Response to Reviewer #1

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

Authors: Aikaterini Tavri et al.

General Comments

Author Response:

We thank the reviewer for their constructive and detailed feedback. Below we provide responses to all general and specific comments. We have carefully revised the manuscript to address the issues raised, improved the explanation of turbulent kinetic energy scaling, and clarified the role of sea-ice.

General Comment 1

Reviewer Comment:

My first concern is on the use of an enhancement factor defined in Eq. (8) to scale the enhancement of TKE dissipation by Langmuir turbulence in Eq. (9). The Langmuir enhancement factor in Eq. (8) describes the enhancement of turbulent velocity scale, which is based on scalings of vertical velocity variance in a set of large eddy simulations described in Van Roekel et al., 2012. The TKE dissipation does not necessarily scale in the same way. In fact, it shouldn't scale the same way as it depends on the turbulent velocity scale cubed. One may instead use Eq. (5) in Belcher et al., 2012 to estimate the enhancement of TKE dissipation due to Langmuir turbulence. But I'm not sure it is possible to clearly attribute the TKE dissipation to shear-driven and Langmuir-induced component. This incorrect scaling of TKE dissipation may explain the mismatch between the results and theory in Fig. 5b. Since this study is based on the turbulence scalings (as summarized in Table 1), the choice of the scaling of TKE dissipation may significantly affect the conclusions and discussions, in particular the interpretation of Langmuir turbulence's influence on TKE dissipation in Section 4.3 and the impact of wind-wave misalignment on the dissipation ratio in Section 4.4.

Author Response:

We agree that the enhancement factor $E(La_x)$ introduced in Eq. (8) follows the formulation of Van Roekel et al. (2012), which was derived from large-eddy simulations to describe the enhancement of vertical velocity variance ($\langle w'^2 \rangle$). As correctly noted, TKE dissipation (ε) scales with the cube of a characteristic velocity scale divided by a length scale ($\varepsilon \sim u'^3/\ell$), and therefore the dissipation should not be expected to scale linearly with $E(La_x)$. Our initial use of $E(La_x)$ to scale ε represented a first-order empirical approximation intended to examine whether the modeled dissipation enhancement follows a similar pattern to the simulated velocity variance enhancement. However, we acknowledge that this formulation is not dimensionally consistent with the TKE balance. In the revised manuscript, we have adopted the physically consistent formulation proposed by Belcher et al. (2012).

Following Belcher et al. (2012), the total dissipation can be expressed as the sum of shear-, Langmuir-, and convective-production terms:

$$\varepsilon_{\text{total}} = A_s \frac{u_*^3}{h} + A_L \frac{w_{*L}^3}{h} + A_c \frac{w_*^3}{h}.$$

In our configuration, buoyancy fluxes are not explicitly represented and convection is expected to be weak under the predominantly stable or ice-covered conditions examined. Neglecting the convective term ($A_c w_*^3/h$) and normalizing by the shear component leads to the simplified parameterization

$$\frac{\varepsilon_{\text{total}}}{\varepsilon_{\text{shear}}} = 1 + \frac{\beta}{La_t^2},$$

where β represents the empirical contribution of Langmuir forcing. We have implemented this revised scaling throughout Section 3 and in Figure 5b. For completeness, we retain the previous $E(La_x)$-based formulation in the Supplementary Material as a sensitivity test, including a version scaled as $E(La_x)^{1.5}$ to approximate the cubic dependence of dissipation on turbulent velocity scale.

General Comment 2

Reviewer Comment:

My second concern is that the turbulence scalings used in this study were derived in ice-free conditions. It is not clear how well these scalings describe the effect of Langmuir turbulence on the turbulent mixing in the presence of sea ice. While I understand that an assessment of the validity of turbulence scalings in the presence of sea ice may be beyond the scope of this study, a more careful discussion on this point would be helpful.

Author Response:

We thank the reviewer for this important observation. We agree that the turbulence scalings of Van Roekel et al, 2012 and Belcher et al. 2012, were derived from open-ocean large-eddy simulations and therefore do not explicitly represent the suppression or modification of Langmuir turbulence in the presence of sea ice. We have now expanded our discussion to clarify that the enhancement factors used in our study represent an upper bound on potential Langmuir-driven dissipation under ice-modulated conditions, and that the effective Langmuir turbulence forcing is expected to weaken with increasing sea ice concentration, wave attenuation, and geometric confinement within leads. Also, we have included ongoing studies (e.g., Lee et al. 2025 (submitted manuscript); Brenner et al. 2023) on resolving Langmuir turbulence under partially ice-covered and weakly stratified regimes, providing parameterizations that are considering stratification . This clarification has been added to Section 4.3.

General Comment 3

Reviewer Comment:

· Finally, the effects of surface buoyancy flux are probably significant in the turbulent mixing in the Arctic, for example, during ice formation/melting and in open waters between sea ice when air-sea temperature difference is large. A discussion on the effects of surface buoyancy flux versus the role of Langmuir turbulence would be helpful.

Author Response:

We note that buoyancy forcing is not explicitly represented in our coupled configuration, which focuses on mechanically driven turbulence. While this assumption is reasonable under the predominantly stable or weakly stratified conditions in ice-covered and melt-season environments, buoyancy effects can locally dominate during freezing or strong surface-cooling events. In this analysis, we assume additivity of turbulent production mechanisms and treat Langmuir turbulence as a primarily mechanical process, distinct from buoyancy-driven convection. We now clarify this limitation in the text and emphasize that future coupled implementations could explicitly include surface buoyancy fluxes to assess their interaction with Langmuir-driven mixing.

Specific Comments

Below we provide point-by-point responses to specific comments.

- **L60:** Define “LT potential.”
  Defined in manuscript

- **Section 2 and 3:** Something wrong with the section title? *Fixed*

- **L91–92:** Was WW3 forced with the same ocean and atmosphere forcing?
  Yes, both neXtSIM and WW3 used ERA5 wind and sea ice concentration forcing for consistency.

- **L98:** delete the second “both”? *Fixed*

- **Eq. (2):** Why not account for ocean currents? Does it matter here?
  In our formulation, Eq.(2) represents the bulk parameterization of the direct atmosphere–ocean stress as a function of the 10-m wind velocity, following standard open-water drag laws. The ocean current is not explicitly subtracted from the wind field, consistent with the bulk formulation used in many coupled wave–ice studies (e.g., Brenner et al., 2021). In our setup, the effects of surface currents enter implicitly through the momentum balance in neXtSIM and through the Stokes drift velocity $u_s(0)$ used in the Langmuir number and turbulence diagnostics. Because typical upper-ocean currents in the MIZ are small compared to wind speed (O(1–10 cm s^{-1}) vs O(10 m s^{-1})), their contribution to τ_{ao} is expected to be minor at the scales considered here. We now clarify this point in the manuscript.

- **L104**: C_{ao} should not be in bold font? *No, it is a scalar not a vector.*

- **L107–108:** Be more specific on what do “the surface forcing of momentum pathways”? It would be helpful to list what variables in the GLORYS12 reanalysis and ERA5 were used.
  Considered.

- **L132–133:** In addition to wind-wave misalignment, another refined formulation is to account for the decay of Stokes drift with depth. Any comments on this?
  We agree that Stokes drift decays rapidly with depth, which effectively limits its contribution to Langmuir forcing in ice-covered and strongly stratified Arctic waters. In our domain, mixed layers are typically deeper than the e-folding scale of short waves, and under-ice attenuation further suppresses near-surface orbital velocities. Consequently, the surface Stokes drift $u_s(0)$ *used in our analysis already represents an upper bound on the available wave-driven momentum. Accounting for the full vertical decay would therefore yield even smaller Langmuir contributions, reinforcing rather than altering our main conclusions.*

- **L153:** Van Roekel et al., 2012 is probably a more appropriate reference here.
  Considered

- **L155 and L176: \citep -> \citet** *Updated*

- **Eq (9): Also (11)**. As I mentioned in my general comment, I don't think the effect of LT on TKE dissipation can be estimated in this way.
  Updated

- **L173**: Not sure this separation can be done.
  We agree that a strict physical separation of dissipation into shear-only and Langmuir-only components is not uniquely measurable, since these pathways interact dynamically. In the revised manuscript, we therefore clarify that the quantity $\varepsilon_{\mathrm{LT}}$ *is not an isolated physical flux but a diagnostic enhancement relative to a shear-driven baseline, consistent with the scaling proposed by Belcher et al. (2012).*

- **L181**: "Langmuir scaling" -> "Langmuir number" *Corrected*

- **L197-201:** It would be helpful to elaborate more on the physical meaning of this metric. The frequency of OW conditions in different seasons depends on the location? Also, OW conditions depends on the seasons?
  The purpose of the OW_Exceedance metric is to quantify how often local forcing beneath ice (for a given grid cell) shows magnitudes typical of open-water conditions within the same season. Physically, it represents the relative occurrence of open-water-like turbulence forcing (wind, waves, or stress) under partial ice cover. The seasonal medians are computed separately for each season to account for the strong climatological variability of wind and wave conditions (e.g., stronger forcing in autumn–winter, weaker in summer). Thus, the metric inherently captures both spatial and seasonal differences in open-water occurrence, allowing comparison of under-ice conditions to seasonally typical open-water states rather than to a fixed global threshold. We have expanded the description in the section to clarify this interpretation.

- **L206:** The distribution does not seem narrow to me. It ranges from 0 to 0.03 m/s? And the seasonal variability is greater than Stokes drift
  Corrected

- **L207-208:** It's variation between seasons does not seem to be bigger than wind stress to me.
We specify that the statement is about the means and the medians.

- **L212-213:** What are the discontinuities in the exceedance rates?
It is unclear what the reviewer is asking here.

- **Fig 1:** What is the area of analysis in these statistics? The area shown in panels (d), (e), (f)?
Using sea ice concentration thresholds we separated the OW and sea ice domains and the sattistics are calculated first for grid cells that $SIC < 0.15$ and then compare wth gricells that $SIC \geq 0.15$.

- **Fig 1b:** Maybe adjust the range of horizontal axis to reduce the empty space?
Considered

- **L225**: "Asymmetry" between what?
Corrected

- **L237**: Not sure the thresholds described below are physically motivated. The effects of waves on the mixing not only depend on the absolute value of Stokes drift, but also its ratio over friction velocity (thus Langmuir number)? What additional information is provided by the distribution of surface Stokes drift as compared to the distribution of Langmuir number?
We agree that Langmuir number ultimately controls the relative contribution of waves to mixing. However, the Stokes drift thresholds complement the Langmuir analysis by isolating the absolute occurrence and magnitude of wave forcing itself, independent of concurrent wind conditions. This helps clarify seasonal and regional variability in wave access beneath ice and provides physical context for interpreting the Langmuir number distributions shown next. We have clarified these points and cited supporting literature in the revised text.

- **L239**: The definition of a MIZ day is confusing. At least one grid cell satisfies the MIZ condition over the whole Arctic Ocean?
The term MIZ day was not intended to denote a domain-wide classification for a given day, but rather to describe local conditions within grid cells that fall inside the MIZ. The exceedance metric (Eq. 14) is computed per grid cell and only for time steps when that cell satisfies the sea-ice condition ($SIC \geq 0.15$). Consequently, the maps in Fig.1 represent spatially resolved exceedance frequencies within ice-covered or MIZ grid cells, not all grid cells on days when any MIZ region exists in the domain. We have revised the text to clarify this definition.

- **L240**: Why put the figure in the Appendix if it is discussed in such details here?
Moved to main text

- **L255-256**: Not sure this conclusion is sufficiently supported by the analysis so far.
Rephrased

- **L259-260**: A Langmuir number of La_t = 0.4 also corresponds to strong Langmuir turbulence? It's also inconsistent the definition of mixing regime in Eq (15).
  Corrected

- **Eq. (15):** The regime boundaries seem arbitrary. How were they determined? Are the results sensitive to the choice of these boundaries? .
  The thresholds follow Li et al. (2019); sensitivity tests confirm the robustness of the results.

- **L276-277:** Why use the number of grid cells instead of the total area? Different grid cells may have different sizes.
  Our regime maps and diagnostics are computed per grid cell. Because no spatial averaging is performed prior to mapping, cell-area variability does not distort spatial patterns—each pixel reflects the state of that location only.

- **L306**: Why "subgrid variability"? Isn't it the variability across neighboring grid cells?
  Corrected

- **L325-326**: This is due to the wrong scaling of TKE dissipation?

- **L331**: "Lusing" -> "using"
  Removed

- **L391-400:** It might be helpful to check the partitioning between swell and wind-waves in the MIZ and their directions. Also their contribution to the Stokes drift. I'd expect the misalignment between wind and waves to be stronger in the MIZ than in the ice-free waters. But it may not significantly affect the surface Stokes drift if locally generated wind-waves are also strong.

- **L447-448:** How was the subgrid variability captured?
  Corrected to local scale variability

- **Appendix A:** I think Table A1 and Figure A1 may be move in the text where they are referred to.
  Relocated as suggested

  References:

- Van Roekel, L. P., Fox-Kemper, B., Sullivan, P. P., Hamlington, P. E., & Haney, S. R. (2012). The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research: Oceans*, *117*(C5).

- Belcher, S. E., Grant, A. L., Hanley, K. E., Fox-Kemper, B., Van Roekel, L., Sullivan, P. P., ... & Polton, J. A. (2012). A global perspective on Langmuir turbulence in the ocean surface boundary layer. *Geophysical Research Letters*, *39*(18).

- Brenner, S., Rainville, L., Thomson, J., Cole, S., & Lee, C. (2021). Comparing observations and parameterizations of ice-ocean drag through an annual cycle across the Beaufort Sea. *Journal of Geophysical Research: Oceans*, *126*(4), e2020JC016977.

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- Lee, A., Hutchings J., Horvat, C., Tavri, A., and Pearson, B. (2025). Impact of Surface Waves on Mixing and Circulation in a Summertime Leads. Submitted in *The Cryosphere*.