Author's response to the interactive discussion

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March 15, 2026

In the following, we will answer each reviewer's comments point-by-point.

1 st reviewer's comments

Comments can be found at https://doi.org/10.5194/egusphere-2025-2671-RC1. These comments are given by italic texts below.

The authors want to express our sincere gratitude to the reviewer for taking the time to review our manuscript. Your thoughtful feedback and constructive suggestions have been immensely valuable in improving the quality of our work.

1.1 Overall assessment

> *The authors have revised the manuscript by adding two appendices that supplement the derivation process in Section 2. I now believe that the basic assumptions and the logical steps of the derivations are clarified, and readers should be able to evaluate the credibility of the theory.*
>
> *That said, I still have doubts about some of the assumptions underlying the formulations. For example, in Appendix B, the authors estimate turbulent mixing through scaling with water-particle displacement and orbital velocity of linear wave solutions. This is questionable from a physical standpoint, since purely oscillatory motions do not lead to irreversible mixing. However, I understand that fully justifying the physical validity of these assumptions may go beyond the scope of the present study, and the paper may be published as long as a rigorous comparison against reliable data is provided.*
>
> *Regarding the comparison of the model against the tank experiments (L320-354), they try to rebut my previous comment that points out the problems in TKE budget framework. Specifically, they argue that wave breaking, wind-driven turbulence, and Langmuir turbulence do not contribute significantly to water turbulence, in a 16 m-long wind-wave flume under 20 to 30 m/s wind forcing, compared with non-breaking wave-induced turbulence. I find this argument physically implausible and not adequately supported. Under such strong wind forcing and limited fetch, it is difficult to accept that these well established turbulence-generating mechanisms would be negligible.*
>
> *Given the weak physical basis of the analysis in L320-354 and the fact that the comparison in L419-451 remains inconclusive due to the large scatter of the reference data, I consider that the proposed model is still not sufficiently validated against realistic observational or experimental evidence, nor supported by a rigorous theoretical foundation. Unless the theoretical arguments underlying the analysis in L320-354 are substantially improved, I cannot recommend the manuscript for publication.*

We would like to sincerely thank the reviewers' valuable comments and suggestions, which have helped us improve the quality and clarity of the paper.

As stated by Babanin (2006, 2011), 'albeit small and negligible from the point of view in majority applications, water viscosity, however, is not zero.' In the presence of a strong exponential vertical gradient of the wave orbital velocity, and this velocity being one or two orders of magnitude larger than the other velocities in the water column usually associated with the shear stresses, wave-caused shear stresses are unavoidable. His suggested concept of the wave-amplitude-based Reynolds number $Re_{\text{wave}} = \frac{a(x_3)u_{\text{orb}}(x_3)}{\nu}$ aims to indicate a transition from laminarity to turbulence for the wave-induced motion, where $a(x_3)$ is the wave amplitude decayed exponentially away from the surface, $u_{\text{orb}}(x_3)$ is the wave orbital velocity and ν is the kinematic viscosity of the ocean water. The linear wave theory was employed merely for estimates of the Reynolds number, and subsequently utilized for the assessment of turbulent mixing in Appendix B. The linear approach is considered to provide a good approximation on average. Babanin (2011)conducted a thorough discussion of this seemingly paradoxical issue. As the reviewer pointed out, fully justifying the assumptions underlying Appendix B is beyond the scope of this study. A series of verifications using laboratory measurements or cruise observations have been significantly advanced over the past two decades. (e.g. Babanin, 2006, 2011; Babanin and Haus, 2009; Yuan et al., 2013; Zhuang et al., 2020, 2021; and others). This work constitutes an effort to apply these research findings to present an analytical dissipation parameterization induced by wave-generated turbulence for the practical numerical simulation of ocean waves.

We apologize that in our previous response, we offered only a preliminary, qualitative perspective on the reviewer's concern regarding the tank experiments (L320-354). In the following, we explored the comprehensive tank experiments of Wei et al. (2018) concerning the surface drag coefficient, have expanded our analysis to provide more quantitative details on the effects of wave breaking, wind-driven turbulence, and Langmuir turbulence. The revised findings are presented below. The discrepancy between the model results and observations in Fig. 4 in our manuscript reveals that turbulence generation may be governed by complex dynamical mechanisms. Though the above dynamical processes are all important in the tank experiments, the shear instability of wave orbital motions appears to be the dominant contributor to turbulence. As the comparison results below involve extensive content that would dilute the main focus of the current study, we therefore propose to address them elsewhere. Regarding the limitation of the statistical model, we have addressed its deficiencies and pointed out that it is designed to capture general trends but is less well-suited for simulating the rapid transient regime of wave breaking.

1.2 Major comments

1.2.1 *Response 1.2.5*

The authors argue that TKE production by breaking waves, wind-driven currents, and Langmuir turbulence is negligible. This claim deviates substantially from the common understanding of wind-wave dynamics and mixed-layer turbulence: in young sea, waves actively break and enhance turbulence; such a situation is also commonly observed in *wind-wave tanks. Such a departure would require particularly strong and convincing justification, not in the Response to Reviewer Comments but in the manuscript itself. However, the theoretical arguments presented by the authors are weak and rely on crude reasoning, as pointed out below. Given possibility of other turbulence source as discussed below, it seems unreasonable to assume* $\varepsilon_{\mathrm{dis}}$ *(TKE dissipation in water) ≈* e_{tid} *(wave energy loss due to nonbreaking wave-induced turbulence).*

- *"… the measurements were recorded for nonbreaking waves, and the wave steepness in Table 1 is less than the classical breaking criterion 1/7, so the breaking effects can in fact be neglected here."*

Even in wave textbooks, it is acknowledged that the criterion $H\ /\ \lambda \approx 1\ /\ 7$ *is the limit of steepness of monochromatic Stokes wave and should be considered as an upper limit of individual wave steepness. In irregular wave fields, waves break at much smaller steepness (e.g., Figure 6 of Holthuijsen and Herbers, 1986, JPO), and in typical sea states* $H_{\mathrm{s}}\ /\ \lambda_{\mathrm{p}}$ *is well below 1/7, yet breaking waves are widely recognized as a major sink of wave energy. Do the authors then suggest that wave breaking is also insignificant in realistic sea states?*

We agree with the reviewer's opinion and acknowledge that our initial argument, which was primarily based on the breaking criterion, was too crude and lacked sufficient rigor. In the paper of Wei et al. (2018), the effects of wave breaking were not addressed. A separate series of laboratory experiments on the measurement of the surface drag coefficient touched upon this issue (Wei, 2017). The following **Fig. A1** (i.e., Figure 3-4 of Wei (2017)) shows that the surface drag coefficient increase with wind speed when wind speed at 15-30 m/s. When the wind speed is larger than 30 m/s, the surface drag coefficient shows a marked drop. He further added to the wave tank a modest amount of foam (produced by mixing dish soap and water) and half of the foam, in order to study the influence of surface foam on the drag coefficient (He also conducted laboratory experiments to study the effects of hot air on the drag coefficient, which is beyond of the scope of the present study.). **Figure A2** (i.e., Figure 3-7 of Wei (2017)) shows comparisons among the three scenarios: not adding foam, adding half the foam and adding full foam. Foam increases surface drag coefficient at low wind speed. With wind speed increases, it decreases surface drag coefficient. The drag coefficient does not change significantly when the wind speed exceeds 30 m/s, which is mainly due to the breaking foam of surface waves (Wei, 2017). His series of laboratory measurements show that breaking effects are negligible, except when wind speeds exceed 30 m/s. For the final scenario, i.e., Experiment 2 in Table 1 in our manuscript, precisely quantifying the effect of breaking is difficult, and his experimental setup was not specifically designed to address this issue. Lamarre and Melville (1991) measured the breaking entrainment depth and derived the result of $0.015\bar{L}$-$0.05\bar{L}$, and the measurements of Kalvoda et al. (2003) satisfy the results of $0.2H$s-$0.5H$s. The latest experimental study found that the penetration depth of breaking-wave-generated turbulence is $0.7H$s-$0.9H$s (Mu et al., 2021), which is consistent with the findings of Rapp and Melville (1990) and Hwang et al. (2016). So the maximum wave-breaking penetration depth is approximately 5 cm for Experiment 2, which is about one-quarter to one-third of the observed $\varepsilon_{\mathrm{dis}}$ depth, and the latter can reach a depth of 15-20 cm

(Fig. 4 in our manuscript). So the breaking events in Experiment 2 appear to be micro-breaking, rather than full wave breaking. This does not imply that micro-breaking is absent in Experiment 1, and we agree with the reviewer’s opinion that wave breaking is perpetually present in realistic sea states and, as such, constitutes an essential dissipation source term in the modern widely-applied third-generation wave models. Wei et al. (2018) may not have specifically addressed the effects of micro-breaking, which we will evaluate in the discussion below.

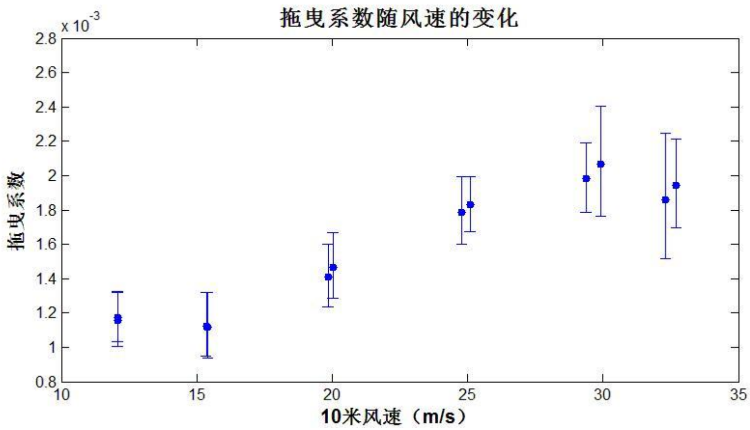

Figure A1. Variation of the drag coefficient with the 10-m wind speed (i.e., Figure 3-4 of Wei (2017))

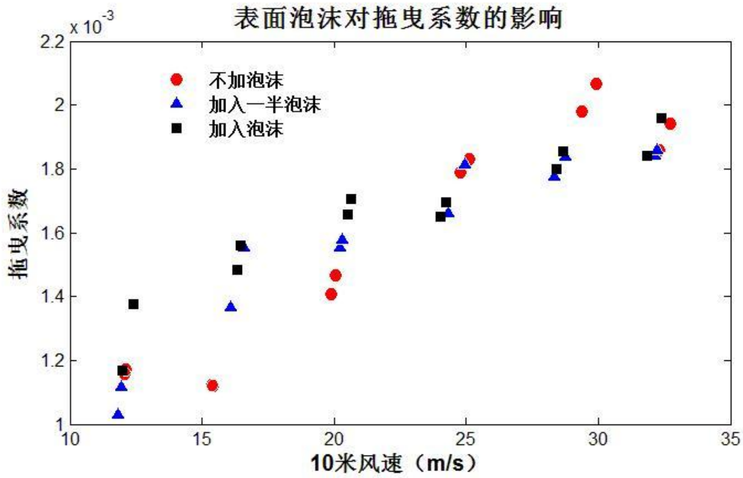

Figure A2. Variation of the drag coefficient with the 10-m wind speed. ●: not adding foam; ▲: adding half the foam; and ■: adding full foam. (i.e., Figure 3-7 of Wei (2017))

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- *"The wave-induced mixing strength is much larger than that calculated from the Mellor-Yamada turbulence closure scheme in the upper layers (e.g. Qiao et al., 2010; Xia,2015). The latter can also be neglected here in the laboratory experiments, for the wind wave tank is only 16 m long and the near-surface wind-driven turbulence is still in its incipient stage due to the short fetch."*

The logic of this argument appears circular: wind-driven turbulence is assumed to be negligible precisely because nonbreaking wave-induced mixing is presumed to be dominant. However, as discussed in the Overall Assessment, the physical basis for estimating nonbreaking wave-induced mixing itself is questionable. Consequently, the claim that wave-induced mixing dominates over wind-driven turbulence is also not convincing.

Furthermore, I do not see a clear justification for assuming that wind effects are also weak in the laboratory experiment. A limited fetch does not necessarily reduce the wind stress or the resulting shear-driven turbulence in the water. Rather, it is the wave growth that is constrained by the short fetch, which directly limits wave-induced mixing. This consideration further undermines the assumption that wind-driven turbulence can be neglected under the experimental conditions considered.

We thank the reviewer for pointing out this issue and acknowledge that our initial argument was also too crude and lacked sufficient rigor. This particular issue was not explored by Wei (2017), Wei et al. (2018) either. In the following, we attempt to employ the parameterization approach of Wang and Liao (2016) to derive somewhat quantitative estimates of the wind-driven near surface turbulent dissipation rate and compare them with our results for the wind-wave Experiments 1-2 (see Table 1 in our manuscript). The measured turbulence in the top layer on Lake Michigan (without noticeable wave breakers, i.e., whitecaps) is likely due to the TKE production through wind shear, micro-breaking events of surface waves by comparing with the Law-Of-the-Wall (LOW) scaling (Wang and Liao, 2016). Based on the arguments of the additional TKE flux from the wave breaking to the wind shear (Terray et al.,1996; Sutherland and Melville, 2015), they proposed an improved parameterization to include wave age in the scaling to account for its impact on the near surface turbulent dissipation rate, i.e.,

$$\varepsilon_{\mathrm{win}} = \begin{cases} 1.3\times10^{-3}\dfrac{c_{\mathrm{p}}A_{\mathrm{g}}u_{*\mathrm{w}}^{2}}{H_{\mathrm{s}}}\left(\dfrac{x_3}{H_{\mathrm{s}}}\right)^{-0.7} & \text{if } \dfrac{x_3}{H_{\mathrm{s}}}<0.4 \\ 1.4\times10^{-3}\dfrac{c_{\mathrm{p}}A_{\mathrm{g}}u_{*\mathrm{w}}^{2}}{H_{\mathrm{s}}}\left(\dfrac{x_3}{H_{\mathrm{s}}}\right)^{-2} & \text{if } \dfrac{x_3}{H_{\mathrm{s}}}\geq 0.4 \end{cases} \tag{A1}$$

where H_s is the significant wave height, c_p is the characteristic wave phase speed, u_{*w} is the water-side friction velocity, and A_g is the wave age defined as the ratio of the characteristic wave phase speed to the friction velocity at air side, i.e., $A_g \equiv c_p / u_{*a}$. Profiles of normalized dissipation rate were also compared with previous literature observations.

In the numerical estimation below, only the second fraction in Eq. (A1) is employed for the tank observation points of Wei et al. (2018) meet only the second condition, i.e., $x_3/H_s > 0.4$. Two parameters H_s and c_p can be derived directly from Table 1 in our manuscript, where the wave dispersion relation is applied. The air-side u_{*a} is calculated from the measured drag coefficient in the above Fig. A1, i.e., $u_{*a} = \sqrt{C_d} \cdot U_{10}$ and the water-side friction velocity u_{*w} is calculated by using $u_{*w} = \sqrt{\frac{\rho_a}{\rho_w}} \cdot u_{*a}$, where ρ_a, ρ_w represent the air density and water density, respectively. The following **Fig. A3** shows the dependence of TKE dissipation rate of wind-driven turbulence (dashed lines) versus layer depth in linear/logarithmic scale for wind wave conditions respectively. The estimated TKE dissipation rates varies in the range of 10^{-7}-10^{-4} m^2 s^{-3}, which are 1-2 orders of magnitude smaller than the laboratory observations of Wei et al. (2018). We also note that, though the 10m wind speed U_{10} in the wind wave Experiments 1-2 is much higher than that (2.7-14.3 m s^{-1}) over the Lake Michigan, the estimated TKE dissipation rates of wind-driven turbulence at a water depth of 10 cm are smaller than the observations over the lake. This is mainly due to the short wave age (0.77 and 0.57) in the wind wave Experiments 1-2 (the wind wave tank is only 16 m long with a short fetch), which is much smaller than that (2.7 - 52.6) over the lake. In this context, the influence of turbulence generated by wind shear and micro-breaking events in the wind wave Experiments 1-2 can be considered negligible. And for the mixed wave Experiment 3, the influence of the wind-driven turbulence component can also be considered negligible. We hope that this addresses the reviewer's concern.

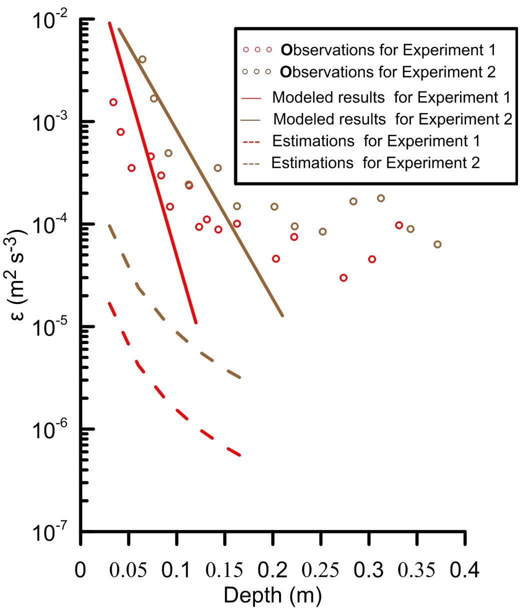

Figure A3. Dependence of TKE dissipation rate ε_{dis} (denoted as ε in the figure) versus layer depth. Observation data for wind waves (circles) are digitalized from Wei et al. (2018). The estimations of the TKE dissipation rate of wave-generated turbulence (Eq. (19) in our manuscript) and wind-driven turbulence (Eq. (A1)) are shown with solid and dashed lines, respectively. Data are plotted in linear/logarithmic scale on the horizontal/vertical axis.

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- *Comparison against Langmuir turbulence (LT)*

  I am unclear about how the scaling for Langmuir turbulence (LT) is chosen. If there are existing studies that support the adopted scaling, the authors should explicitly cite them. It appears inappropriate to characterize LT using the orbital-motion-induced displacement ($\overline{l}_{\mathrm{D}}$), since LT is generally associated with mixed-layer-scale circulations. Furthermore, it is common to characterize the velocity scale with $\left(u_*^2 u_{\mathrm{s}}\right)^{1/3}$, where u_* is water-side friction velocity, on which the present scaling does not depend (see, for example, Grant and Belcher, 2009, JPO).

We thank the reviewer for raising this point and have thoroughly read the recommended literatures (Polton and Belcher, 2007; Grant and Belcher, 2009). Their studies present a highly valuable characteristics scaling of Langmuir turbulence by using the large-eddy simulation (LES) scheme. When the Stokes drift of the wave field is sufficiently large compared to the surface friction velocity, their scaling leads to unique profiles of nondimensional dissipation rate. And the shapes of the LES dissipation profiles agree well with the observations, the Langmuir numbers for these profiles are in the range of 0.15-0.30 (Grant and Belcher, 2009). Based on the measured drag coefficient and the calculated water-side friction velocity $u_{*\mathrm{w}}$ stated above, as well as the Stokes drift $U_{\mathrm{S}} = \omega K A^2 \exp\{2Kx_3\}$ (Mcwilliams et al., 1997), we calculate the corresponding turbulent

Langmuir numbers for Experiments 1-3 (see **Table 1A** below). In our previous response, our analysis focused on the TKE dissipation rate resulting solely from the Stokes drift shear, including that for the swell Experiment 4. For the latter, the characteristic velocity scale that the reviewer proposed may not be suitable. This leads us to adopt the turbulent k - ε model (Yuan et al., 2013) and its equilibrium solutions to estimate the TKE dissipation rate resulting solely from the Stokes drift shear. This is also discussed in **Appendix B** in our manuscript, in which the shear term $\frac{\partial u_{\mathrm{SM}i}}{\partial x_j}$ (it consists of all the relevant shear terms induced by wave motion) is replaced by $\frac{\partial U_{\mathrm{S}}}{\partial x_3}$ i.e.,

$$\bar{k} \approx \pi \bar{l}_{\mathrm{D}}^{2} \left(\left| \frac{\partial U_{\mathrm{S}}}{\partial x_3} \right| \right)^2 \tag{A2}$$

$$\bar{\varepsilon} \approx \bar{l}_{\mathrm{D}}^{2} \left(\left| \frac{\partial U_{\mathrm{S}}}{\partial x_3} \right| \right)^3 \tag{A3}$$

So the Reynolds average of Eq. (A3) on wave motion is

$$\langle \bar{\varepsilon} \rangle_{\mathrm{SM}} \approx \langle \bar{l}_{\mathrm{D}}^{2} \rangle_{\mathrm{SM}} \left\langle \left(\left| \frac{\partial U_{\mathrm{S}}}{\partial x_3} \right| \right)^3 \right\rangle_{\mathrm{SM}} = \frac{1}{2} A^2 \exp\{2Kx_3\} \cdot \left\{ 2\omega K^2 A^2 \exp\{2Kx_3\} \right\}^3 = 4\omega^3 K^6 A^8 \exp\{8Kx_3\} \tag{A4}$$

Here we assume the relations $\bar{l}_{\mathrm{D}} \approx \left| A \exp\{Kx_3\} \exp\left\{ i\left(\vec{\boldsymbol{k}} \cdot \vec{\boldsymbol{r}} - \omega t\right)\right\} \right|$ and $\langle \bar{l}_{\mathrm{D}}^{2} \rangle_{\mathrm{SM}} \approx \frac{1}{2} A^2 \exp\{2Kx_3\}$ between the turbulent mixing length and the wave amplitude *A*, this reflects the effective scale of turbulent eddy motion and mixing in a wave-influenced environment. While this is a simplification, we deem it is a reasonable assumption for the scope of this study. We also agree with the reviewer' opinion that LT is generally associated with mixed-layer-scale circulations, this is from the perspective of the overall profile structure and large-scale effects of LT. In the following **Fig. A4**, the estimated TKE dissipation rates for Experiments 1-3 and the swell Experiment 4 in Table 1 are also shown, in which the latter was not shown in the previous response. Though the turbulent Langmuir number $L_{\mathrm{a}} > 0.5$ for Experiments 1-3, the magnitude of the TKE dissipation rate resulting solely from the Stokes drift shear is comparable to that of the wind-driven turbulence displayed above.

Literature on this topic is considerable, e.g., a two equation (k - ε) model coupled to momentum equations, in which the Stokes-vortex forcing term was taken into account, were used to investigate the enhanced turbulence (Araujo et al., 2001). Skyllingstad (2005) analyzed the LES modeled TKE budget to clarify the entrainment affected by Langmuir circulation, including mean flow and Stokes shift shear-productions, vertical transport by turbulent eddies, Stokes-vortex forcing, etc. It must be acknowledged that our estimation method used above is a rather rough one and has some drawbacks e.g., only the Stokes shift shear-production is included, but the Coriolis-Stokes forcing, the Stokes-vortex forcing and convection/diffusion terms are not considered for the measurements of the flow field were not prioritized in the wave tank experiments. Polton and Belcher (2007) concluded that the conjunctive effects of the Coriolis-Stokes forcing and the Stokes-vortex forcing result in a reduced mean shear and enhanced vertical transport of TKE into the mixed layer. Our estimate above may be somewhat overestimated, which requires further study.

Experiment number	Wave condition	Significant wave height Hs (cm)	Peak frequency (Hz)	Wave length (m)	Turbulent Langmuir number L_a
1	21 m s^{-1} wind	3.75	2.72	0.42	0.60
2	32 m s^{-1} wind	6.03	1.97	0.83	0.84
3	1.6 Hz swell with 21 m s^{-1} wind	5.26	1.64	0.86	0.79
4	1.2 Hz swell	3.98	1.20	1.36	---

Table A1. Wave parameters and turbulent Langmuir numbers for selected wave conditions

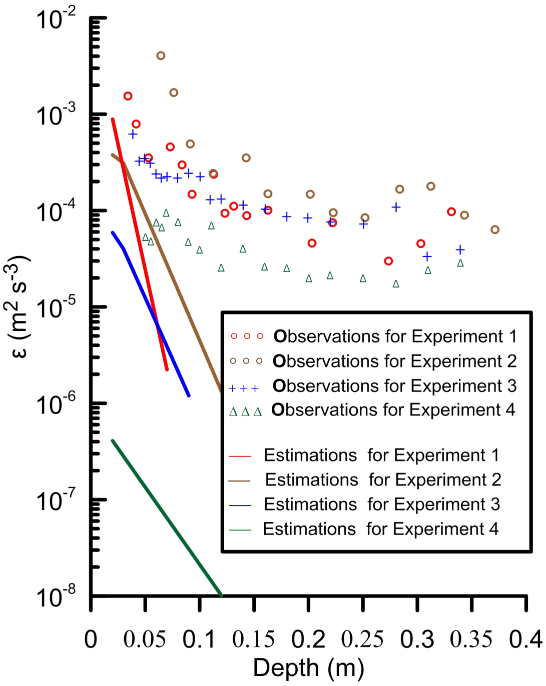

Figure A4. Dependence of TKE dissipation rate ε_{dis} (denoted as ε in the figure) versus layer depth. Observation data (circles, pluses and triangles) are digitalized from Wei et al. (2018). The estimations of the TKE dissipation rate of Langmuir turbulence are shown with solid lines. Data are plotted in linear/logarithmic scale on the horizontal/vertical axis.

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2 Revisions of the manuscript

As stated in 1.1, the above comparison results involve extensive content that would dilute the main focus of the current study. We further addressed the uncertainty associated with the second set of measurement data at the end of Section 2.1 of our manuscript as follows:.

> While in the second set of measurement data, turbulence generation may be governed by complex dynamical mechanisms, including wave breaking, wind-driven turbulence, Langmuir turbulence, etc., and only the shear instability of wave orbital motions to turbulence is considered here. Preliminary studies indicate the latter may be the dominant contributor to turbulence, their detailed comparison is beyond the scope of this study and will be addressed in future work.