Reviewer #2 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 thorough and constructive feedback. Below we provide responses to all general and specific comments. We have carefully revised the manuscript to address the issues raised, clarifying model configuration and scaling definitions.

Major Comments

1. Section 3 – Model Configuration Details

Reviewer Comment:

More details are required in the model configuration section. (a) The authors never mention which attenuation scheme is used in WW3. (b) What is the regional domain cutoff for your regional model? (c) What are the lateral boundary conditions used for WW3? (d) You specify that atmospheric and oceanic forcing are for NeXtSIM—does WW3 receive the same forcing? (e) Please explain what "oceanic boundary conditions for NeXtSIM" means. Does this include both lateral boundary conditions and oceanic forcing? (f) You specify that "Our simulation spans the period 2018–2022 over a pan-Arctic domain with 25 km nominal resolution"—does this assume both NeXtSIM and WW3 are defined on the same mesh? (g) What is the advantage of this configuration over just analyzing sea-ice data and ERA5 wave fields? Is it simply to get Stokes drift? Did you consider using Webb (2011) to estimate Stokes drift from H_s? (h) The waves should also modify the ocean, and this cannot happen—can you comment on this potential impact?

Author Response:

We appreciate these detailed configuration questions. We answer here each of the questions:
(a) The attenuation scheme used correspond to the switch IS2 and IC2 in the WW3 model. It combines 3 attenuations processes: scattering, friction, and inelastic dissipation due to the repeated flexure of sea ice. These processes and their effects are discusse in Boutin et al. 2018. This combination of attenuation processes has been shown to provide reasonable wave-in-ice estimates for events that occurred the Barents Sea (Boutin et al., 2018), Beaufort Sea (Ardhuin et al., 2018) as well as MIZ extent consistent with observations from ICESat-2. (Boutin et al., 2022).
(b) We cut off the regional domain south of 54degN.
(c) We provide the southern lateral boundaries in WW3 with wave spectra from the global hindcast from Ifremer: Data from WAVEWATCH-III simulations, from the project «Modélisation et Analyse pour le Recherche Côtière » (MARC) https://marc.ifremer.fr, Ifremer, University of Brest, CNRS, IRD, Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, Brest,

France.
(d) Yes, atmospheric forcings are the same (hourly ERA5). WW3 does not use any oceanic forcings (the effects of ocean currents on waves is not accounted for).
(e) neXtSIM does *not* have forced lateral boundary conditions, only forcings. At the lateral boundaries of the domain,sea ice neXtSIM will flow out as if there was no resistance and flow in as if the ice state outside the boundary was the same as that inside it (Olason et al., 2025).
(f) They do not share the exact same mesh, because neXtSIM is a Lagrangian model that uses a moving triangular mesh, while WW3 is run on a stereographic grid. However, the mesh was built to have an resolution equivalent to the grid used by WW3. As neXtSIM runs, this mesh moves and deform, but undergoes regular "local remeshing" to avoid too high deformations of the triangles and conserve the resolution. Every coupling timestep, neXtSIM interpolates the exchanged quantities from its mesh to the exchange grid, which is the same as the one we use to run WW3.
(g) We appreciate the reviewer's suggestion and the reference to Webb (2011). While empirical relations between Hs and surface Stokes drift are effective in the open ocean, they assume fully developed, ice-free seas. In the Arctic, wave spectra is strongly attenuated and directionally filtered by sea ice. The neXtSIM–WW3 configuration provides a physically consistent treatment of these effects. Specifically, WW3 provides wave statistics (Hs, fp, directional spreading) and a bulk estimate of Stokes drift that accounts for attenuation by sea ice through parameterized energy loss. neXtSIM provides the evolving ice concentration fields that constrain wave propagation and the effective surface stress partition. ERA5 does not represent the wave attenuation in a realistic manner, it simply assumes ice is land above a certain concentration threshold. neXtSIM-WW3 is an existing dataset, where the wave attenuation in ice has been, if not demonstrated in every circumstances, at least discussed in 2 publications (Boutin et al., 2021;2022). It is also self-consistent throughout the time period (doesn't depend on observations through data assimilation).
(h) We agree that, in the present configuration, the ocean is not dynamically coupled to the wave field. The coupling is one-way through surface stress and Stokes drift forcing. Consequently, the diagnosed dissipation and Langmuir metrics represent the potential turbulent forcing rather than the fully realized oceanic response. Including an interactive ocean component would allow the wave-induced momentum and TKE to be redistributed vertically and laterally, modifying local stratification and mixed-layer depth. However, previous coupled studies (Li et al., 2019) show that these feedbacks mainly alter the magnitude of ε while preserving the spatial patterns of Langmuir forcing. We have clarified this limitation in Section 5 and now explicitly describe our diagnostics as representing Langmuir turbulence potential rather than resolved mixing.
In addition, each section in the manuscript has been expanded to include this information.

2. Section 3.1 – Momentum Flux Formulation

Reviewer Comment:

Using an absolute-wind formulation may overestimate the momentum flux into the ocean since momentum loss due to wave generation is neglected. What is the potential impact of this choice? It may be possible to estimate this from GLORYS data.

Author Response:

We agree that using the bulk absolute-wind formulation ($\tau_{ao} = \rho_a C_{ao}|u_a|u_a$) neglects the portion of atmospheric momentum transferred to wave growth, which may slightly overestimate the effective ocean stress. In our coupled setup, the sea-state dependence of surface drag is not represented because WAVEWATCH III and neXtSIM are not dynamically coupled. Thus, the stress applied to the ocean represents an upper bound on the true momentum flux into the mixed layer.

This assumption primarily affects the absolute magnitude of u_* and $\varepsilon_{\text{shear}}$ during active wave-growth conditions, but it does not alter the spatial patterns or relative Langmuir enhancements analyzed here. The effect is minimal under high–sea-ice conditions where wave growth is suppressed. We have clarified this limitation in the revised text and noted that future coupled implementations could incorporate wave-modified stress terms or evaluate corrections using sea-state diagnostics from GLORYS.

3. Section 3.2 – Definition of α_L

Reviewer Comment:

α_L is not introduced well. I suggest 'dynamic orientation of the Langmuir cells relative to the wind direction (α_L)' or something similar. I understand not including α_L, but an α_{LOW} is proposed at the end of Van Roekel et al 2012 that could be used here. Given the overestimation with θ_{ww} produces a muted response, I would expect α_{LOW} to be less as well. But it would be useful to discuss this better.

Author Response:

We have now clarified that α_L represents the dynamic orientation of the dominant Langmuir cells relative to the wind direction, which modulates the effective wave–wind coupling strength. Following the suggestion, we incorporated α_{LOW} from Van Roekel et al. (2012) to test the effect of Langmuir cell reorientation under wave–wind misalignment. In our revised analysis, α_{LOW} is defined as the empirical correction angle that minimizes the misalignment between the Stokes drift and the wind stress directions, such that $\theta_{ww} - \alpha_{\text{LOW}}$ represents the effective alignment of the Langmuir circulation with the mean flow. We compute the adjusted cosine alignment $|\cos(\theta_{ww} - \alpha_{\text{LOW}})|$ and show that it produces a more physically consistent distribution compared to $|\cos(\theta_{ww})|$, particularly in high–sea-ice or strongly misaligned regimes (Figure 8, Section 4.4). As expected, the inclusion of α_{LOW} increases effective alignment, indicating that Langmuir cells reorient toward the dominant combined Stokes–shear forcing.

4. Section 3.2.1 – Turbulence Scalings and TKE Relations

Reviewer Comment:

(a) Use of the scaling- The scalings from Van Roekel et al 2012 were derived from destabilizing LES conditions primarily. I'm not aware of any work examining LT and the scaling in stabilizing conditions. Therefore, it's not clear how applicable the VKE scalings, LaT etc... are to the arctic. (b) The relationships between Eqns (9–11) are unclear—what is the wave-driven

TKE contribution? If Eqn (9) is total dissipation, Eqns (9) and (11) seem redundant. (c) It would be helpful to explicitly state that these dissipation relationships emerge from a vertically integrated turbulence kinetic energy budget.

Author Response:

(a) Indeed, the turbulence scalings of Van Roekel et al 2012 were derived from idealized large-eddy simulations under destabilizing surface forcing, where convective mixing reinforces Langmuir cell overturning. In contrast, Arctic mixed layers are often stably stratified due to ice melt and freshwater input, which suppresses overturning and modifies the partition between shear-driven and Langmuir-driven turbulence. We have added a new paragraph clarifying that our use of the Van Roekel scaling is intended as a diagnostic framework for relative enhancement potential, not as a direct representation of absolute dissipation in stratified conditions. We also note that the resulting Langmuir number and enhancement factors should be interpreted as indicators of the potential for Langmuir forcing, with the effective magnitude likely reduced under stable Arctic conditions. Also, we have expanded our discussion to mention that ongoing studies (e.g., Lee et al. 2025 (preprint);Brenner et al. 2023) are working to resolve Langmuir turbulence under partially ice-covered and weakly stratified regimes, providing a pathway toward stratification-aware parameterizations. This clarification has been added to Section 4.3.

(b) We write the boundary-layer dissipation as a wind–only baseline multiplied by a Langmuir enhancement,

$$\varepsilon_{\text{total}} \;=\; \varepsilon_{\text{shear}}\, E(La_x), \tag{1}$$

where

$$\varepsilon_{\text{shear}} \;=\; \frac{u_*^3}{h}, \tag{2}$$

and $E(La_x)$ is the enhancement factor derived from LES scalings of vertical velocity variance (Van Roekel et al., 2012). For diagnostic attribution we define the Langmuir (wave-driven) excess as

$$\varepsilon_{\text{LT}} \;\equiv\; \varepsilon_{\text{total}} - \varepsilon_{\text{shear}} \;=\; \varepsilon_{\text{shear}}\,[\,E(La_x) - 1\,]. \tag{3}$$

Equations (1)–(3) thus define the total, baseline, and residual terms without redundancy.

Because dissipation scales with a cubic velocity measure, we additionally report a Belcher-style form (Belcher et al., 2012) at mid–mixed layer,

$$\varepsilon_{\text{Belcher}} \;\approx\; \frac{u_*^3}{h}\left(1 + \frac{\beta}{La_t^2}\right), \tag{4}$$

where β is obtained from a least-squares fit to the observed ratio $\left(\varepsilon_{\text{total}}/\varepsilon_{\text{shear}} - 1\right)$ versus $1/La_t^2$. In our analysis we present both (1) and (4) to illustrate sensitivity to the assumed scaling. We emphasize that ε_{LT} in (3) is a diagnostic residual rather than a uniquely identifiable production term. For completeness, we also test $\varepsilon_{\text{total}} = (u_*^3/h)\,[E(La_x)]^p$ with $p = 1.5$, which improves consistency with cubic velocity scaling while retaining the empirical E shape.

(c) We agree and thank the reviewer for this suggestion. The dissipation formulations used in our analysis are indeed derived from the vertically integrated TKE budget of the ocean surface boundary layer. In this framework, $\varepsilon_{\text{shear}} = u_*^3/h$ represents the depth-averaged dissipation associated with shear-driven turbulence, while the Langmuir-enhanced terms scale this baseline according to parameterized production and transport by Stokes drift. We have revised the manuscript to make this origin explicit, and clarified the used equations.

5. Section 4 – Results and Interpretation

Reviewer Comment:

(a) Figure 1: Why does Hs exceed but not Us(0)? I usually expect Hs and Us to be related. Is there any way to calculate these exceedance rate from observations? How well does the WW3-NeXTSIM coupled model reproduce observed statistics?

(b)Wouldn't the exceedance statistic (eqn 14) be biased since the OW cells are systematically located at lower latitudes, and experience different forcings than ice covered cells higher latitude cells?

Author Response:

(a) While $u_{s(0)}$ and h_s are both related to wave energy, they respond differently to ice-induced spectral attenuation. The Stokes drift magnitude $u_{s(0)}$ depends primarily on the high-frequency tail of the wave spectrum, which is strongly damped under partial ice cover. In contrast, significant wave height h_s integrates energy across the full spectrum and is therefore less sensitive to the loss of short waves, allowing exceedance events to persist closer to the ice edge. This explains why h_s occasionally exceeds open-water medians while $u_{s(0)}$ rarely does.At present, comparable exceedance statistics cannot be directly derived from satellite observations, as continuous u_* and $u_{s(0)}$ measurements under ice are unavailable. However, the spatial structure and seasonal ranges of h_s in the WW3–NeXtSIM simulations agree well with altimeter-based climatologies (e.g., Ardhuin et al., 2020; Stopa et al., 2018), providing confidence in the model's realism. We have added this clarification to the text.
(b) We agree that open-water grid cells are preferentially located at lower latitudes, where wind and wave forcing differ from the high-latitude ice-covered regions. Our exceedance metric in Eq. (14) is not intended as a strict bias-free comparison of magnitudes across latitudes, but rather as a *relative indicator* of how often local conditions beneath ice reach levels typically observed in OW environments. By normalizing against the seasonal median of OW conditions, the metric highlights regions where ice-covered forcing approaches or exceeds the typical OW baseline, independent of absolute latitude. We have clarified this interpretation in the revised manuscript and now explicitly note that this statistic should be viewed as a relative, not absolute, measure of forcing equivalence.

6. Section 4.3 – Mixing Interpretation and Stratification

Reviewer Comment:

The conclusion at the start of section 4.3 doesn't seem supported well by evidence. This could be fixed by specifying " in the MIZ" as opposed to "in the Arctic". The current phrase suggests this is pan-Arctic.

Author Response:

We agree that the current wording could be misinterpreted as implying a pan-Arctic enhancement of dissipation, whereas the evidence supports this conclusion primarily within the marginal ice zone. We have revised the opening sentence.

Reviewer Comment:

L 355 - The text here is speculative. Have you examined ocean stratification over this period? This would be a useful compliment to your analysis. Even for your mixing discussion, you have more mixing energy, but there is no guarantee there is more mixing without examining stratification.

Author Response:

We agree that enhanced turbulent dissipation does not necessarily imply greater vertical mixing without accounting for ocean stratification. We have revised the paragraph to explicitly acknowledge this limitation and to clarify that our analysis focuses on the surface forcing tendency rather than realized mixing. We do not have stratification data, but we have conducted a sensitivity test based on the mixed-layer depth dataset from GLORYS, which serves as a proxy for upper-ocean stability. We have clarified this limitation in Section 4.3 and highlighted the need for future work linking LT diagnostics with direct measures of stratification.

7. Section 4.4 – Kernel and Subgrid Variability

Reviewer Comment:

Please clarify what the connection between the kernel analysis is and subgrid variability. It's a measure of local heterogeneity but using a spatial kernel doesn't say anything about variability below the model grid scale. There certainly is a lot of spatial variability, but this doesn't mean it's subgrid

Author Response:

We agree and have replaced subgrid with local spatial variability throughout. The text now clarifies that kernel analysis measures horizontal gradients in modeled fields, not unresolved subgrid turbulence.

Minor Comments

- **L58 & L73:** Replace "WaveWatch III" with the official name "WAVEWATCH III".
  Corrected throughout.
- **L75:** Remove "fully."
  Corrected.
- **L76:** WW3 already defined.
  Removed redundancy.

- **L143:**tilda is above the 2 in 25km?
  Fixed.

- **Figure 2:** caption the Median 15% and 80% SIC contours are overlaid in black and blue. Based on the image, the 15% SIC is actually BLUE and the 80% line is black - make sure the listed order of the contours match
  Corrected caption and figure.

- **L239:** the concept of a MIZ day is confusing… please clarify if you mean that a "MIZ day" is defined as when ANY grid cell in the entire domain on a given day is between 15-80% SIC. If so, I would expect every 'day' in the time series to be classified as a MIZ day, which would make this metric essentially meaningless. Is there any spatial requirement for a grid cell to be located within the MIZ in this definition? In other words, please clarify if these exceedance values (in Fig A) are only valid for grid cells within the MIZ, or ALL grid cells on a day where any MIZ cell is present within the domain (which would be 100% of the time).
  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 marginal ice zone. The exceedance metric (Eq. 14) is computed per grid cell and only for time steps when that cell satisfies the sea-ice condition (SIC ≥ 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.*

- **Figure 3:** results - what is the definition of persistence? "
  Added definition as the consecutive-day duration of a given LT regime.

- **L330–332:** Add missing reference and fix equation/typo.
  Added citation and corrected inline equation.

- **L375–376:** Reiterate overestimation when using θ_{ww}.
  Noted

- **L391–397:** Clarify difference between analyses 1 and 2 and mention Van Roekel et al. (2012) Fig 16 confirmation.
  Expanded discussion and included direct comparison.

- **L402:** Remove "comprehensive."
  Corrected.

- **L420 & L447:** Replace "subgrid" with "fine-scale."
  Corrected throughout.

- **L438–440:** - what are the implications of overestimates from Langmuir diagnostics? Are you making connections to things like the KPP enhancement factor being based on LaT? Couldn't this capture the regime if Stokes drift is dynamic (say from WW3?)?
  In our study, the diagnosed enhancement factors (E_{La_t}*) can be viewed as basin-scale analogs*

of the empirical terms used in such schemes. Hence, the regions where our diagnostics overestimate Langmuir turbulence—particularly under compact ice—highlight where La_T-based parameterizations may likewise inject excessive mixing if wave attenuation or drag partition effects are not considered. Our configuration captures the time-varying sea state, but it employs only the surface Stokes drift magnitude (u_{s0}) rather than a depth-integrated or profile-weighted metric. As a result, Langmuir numbers based on u_{s0} can still be biased low (stronger LT) where the Stokes profile decays rapidly beneath ice or under stabilizing conditions. This simplification partly explains the residual overestimation we observe in high–sea-ice regimes. We now clarify this point in the discussion and note that incorporating a vertically weighted Stokes drift or explicit sea-ice attenuation would further improve the realism of Langmuir forcing and help constrain La_T-based parameterizations in ice-covered regions.

- **L452:** Clarify "integrating directional wave spectra."
  Clarified

- **L452:** "Fully coupled" implies inclusion of an active atmosphere.
  Revised

References

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. https://doi.org/10.1002/2018JC013784

Boutin, G., Ardhuin, F., Dumont, D., Sévigny, C., Girard-Ardhuin, F., & Accensi, M. (2018). Floe Size Effect on Wave-Ice Interactions: Possible Effects, Implementation in Wave Model, and Evaluation. *Journal of Geophysical Research: Oceans*, *123*(7), 4779–4805. https://doi.org/10.1029/2017JC0136

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: Mathematical, Physical and Engineering Sciences*, *380*(2235), 20210262. https://doi.org/10.1098/rsta.2021.0262

Boutin, G., Williams, T., Rampal, P., Olason, E., & Lique, C. (2021). Wave–sea-ice interactions in a brittle rheological framework. *The Cryosphere*, *15*(1), 431–457. https://doi.org/10.5194/tc-15-431-2021

Ólason, E., Boutin, G., Williams, T., Korosov, A., Regan, H., Rheinlænder, J., Rampal, P., Flocco, D., Samaké, A., Davy, R., Spain, T., & Chua, S. (2025). The next generation sea-ice model neXtSIM, version 2. *EGUsphere*, 1–33. https://doi.org/10.5194/egusphere-2024-3521

Li, Q., Reichl, B. G., Fox-Kemper, B., Adcroft, A. J., Belcher, S. E., Danabasoglu, G., ... & Zheng, Z. (2019). Comparing ocean surface boundary vertical mixing schemes including

Langmuir turbulence. *Journal of Advances in Modeling Earth Systems*, *11*(11), 3545-3592.
Brenner, S., Horvat, C., Hall, P., Lo Piccolo, A., Fox-Kemper, B., Labbé, S., & Dansereau, V. (2023). Scale-dependent air-sea exchange in the polar oceans: Floe-floe and floe-flow coupling in the generation of ice-ocean boundary layer turbulence. *Geophysical Research Letters*, *50*(23), e2023GL105703.
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*.