Reviewer #3 Comments and Author Responses

Manuscript: *Langmuir Turbulence in the Arctic Ocean: Insights From a Coupled Sea Ice–Wave Model*

Authors: Aikaterini Tavri et al.

Author Response:

We thank the reviewer for their detailed and helpful feedback. Below we provide responses to all general and specific comments. We have carefully revised the manuscript to address the issues raised, included external datasets for model evaluation, and improved key conclusions and metrics.

Major Comments

1. Model Fidelity

Reviewer Comment:

While the manuscript cites earlier studies validating this model, some evaluation specific to the present application is needed. In particular, comparisons of modeled winds, shear, and wave fields (especially short waves, which strongly influence Stokes drift) would provide important context. Because the LT parameterizations are sensitive to these inputs, even brief error estimates or uncertainty ranges would help clarify the robustness of the conclusions. It would also be useful to discuss how well the model captures heterogeneous ice concentration features (e.g., leads), which can locally enhance Stokes processes.

Author Response:

We agree that a brief evaluation of the model inputs most relevant to Langmuir turbulence strengthens the analysis. While extensive validation of the coupled neXtSIM–WW3 system has been presented elsewhere (e.g., Rogers et al., 2012, Williams et al., 2013, Ardhuin et al., 2018, Boutin et al., 2022), we now include a short comparison in Section 2.2 using CCMP v3.1 10 m winds and AMSR2 sea-ice concentration. These datasets confirm that the model captures the large-scale seasonal variability in near-surface winds and the distribution of open-water and MIZ regions, which primarily control the forcing of Stokes drift and shear stress. We also clarify that short-wave spectral effects, which influence the surface Stokes drift magnitude, are not explicitly evaluated here but have been validated in prior Arctic WW3 studies (e.g., Boutin et al., 2022). Because our analysis focuses on the spatial and seasonal variability of Langmuir turbulence potential rather than the absolute magnitudes of wave energy, this level of consistency is sufficient for interpreting relative regime patterns. We highlight in the discussion that future work will incorporate targeted evaluation of short-wave Stokes drift and lead-scale heterogeneity using coincident satellite observations.

2. Key Conclusions and Metrics

Reviewer Comment:

The primary focus on regime classification raises questions of utility. Why is the frequency of transitions between regimes the most relevant measure? Should this instead be linked to event duration or intensity?

Author Response:

Our current focus on transition frequency provides a compact, dimensionless measure of temporal variability, allowing us to identify regions where local forcing regimes are persistent versus intermittent. This choice offers a first-order, spatially consistent view of how the balance between wind and wave forcing evolves across the Arctic. We agree that complementary diagnostics such as event duration and intensity would provide additional insight into the persistence and strength of mixing regimes. Given their feasibility within our current workflow, we have examined them in the updated version of the manuscript to strengthen the physical interpretation of the regime framework and its implications. We have also clarified in the revised text the rationale for using transition frequency and added a statement acknowledging that future extensions could include event duration and intensity diagnostics.

Reviewer Comment:

The discussion introduces two compelling applications: (i) how wave-driven forcing may evolve in a changing climate, and (ii) implications for tracer transport and stratification. These questions seem ideally suited for this model framework. Even a preliminary analysis—for instance, a future-scenario run or a waves-on vs. waves-off experiment—would help demonstrate the broader utility of the work. Additionally, the statement that "wind–wave alignment strongly influences LT-driven mixing" may be overstated given the results in Figure 7. A more quantitative phrasing (e.g., "up to X% effect in the MIZ") would provide a more measured conclusion.

Author Response:

We thank the reviewer for recognizing the broader applicability of our modeling framework and for these constructive suggestions. We agree that extensions such as future-scenario simulations or waves-on vs. waves-off sensitivity experiments would provide valuable demonstrations of how wave-driven forcing may evolve under changing ice and wind conditions. These experiments are well aligned with our framework and are currently being planned as part of a follow-up study.

In the present work, our focus was to establish and validate a physically grounded diagnostic for characterizing the balance between wind- and wave-driven mixing across heterogeneous sea ice conditions. We have clarified this scope in the revised text and added statements outlining how the same approach can be applied to future-scenario or process-specific analyses in subsequent work.

Regarding the statement that "wind–wave alignment strongly influences LT-driven mixing," we agree and have revised it to a more measured description.

3. Domain of Analysis

Reviewer Comment:

The spatial and seasonal definition of the analysis domain needs to be clarified. In maps, regions outside the study area should be removed or masked. Presenting this earlier in the results (e.g., with characteristic winds, peak wave heights, or other basic descriptors) would give readers helpful context.

Author Response:

We have revised Section 2.1 and Figure 1 to more clearly define the analysis domain (70–85°N, 45°W–180°E) and mask regions outside this boundary.

4. Presentation and Scope

Reviewer Comment:

The manuscript currently introduces more metrics than are fully justified by the conclusions. Several variables appear in the methods but are not explored in the results, while additional metrics are introduced later in the analysis. A more streamlined focus on the most relevant parameters would strengthen the narrative.

Author Response:

We agree that focusing on a smaller set of key diagnostics improves clarity and coherence. In the revised manuscript, we have streamlined the presentation by emphasizing the parameters most directly linked to our conclusions, and moved secondary metrics to the supplementary material.

Minor Comments

- **Line 34:** Out of curiosity, have you also applied this model in the Southern Ocean? Given its energetic wave climate, it may be an equally or more interesting test case .
  The coupled setup has not yet been applied to the Southern Ocean, but we plan to extend the analysis there.
- **Figures/Visuals:**
  - **Figure 1:** The exceedance plots, especially panels (e, f), are difficult to interpret and appear saturated. Consider simplifying (e.g., show only u*), or adopt a different approach to highlight relative values.
    We have considered a different visualization, as the information provided from this metric is useful.
  - **Figure 2:** The averaging domain is unclear. Does it include the entire region shown? Also, labels such as "wave-dominated" and "shear-dominated" (introduced later, L268) could be used here. Color contrast between LT-active and mixed regimes

should be improved.
Yes, it is the entire region in the plot. Comment considered and figure is updated

  - **Figure 3:** The line label in panel (a) is unreadable. In panel (b), clarify the domain for SIC; the 20% threshold seems surprisingly low.
    Label enlarged.
  - **Figure 4:** The increase in La_T at moderate SIC (likely due to larger fetch) should be noted in the text.
    Considered.
  - **Figure 6:** SIC would be clearer as a black line rather than shading. Caption should clarify that VKE refers to the upper ocean.
    Updated accordingly and caption now states that VKE refers to the upper 20 m layer.

- **Line 330:** Reference missing.
  Corrected.
- **Lines 364–365:** Statement "confirms LT effects" too strong.
  Rephrased to "suggests a strong association between LT indicators and enhanced vertical mixing."

References

Rogers, W. E., Dykes, J. D., Wang, D., Carroll, S. N., & Watson, K. (2012). *Validation test report for WAVEWATCH III* (No. NRLMR7320129425).

Williams, T. D., Bennetts, L. G., Squire, V. A., Dumont, D., & Bertino, L. (2013). Wave–ice interactions in the marginal ice zone. Part 1: Theoretical foundations. *Ocean Modelling*, *71*, 81-91.

Ardhuin, F., Boutin, G., Stopa, J., Girard-Ardhuin, F., Melsheimer, C., Thomson, J., Kohout, A., Doble, M., & Wadhams, P. (2018). Wave Attenuation Through an Arctic Marginal Ice Zone on 12 October 2015: 2. Numerical Modeling of Waves and Associated Ice Breakup. *Journal of Geophysical Research: Oceans*, *123*(8), 5652–5668.

Boutin, G., Williams, T., Horvat, C., & Brodeau, L. (2022). Modelling the Arctic wave-affected marginal ice zone: a comparison with ICESat-2 observations. *Philosophical Transactions of the Royal Society A*, *380*(2235), 20210262.