figure S2. Time series of ice cover at Spectacle Reef for the 2014–2015 winter season, comparing observations from the Great Lakes Surface Environmental Analysis (GLSEA, blue, which has ice data sourced from the National Ice Center) with the Lake3D model simulation (red).

8. The C2-related analysis is currently included in the discussion section (Section 5), which is unusual. This content should be moved to the results section. The discussion section should focus on synthesizing findings from both C1 and C2 experiments rather than presenting new results. The C2 experiments are important and should not be overlooked or buried in the discussion.

Response: Agreed. we have now relocated and retitled this section as result section 4.2 "Diagnosing the Key Hydrodynamic Processes Missing in 1D Lake Models"

9. The explanation of equations in Section 5.2/5.3 would be better placed in the methods section, maybe in the experiment design subsection for C2 experiments. This would improve the flow and readability of the manuscript.

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.

10. For the C2 experiments, it would be valuable to include analysis of sensible/latent heat, T2, and wind speed comparisons for the different physics turnoff experiments. This would provide a more comprehensive understanding of the impacts on lake-atmosphere interactions. If space is limited, consider adding this analysis as supplementary material.

Response: We sincerely thank you for this thoughtful comment. We both agree that looking at sensible and latent heat fluxes along with near-surface atmospheric variables (like air temperature at 2 meters and wind speed) can help us learn more about how lake processes affect the atmosphere above them. However, we respectfully clarify that the primary goal of the **C2 experiment** is more narrowly focused in both scope and contribution, as elaborated at the beginning of our response. We note in lines 608-611 "*Note that in the discussion of the C2 experiments below, analyses are focused on the major 3D lake processes that influence the simulated limnological patterns of lake temperature and ice cover, not the overlying atmospheric conditions, which are beyond the scope of this study.*"

We also acknowledge that, due to project closeout and the expiration of our HPC allocations, we were unable to archive the complete atmospheric datasets. As this study focuses specifically on hydrodynamic processes within the lake system, we made a strategic decision to prioritize diagnostics directly relevant to lake thermal structure and ice cover. Re-running the full coupled system to extract atmospheric fields would require significant computational resources and is currently beyond our capacity. However, we believe the process-level analysis and evidence we have presented are robust and sufficiently address the central scientific question.

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.