Response on RC1

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First and foremost, the authors want to express our sincere gratitude to the reviewer for taking the time to review our manuscript titled “Analytical approaches for wave energy dissipation induced by wave-generated turbulence and random wave-breaking”. Your thoughtful feedback and constructive suggestions have been immensely valuable in improving the quality of our work.

The authors thank the reviewer for the overall very comprehensive summary of our work。 And we fully agree with the reviewer’s suggestion that our manuscript should be edited by native English speakers.

In Section 2.1, we attempt to detect the scales of the proposed dissipation source function induced by wave-generated turbulence in Eq. (15) by comparing to wave growth formulations, and verify the modeled TKE dissipation rate, generated by shear instability of irregular wind waves or swells, with laboratory observations (Figs. 3 and 4). We entirely approve of the reviewer’s point that the input mechanisms and in particular bulk transfer of energy action and momentum to waves is not well established either. Figures 1 and 2 in our manuscript show the growth/dissipation rate between input and dissipation terms under normal and extreme sea conditions, though both are comparable in spatial distribution and magnitude, and the growth is dominated by spectral signatures of the difference definitely. There is lack of comparison and assessment of Eq. (15) with previous formulations in the manuscript, which will be pursued in our future study. To further note, Figure 7 in Section 3 shows obliquely the role of Eq. (15) , comparable to that of previous parameterizations due to wave-breaking in the WAM and MASNUM wave models.

In Section 2.2, we present a new dissipation coefficient (26) based on the basic statistics of wave breaking by Yuan et al. (2009) and follow-up inspections and verifications (Wang et al., 2017, 2018; Shi et al., 2025). For easily displaying its relation to the previous formulation (24) (Yuan et al., 1986; Yuan et al.,1993; Donelan and Yuan, 1994), the new dissipation coefficient is rewritten as (27) by introducing the ratio of the kinetic energy loss to the potential one due to wave-breaking. Comparison to the previous formulation (24) indicates the new one varies with the ratio of the kinetic energy loss to the potential one due to wave-breaking, and it aligns with the previous one under certain conditions, while the constant coefficient in the previous one comes originally from the complicated 0-1st order asymptotic expansions of the covariance of surface elevation. That is to say, it is more reasonable physically to introduce the kinetic energy loss and the potential one to the dissipation coefficient. While this theoretical argument indicates the improvement of the new dissipation coefficient to the previous one, we agree that it is not a direct comparison which needs our further study. And we apologize for our ambiguous expressions for lacking clarity and will rephrase and/or extend to improve the readability of the text. We also agree that there is considerable noise for the shorter wave scales in the observation data in Figs. 5

and 6, which Young and Babanin (2006) also stated. Polnikov (2012) also criticized the observation data of "inevitable statistical noise", we think the observation data still impart the fact that the longer wave scales are more affected by the dominant breaking than the shorter wave scales. Besides, as we know until now, it is the only in-lake site measurement to obtain the valuable breaking spectra and the nonbreaking spectra for the spectral difference. Comparisons of the attenuation coefficients by using Eq. (26) with the ratio of the two observed spectra may yield valuable insights, which also need further interpretations.

Key references

Donelan, M. A., and Yuan, Y.: Wave dissipation by surface processes, in: Dynamics and Modelling of Ocean Waves, edited by: Komen, G. J., Cavaleri, L., Donelan, M.,Hasselmann, K., Hasselmann, S., and Janssen, P. A. E. M., Cambridge University Press, Cambridge, UK, 143-155, ISBN 0-521-47047-1, 1994.

Yuan, Y., Han, L., Hua, F., Zhang, S., Qiao, F., Yang, Y., and Xia, C.: The statistical theory of breaking entrainment depth and surface whitecap coverage of real sea waves, J. Phys. Oceanogr., 39, 143-161, https://doi.org/10.1175/2008JPO3944.1, 2009.

Wang, H., Yang, Y., Sun, B., and Shi, Y.: Improvements to the statistical theoretical model for wave breaking based on the ratio of breaking wave kinetic and potential energy, Sci. China Earth Sci., 60(1), 180-187, https://doi.org/10.1007/s11430-016-0053-3, 2017.

Wang, H., Yang, Y., Dong, C., Su, T., Sun, B., and Zou, B.: Validation of an improved statistical theory for sea surface whitecap coverage using satellite remote sensing data, Sensors, 18, 3306, https://doi.org/10.3390/s18103306, 2018.

Shi, Y, Yang, Y., Qi, J., and Wang, H.: Adaptability assessment of the whitecap statistical physics model with cruise observations under high sea states, Front. Mar. Sci. 12:1486860, https://doi.org/10.3389/fmars.2025.1486860, 2025.

Young, I. R., and Babanin, A. V.: Spectral distribution of energy dissipation of wind-generated waves due to dominant wave breaking, J. Phys. Oceanogr., 36, 376-394, https://doi.org/10.1175/JPO2859.1, 2006.

Polnikov, V.G.: Spectral description of the dissipation mechanism for wind waves. Eddy viscosity model, Mar. Sci., 2(3), 13-26. https://doi.org/10.5923/j.ms.20120203.01., 2012

In order to evaluate the new dissipation formulations due to wave-generated turbulence and wave-breaking, which are focal points of the present study, the scaling behavior only for the duration-limited growth and decay is demonstrated and interpreted preliminary in section 3. Simple numerical experiments were performed and model results were compared to the original MASNUM wave model and WAM wave model (Janssen et al., 1994). We agree the reviewer' opinion that this is the weakest part of the manuscript and the listed 4 reasons in Rcs.

1. For duration-limited growth, no good observations lead us to compare to the original MASNUM wave model and WAM wave model (Janssen et al., 1994), to evaluate the

stable and reliable performance of the new dissipation formulations, and furthermore, to perceive directly the different effects between the two new dissipation formulations due to wave-generated turbulence and wave-breaking.

2. We agree the reviewer's opinion that it is possible to tune the models to get similar results by using free tuning parameters. Indeed in the new proposed dissipation formulations, there are still two undetermined parameters. Their valid ranges are inferred individually from the independent observation verifications. We discussed more concentrately about the two undetermined parameters in "Section 4 Dicussions". We think we pursued an attempt in numerical modeling not to tune parameters freely but to inspect their physics based on observations.
3. We thank the reviewer's advice that matching the new physical model with fetch-limited data associated with wave growth. In fact, we are conducting such studies for uniform wind, turning wind and rotatory wind in fetch-limited conditions which are also stated in Section 5. These model results and verifications with abundant fetch-limited observation data will be part of scaling behaviors in our future series papers (also due to the length limit of the journal). Here in the present study, we focus on the effects of the new dissipation formulations due to wave-generated turbulence and wave-breaking. For conditions of wind seas into swells, we agree the reviewer's point that different models exhibit different behavior about the decline of wave height. The different effects between the two new dissipation formulations are of concern to us and to manifest explicitly in this study.
4. We thank the reviewer's advice that it is better to show the spectral shapes, it will be pursued in our future project and displayed in other papers.

In Section 4, we concentrate on the undetermined parameters in the new dissipation formulations due to wave-generated turbulence and wave-breaking, including their physical meanings, respective origins, underlying challenges and possible future solutions. Although their valid ranges are inferred individually from independent observation verifications in sections 2 and 3, they are still the remain uncertainty issues which concern the main topics of the present study. The other purpose we discussed the undetermined parameters is to propose a potential way not to tune free parameters, which was commonly used previously for dissipation terms to balance the input ones in numerical modeling. We agree the reviewer's constructive suggestions to supplement the valuable comments and discussions provided above to Section 4, especially the deficiencies of scaling behavior of the new model. In the beginning of Section 4, we supplement these deficiencies as follows：

The analytical approaches and the corresponding comparisons to laboratory or in-lake site measurements improve further understandings of wave energy dissipation due to wave-breaking and wave-generated turbulence. This study still exhibits some deficiencies and needs to be addressed on comparative assessments and metrics to previous formulations, as well as evaluations of scaling behavior of the new model, etc. Model validation is tentative and requires future enhanced observations correspondingly.

We apologize for our ambiguous and confused expressions for lacking clarity and rigor in section 5. Following the reviewer's comments, we rewrote some paragraphs in this section.

1. We rewrote the first paragraph to “The ocean wave energy dissipation is the least understood of the major source terms, previous approaches to estimate the dissipation source function depended on an incomplete description of the physics of the processes including wave-breaking and wave-turbulence interaction. The latest observational efforts offer a possible approach to explore the underlying comprehensive mechanisms.’ Some ambiguous words and subjective words are deleted according to the reviewer’s suggestions.
2. We agree with the reviewer’s opinion, and we rewrote the second paragraph to “In the present paper, we attempted to explore the dissipation effects of wave-generated turbulence reacting on ocean waves, and to estimate the energy loss due to wave-breaking via an improved postbreaking spectrum expression based on the breaking wave statistical method. Two new source functions for the above two dissipation processes are proposed and compared respectively to the laboratory or in-lake observations tentatively in section 2, and their different dissipation effects are experimentally analyzed in section 3.”
3. As per the reviewer’s suggestions, all subjective descriptors were removed to ensure academic rigor and appropriateness. The third paragraph is rewritten as “The main conclusion of the study is that we propose an analytical dissipation source function induced by wave-generated turbulence S_{tid} formulated by Eq. (15), together with an improved postbreaking spectrum expression $E_{\mathrm{b}}(k_1,k_2)$ by Eqs. (20) and (26). The former dissipation term represents the feedback of imparting of wave shear instability generations on turbulence, and the latter expression depicts the intermittent wave-breaking events. Sum of both contributions play critical role of wave energy dissipation.”
4. We fully agree with the reviewer’s opinion that there are uncertainties in wave growth formulations, as well as large uncertainties remained in different bulk energy input approaches stated in section 2.1. So in section 3, only the linear and quasi-linear wind input source functions are used for simplicity. Although the valid ranges of the two undetermined parameters in the new dissipation formulations are inferred individually from independent observation verifications, their certainty is still a significant challenge which we also discussed in section 4. So we are currently unable to conclusively address the reviewer’s concerns about the overestimation of the input source term. We think we proposed a potential approach in this regard, but requires future enhanced observations correspondingly.
5. We thank the reviewer’s advice and we are conducting such studies which will be part of our future series papers.

Some additional revisions are listed below, following the guidance of the reviewer:

Line 19: We rewrote the sentence to “Though input mechanisms, in particular bulk transfer of energy action and momentum to waves, and other source terms are not well established either, the least understood aspect of the physics of wave model is the dissipation terms (Donelan and Yuan, 1994; Young and Babanin, 2006; Babanin, 2011)”.

Line 35-50: As per the reviewer’s suggestions, the description and foundational journal references to WW3 were supplemented in these lines.
Based on the random phase spectral action density balance equation for wavenumber-direction spectra and evolved from earlier WW1 and WW2 (WAVEWATCH I & II) model packages (Tolman, 1991, 1992), the comprehensive source terms were incorporated and employed in WW3 ((WAVEWATCH III) wave model by Tolman and Chalikov (1996), Chalikov and Belevich (1993), Chalikov (1995) , Tolman (2002), etc.
Key references

Chalikov, D.: The parameterization of the wave boundary layer, J. Phys. Oceanogr., 25, 1,333-1,349 , 1995.

Chalikov, D. V., and Belevich, M. Y.: One-dimensional theory of the wave boundary layer, Bound.-Layer Meteor., 63, 65-96, 1993.

Tolman, H. L.: A third-generation model for wind waves on slowly varying, unsteady and inhomogeneous depths and currents, J. Phys. Oceanogr., 21, 782-797, 1991.

Tolman, H. L.: Eﬀ ects of numerics on the physics in a third-generation wind-wave model, J. Phys. Oceanogr., 22, 1,095-1,111, 1992.

Tolman, H. L.: Validation of WAVEWATCH III version 1.15 for a global domain, Tech. Note 213, NOAA/NWS/NCEP/OMB, 33 pp., 2002.

Tolman, H. L., and Chalikov, D.: Source terms in a third-generation wind-wave model, J. Phys. Oceanogr., 26, 2497-2518, 1996.

Lines 71-72: We apologize for our inappropriate description of Tolman and Chalikov’s work, we rewrote the sentence to “Tolman and Chalikov (1996) also suggested a turbulent dissipation analogy for tunable closure modeling.”

Lines 79-83: The “third frequency range” here means the smooth transition between the low- and high-frequency dissipation mechanisms. We are grateful to the reviewer for spotting this, and we remove the sentence for it is not highly relevant to the main topics of the present study.

Thanks for your advice and we apologize for our ambiguous expressions lacking clarity of upper-case *K* and lower-case *k*, upper case *K* hat, K_0 , etc. in derivations leading up to Eq. (15) on line 220 . We supplemented their definitions in the revised manuscript respectively.
For the unified mean $\hat{\omega}, \hat{K}$ introduced for various integral mean variables for practical numerical applications, which satisfy

$\iint_{\vec{k}} E(k_1,k_2)\exp\{2Kx_3\}\mathrm{d}k_1\mathrm{d}k_2 \approx \exp\{2\hat{K}_1x_3\}\iint_{\vec{k}} E(k_1,k_2)\mathrm{d}k_1\mathrm{d}k_2$, $\iint_{\vec{k}} \omega^2K^2E(k_1,k_2)\exp\{2Kx_3\}\mathrm{d}k_1\mathrm{d}k_2 \approx \hat{\omega}^2\hat{K}_2^2\exp\{2\hat{K}_2x_3\}\iint_{\vec{k}} E(k_1,k_2)\mathrm{d}k_1\mathrm{d}k_2$ and

$\iint_{\vec{k}} \frac{1}{2K+2\hat{K}_1+\hat{K}_2}\omega^2K^2E(k_1,k_2)\mathrm{d}k_1\mathrm{d}k_2 \approx \frac{1}{5\hat{K}_3}\iint_{\vec{k}} \omega^2K^2E(k_1,k_2)\mathrm{d}k_1\mathrm{d}k_2$, here we assume that $\hat{K}_1 \approx \hat{K}_2 \approx \hat{K}_3 \approx \hat{K}$

approximately.

Lines 409-411: Two input source terms were used with the new dissipation source terms. One is the parameterization of linear growth in spectral density proposed by Komen et al. (1984), scaled in terms of the friction velocity rather than the wind speed at 5 m height which was adopted by Snyder et al. (1981). The other is the parameterization of quasi-linear one by Janssen (1991). We apologize for our ambiguous expressions to mislead the readers, We remove the reference of Snyder et al. (1981) for clarity.