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Title: Energetic near-inertial waves induced by winter storms and mesoscale eddies in the subtropical Northwestern Pacific Ocean

July 12, 2026

FROM: Hongkai Wang, Zifei Chen, Xinyuan Diao, Fei Yu, Xingchuan Liu, Qiang Ren, Feng Nan

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Dear Reviewer,

Thank you very much for your letter and for taking the time to review our manuscript. The constructive comments and valuable recommendations are very helpful for improving the quality of the manuscript. We have carefully revised the relevant parts of the manuscript following the reviewer's comments and suggestions.

Now we answer the reviewer's concerns and suggestions point by point and revise the manuscript. For the reviewer's and editor's reference, we highlight the revisions in blue in the revised manuscript with marked changes.

We sincerely hope that these responses and revisions can satisfactorily answer the reviewer's concerns. Thank you!

Response to Reviewer's Comment

This manuscript addresses an important question regarding the propagation of wind-generated near-inertial internal waves. The fate of near-inertial waves' energy is an important topic because the breaking of near-inertial waves serves as a source of energy for vertical mixing in the ocean interior, particularly in the upper ocean. This study investigates the propagation of near-inertial wave energy into the interior and the energy transfer rate between waves and eddies for two winter storm events, based on the data from the mooring system and reanalysis product. Their results highlight the need to account for the interactions between waves and eddies when interpreting the propagating near-inertial energies and their dissipation, leading to turbulent mixing. While the paper is well-motivated and contributes to science, I believe the manuscript requires substantial revision before it can be considered for

publication.

Response:

We sincerely thank the reviewer for the detailed, insightful, valuable, and constructive comments on our manuscript, which are very useful for us to improve the quality of this work. Following the reviewer's suggestions, we have substantially revised the manuscript, particularly by clarifying the motivation and novelty of the study in the Introduction and by expanding the discussion of the near-inertial energy budget, including possible energy losses through turbulent dissipation and the radiation of freely propagating near-inertial waves.

1.Major

(A) ***The introduction section is well-structured, citing observational studies of wind-generated near-inertial internal waves. However, the novel aspects of the present study compared to these prior studies, as well as the motivation for this research, remain somewhat unclear to readers who are not familiar with these fields. I think it would be better if these points were summarized as the first few sentences of the final paragraph of the Introduction.***

Response:

Thank you very much for this valuable suggestion. We agree that the motivation and novelty of the present study should be stated more explicitly, especially for readers who are not closely familiar with this field. Following the reviewer's suggestion, we have revised the final paragraph of the Introduction by adding a concise summary of the motivation and novel aspects of the present study.

Specifically, we now emphasize that although wind-generated NIWs have been widely studied, the propagation characteristics and modal structure of winter-storm-generated NIWs in the subtropical Northwestern Pacific Ocean remain insufficiently understood. We further highlight that the two winter storms examined in this study produced markedly different wind-generated near-inertial energy inputs, whereas the observed near-inertial kinetic energy was comparable. This contrast motivated us to investigate the roles of mesoscale eddy modulation, eddy-NIW energy exchange, and modal energy content.

The revised text is as follows (Line 69-83):

The subtropical Northwestern Pacific Ocean is a hotspot characterized by energetic wind energy input and abundant mesoscale eddies. Although tropical cyclones are drastic synoptic events, winter storms remain an important source of near-inertial energy in this region (e.g., Zheng et al., 2022). Compared with tropical cyclones, winter storms are characterized by larger spatial scales and longer durations (Bieli et al., 2020; Cheung et al., 2025). In addition, active mesoscale eddies in this region can lead to prominent interactions between mesoscale eddies and NIWs (Qiu, 1999). Due to strong wind stirring and weak stratification in winter, the mixed layer depth is evidently deeper than that in summer (de Boyer Montégut et al., 2004). However, the propagation and characteristics of storm-induced NIWs in the subtropical Northwestern Pacific Ocean remain insufficiently understood.

Combined with subsurface mooring observations and reanalysis products in the subtropical Northwestern Pacific Ocean, **we found that during two winter storms, the wind-generated near-inertial energy input differed markedly, whereas the observed near-inertial kinetic energy was comparable.** Motivated by this contrast, the generation and characteristics of these two NIW events were investigated in this study. Specifically, mesoscale eddies extract about 46% of the wind-generated near-inertial energy during the first NIW event, whereas they supply an amount equivalent to about 43% of the wind input to NIWs during the second NIW event. In addition, we examine how mesoscale eddy modulation, together with the modal projection of wind energy, contributes to differences in the modal content of the two NIW events.

(B) ***In Section 4.1, the authors explain that the similar NIKE values between the two events—despite significant differences in the input of wind-generated near-inertial energy—can be understood by taking into account the difference in energy transfer rates between mesoscale eddies and NIW. However, is it reasonable not to consider other energy sinks for the wind-generated NIW's energy inputs? Kunze et al. (1995) assumed that there are three possible energy sinks for wind-generated NIW in the anticyclonic eddy, including i) loss to the mean flow, ii) loss to un-trapped waves that***

can freely propagate, and iii) instability of shear, leading to turbulence production. Although this manuscript considers only i), is it acceptable to ignore the other two candidates in the interpretation of your observational data? I understand that quantification is difficult—particularly regarding point iii), given the absence of turbulence observations—but the possible effects by ii) and iii) should at least be discussed in the discussion section.

Response:

Thank you very much for this important and constructive comment. We agree with the reviewer that the energy exchange between mesoscale eddies and NIWs represents only one possible pathway in the near-inertial energy budget. Other processes, including the radiation of untrapped waves away from the observation site and turbulent dissipation associated with shear instability, may also contribute to the loss of wind-generated near-inertial energy (Kunze, 1995). Following the reviewer's suggestion, we have added a discussion of these two additional pathways in Section 4.2 to provide a more complete interpretation of the observed energy budget.

Because direct turbulence measurements were not available, we could not directly quantify turbulent dissipation from microstructure observations. Instead, we estimated the parameterized dissipation rate using the Gregg–Henyey–Polzin (GHP) parameterization based on the observed velocity and stratification fields (Henyey et al., 1986; Gregg, 1989; Polzin et al., 2014; Kunze, 1995). It should be noted that the GHP estimate reflects the dissipation associated with the internal wave shear and therefore include contributions from NIWs, diurnal tides, and semidiurnal tides.

The dissipation rates during WS1 and WS2 are 3.9 $\times10^{-10}$ and 5.0 $\times10^{-10}$ m^2/s^3, respectively (Fig. 10a in the revised manuscript). The corresponding time-integrated energy dissipation values are 4.1 $\times10^{-4}$ and 4.3 $\times10^{-4}$ m^2/s^2, respectively. These comparable values indicate that the energy loss associated with turbulent dissipation is of a similar magnitude during these two NIW events. **Therefore, the pathway of turbulent dissipation is unlikely to be the primary reason for the comparable magnitude of NIKE during WS1 and WS2.**

To further identify the dominant shear component of internal waves, the total vertical shear was decomposed into the near-inertial, diurnal, and semidiurnal components. The corresponding vertical shear variances were calculated as $S_{\mathrm{ni}}^2 = |\partial u_{\mathrm{ni}}/\partial z|^2 + |\partial v_{\mathrm{ni}}/\partial z|^2, S_{\mathrm{D}}^2 = |\partial u_{\mathrm{D}}/\partial z|^2 + |\partial v_{\mathrm{D}}/\partial z|^2$, and $S_{\mathrm{M}}^2 = |\partial u_{\mathrm{M}}/\partial z|^2 + |\partial v_{\mathrm{M}}/\partial z|^2$, where S_{ni}^2, S_{D}^2, and S_{M}^2 represent the near-inertial, diurnal, and semidiurnal shear variances, respectively. The mean near-inertial shear variances during WS1 and WS2 is approximately three to four times larger than those of diurnal and semidiurnal components (Fig. 10b in the revised manuscript). This dominance of near-inertial shear suggests that near-inertial motions played a more important role than diurnal and semidiurnal tidal motions in enhancing the total shear and the associated dissipation rate during the two storm events.

In addition to turbulent dissipation, the radiation of untrapped waves may also contribute to the loss of locally observed near-inertial energy. The modal analysis shows that WS1 is characterized by a higher contribution from low modes, whereas WS2 contains a larger proportion of high-mode energy (Figs. 8a and 8b in the revised manuscript). Low-mode NIWs are generally more efficient at propagating away from their generation region, while high-mode NIWs are more likely to generate strong local shear and dissipate locally. Thus, near-inertial energy during WS1 may exhibit stronger outward propagation compared to that during WS2. However, the outward radiation of near-inertial energy cannot be quantitatively evaluated from a single subsurface mooring.

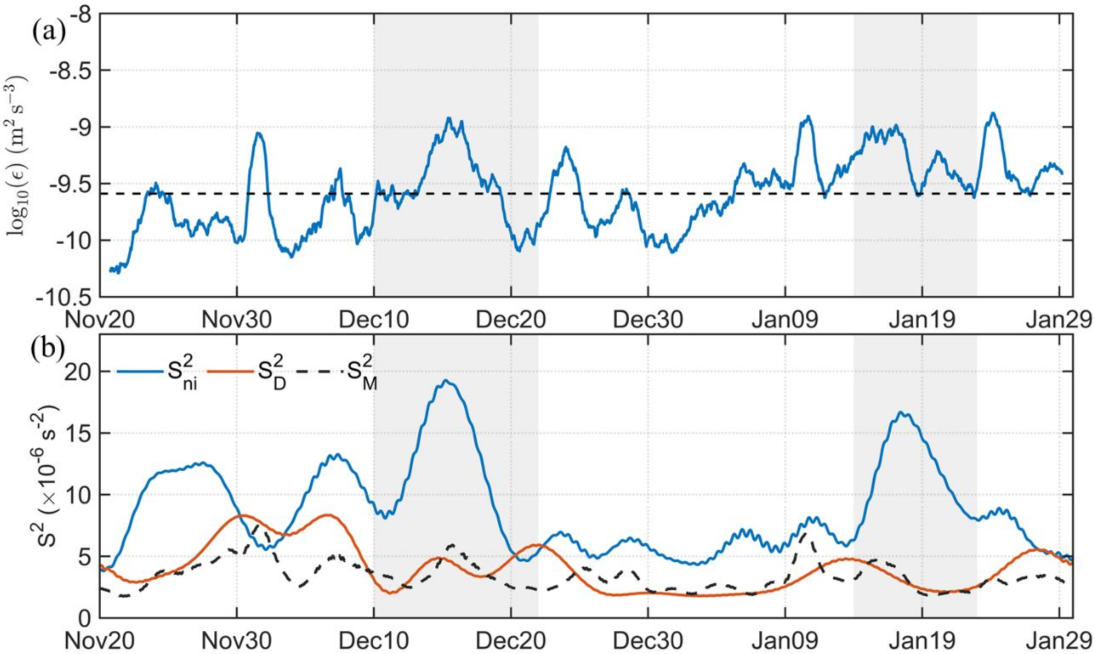

Figure 10 in the revised manuscript. (a) Time series of the turbulent dissipation rate from GHP parameterization, during the observational period (50-300 m). The gray shading indicates the two NIW events. The horizontal dashed line denotes the time-averaged value. (b) Time series of vertical shear variance of near-inertial, diurnal, and semidiurnal components.

2.Minor comments

(1) ***Line 86: Please consider showing the deployment depth of each instrument (ADCPs, SBE 37-SM, and SBE 56) as a figure. It could be helpful for readers to see the vertical resolution of the observed density profile.***

Response:

Thank you very much for this suggestion. A schematic diagram of the subsurface mooring structure has been added in Fig. 1(b), showing the deployment depths of the ADCPs, SBE 37-SM, SBE 56, and Aquadopp single-point current meter (AQD).

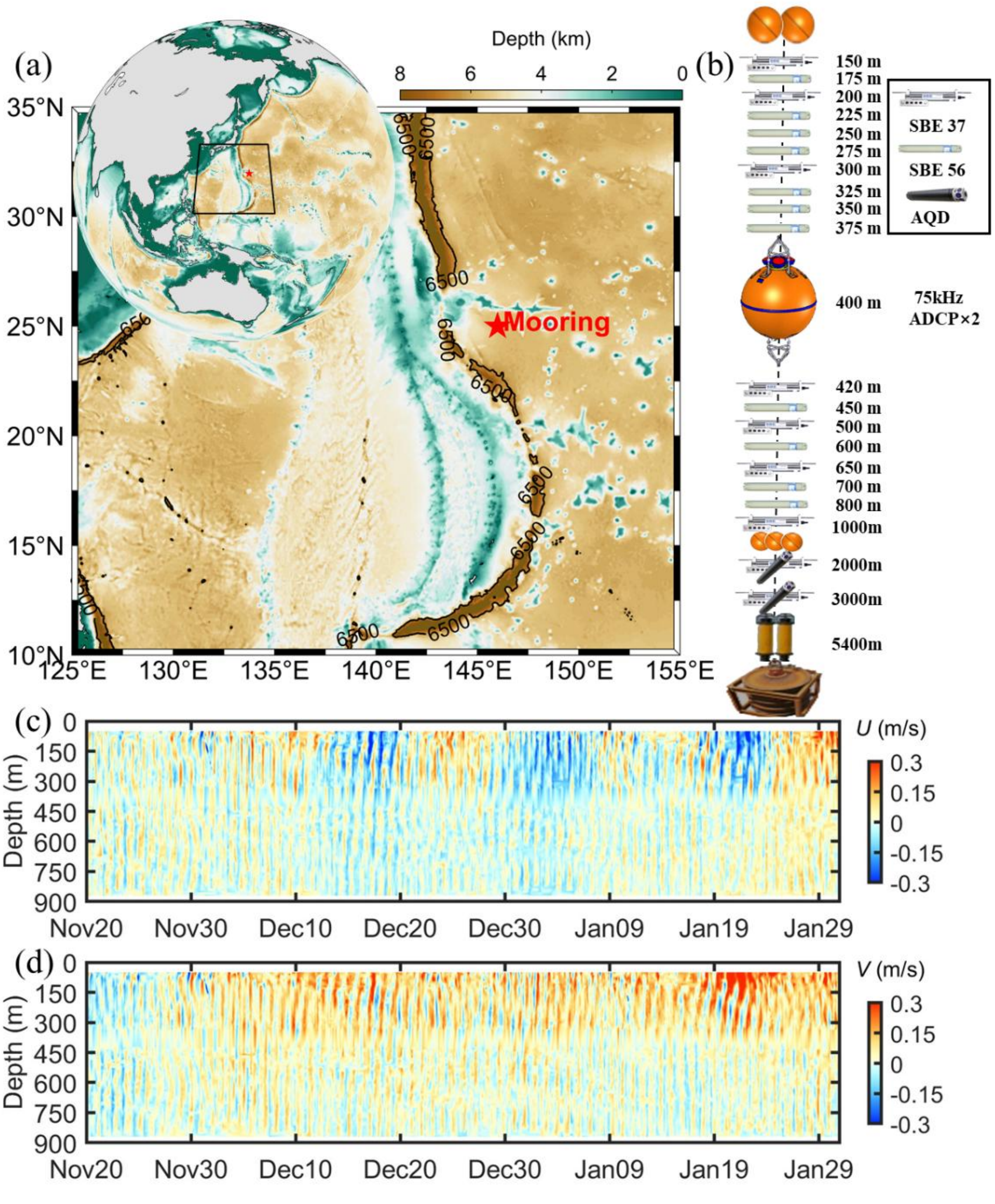

Figure 1 in the revised manuscript. (a) Location of the subsurface mooring (marked by a red pentagram), with color shading representing the topography. (b) Deployment depths of instruments on the subsurface mooring. (c) and (d) Depth-time plot of zonal and meridional velocities from 20 November 2017 to 31 January 2018.

(2) ***Line 93: What value of the damping parameter is applied in the slab model?***

Response:

Thank you very much. In the slab model, the damping parameter is set to 0.06 f_0. We have added it to the revised manuscript. **(Line: 99)**

(3) ***Line 99-101: Please clarify how the mixed layer depth (MLD) is defined in the present study.***

Response:

Thank you very much. In the present study, the mixed layer depth is defined as the depth where temperature is 0.5 °C lower than the sea surface temperature. We have clarified it in the revised manuscript. **(Lines: 111-112)**

(4) ***To verify the validity of the reanalysis product, please add a depth-time plot of the squared buoyancy frequency N^2 and the plots of the mixed layer depth (MLD) of both the observations and the reanalysis product in the supp info. The reproducibility of these variables is important considering that they are used to estimate the near-inertial energy inputs and their modal decomposition.***

Response:

Thank you very much. According to your suggestion, we have added the depth-time plots of squared buoyancy frequency (N^2) from observations and the reanalysis product in the supplementary material (Fig. S1). The comparison shows that the reanalysis product reproduces the observed stratification reasonably well.

Because the shallowest depth of the observed temperature is located approximately at 150 m (Fig. 1b in the revised manuscript), the MLD cannot be directly resolved from subsurface mooring observations. To verify the validity of the MLD from the reanalysis product, we compare it with that from nearby Argo observations (Fig. 8c in the revised manuscript). It was also found that the MLD from the reanalysis product shows good agreement with Argo observations.

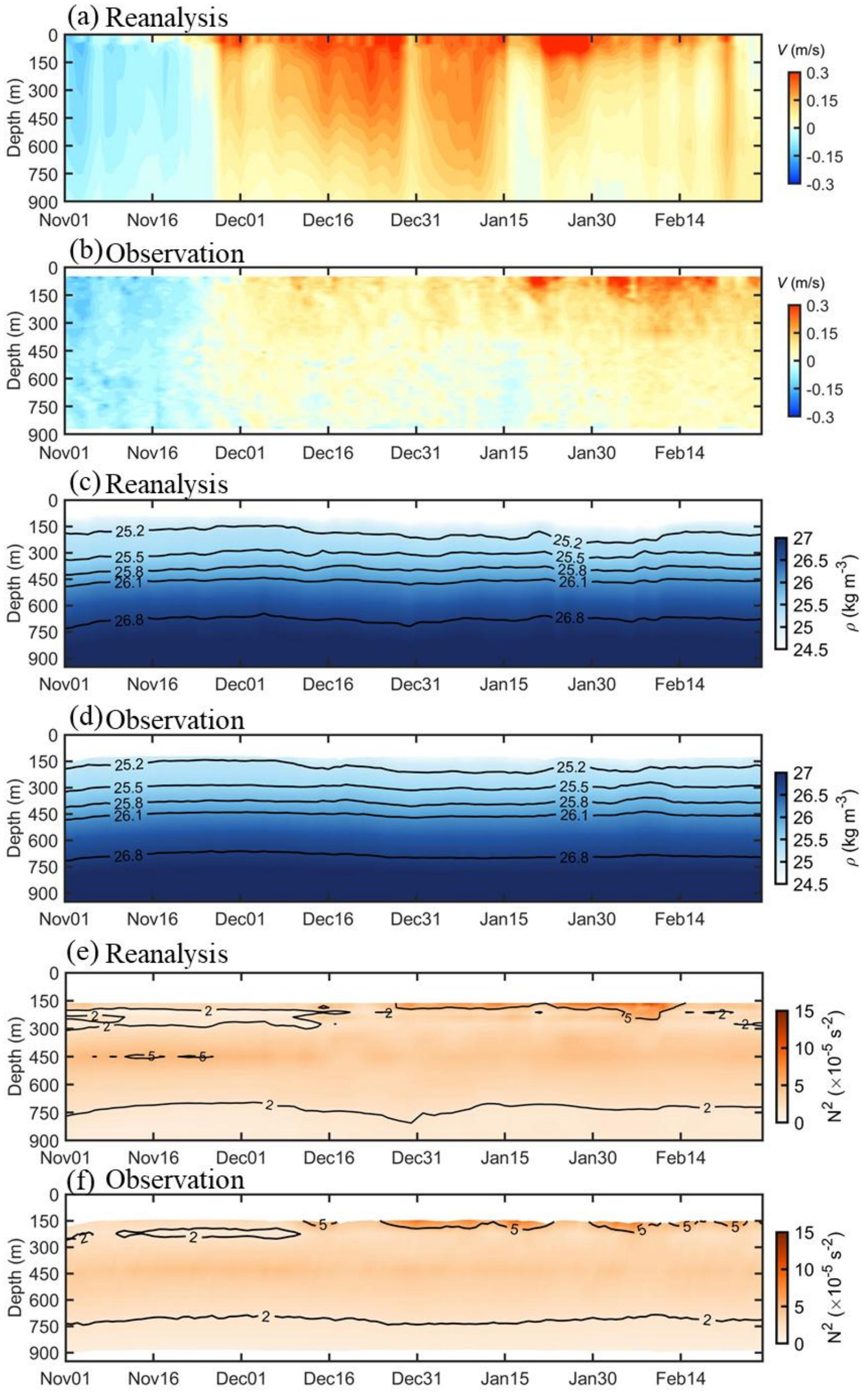

Figure S1. Comparison of background horizontal velocity (V), potential density (ρ), and squared buoyancy frequency (N^2) between the reanalysis product and subsurface mooring observations from 1 November 2017 to 28 February 2018. (a, b) The meridional velocity from the reanalysis product and observations, respectively. (c, d) and (e, f) The same as (a, b), but for ρ and N^2.

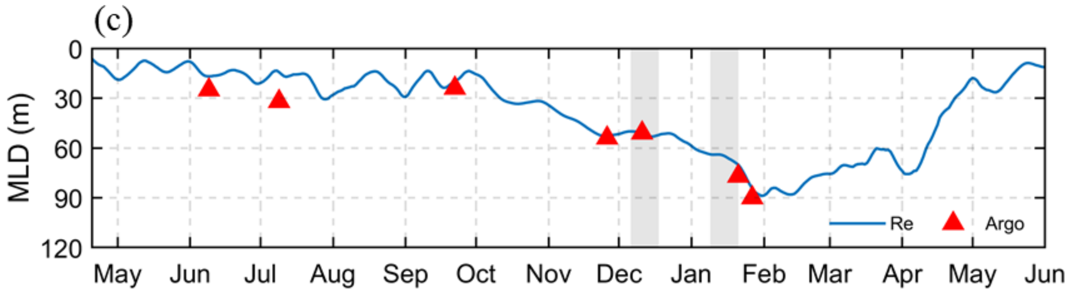

Figure 8(c) in the revised manuscript. Mixed layer depth during the full observational period calculated from reanalysis data (blue line), and Argo profiles (red triangles). Gray shading represents two storm events.

(5) ***Line 110: Please check if the citations for this sentence are correct. I guess that the other citations (e.g., Gill (1982)?) would be more appropriate.***

Response:

Thank you very much. We agree with you. This reference has been added to the revised manuscript. **(Line: 121)**

(6) ***Line 127: Please clarify the definition of background horizontal velocity (U, V). Do the authors apply the low-pass filtering spatially and/or temporally to estimate 'background' velocity from the daily outputs of the reanalysis product?***

Response:

Thank you very much for this helpful comment. In the present study, the background horizontal velocity fields (U, V) refers to the horizontal velocities obtained from reanalysis product after applying a 5-day temporal low-pass filter. We have clarified this definition in the revised manuscript. **(Lines 138-140)**

(7) ***Line 137: Is the velocity vector V the same as the background flow (U, V) used in Eq. (4)? Please clarify it.***

Response:

Thank you very much. Both the velocity vector V and the horizontal velocity fields

(U, V) in Eq. (4) represent the background flow, but they are estimated from different datasets. The U and V in Eq. (4) are obtained from the reanalysis product, whereas velocity vector V in the ellipse analysis is obtained from the mooring ADCP observations.

(8) ***Line 138: I think that*** $|V|$ ***in this sentence should be*** V.

Response:

Thank you very much. In Eq. (7) in the revised manuscript, the Doppler shift is calculated as the projection of the background flow onto the wave propagation direction, i.e., $\omega_{\mathrm{i}} = \omega_{\mathrm{o}} - |k_{\mathrm{h}}||\boldsymbol{V}|\cos(\Phi - \theta)$, where $|\boldsymbol{V}|$ is the magnitude of background flow.

(9) ***Line 140: Do both*** k_z ***and* m *represent the vertical wavenumber? Please use the consistent representation.***

Response:

Thank you very much. We have corrected this in the revised manuscript, consistently using m to denote the vertical wavenumber.

(10) ***Line 142 Please remove 'horizontal' in this sentence. Only the vertical group velocity is defined here.***

Response:

Thank you very much. We have removed 'horizontal' from the revised manuscript. **(Line: 156)**

(11) ***Line 144: I think Equation (9) needs a minus sign. Please check it.***

Response:

Thank you very much for pointing this out. We have corrected it in the revised manuscript. **(Line: 158)**

(12) ***Line 159: It would be helpful to include a comparison between the*** u_{ni} ***derived from the slab model and the bandpass filtered*** u_{ni} ***from the observations, even if it's***

just in the supplementary information.

Response:

Thank you very much for this valuable suggestion. According to your suggestion, we have added a comparison between the near-inertial velocity obtained from the slab model and the observed near-inertial velocity from the mooring observation in the Supplementary material (Fig. S2). Because direct current observations were not available within the mixed layer, the observed near-inertial velocity at 50 m depth was used for comparison with the slab model derived velocity. The comparison results show that the near-inertial velocities obtained from the slab model are essentially consistent with the observed results in amplitude and phase.

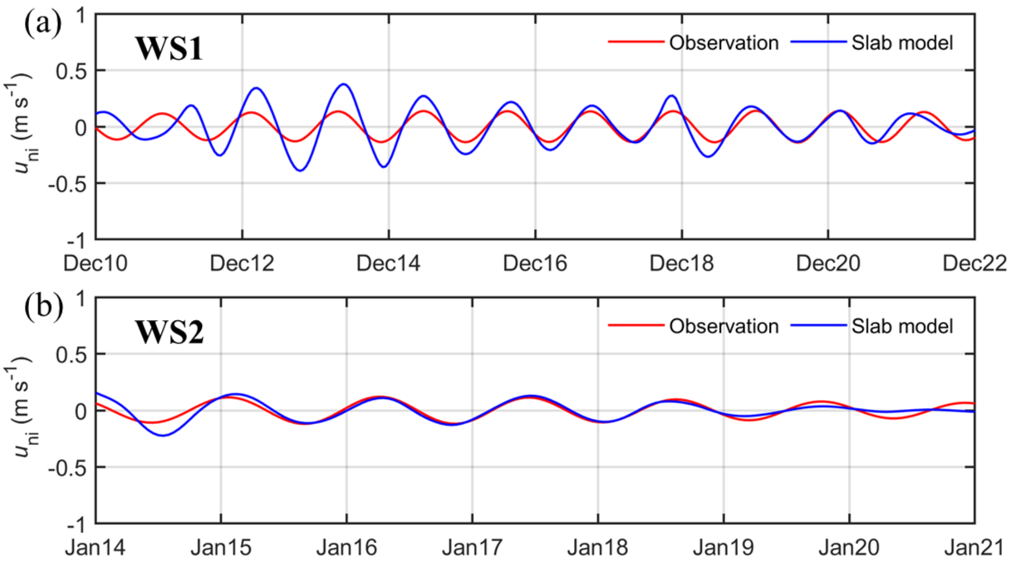

Figure S2. Comparison of the near-inertial zonal velocity (u_{ni}) derived from the slab model (blue lines) and the observational u_{ni} (red lines) at the depth of 50 m during WS1 (a) and WS2 (b).

(13) ***Line 177-179: Why does the total NIKE (Fig 5c) appear to be smaller than the decomposed downward energy (Fig 5d) at certain time periods and depths, such as 150 m depth in WS1 and WS2?***

Thank you very much for this insightful comment. The total NIKE in Fig. 5c is calculated from the total near-inertial velocities, which are the superposition of upward and downward propagating components. These two components may have different phases, so their velocity magnitude can be partially eliminated at some depths and times. Therefore, the downward-propagating NIKE may be larger than the total NIKE.

To clear show this interpretation, we compared the total near-inertial velocity with the reconstructed velocity obtained by summing the downward and upward propagating components at 150 m depth (Fig. R1). The results show that the reconstructed zonal and meridional velocities are consistent with the total near-inertial velocities (Figs. R1a and R1b). However, it can be seen that the downward NIKE calculated from CW near-inertial velocities can be larger than the total NIKE (Fig. R1c). Thus, the NIKE calculated from the total velocities could appear to be smaller than the downward energy.

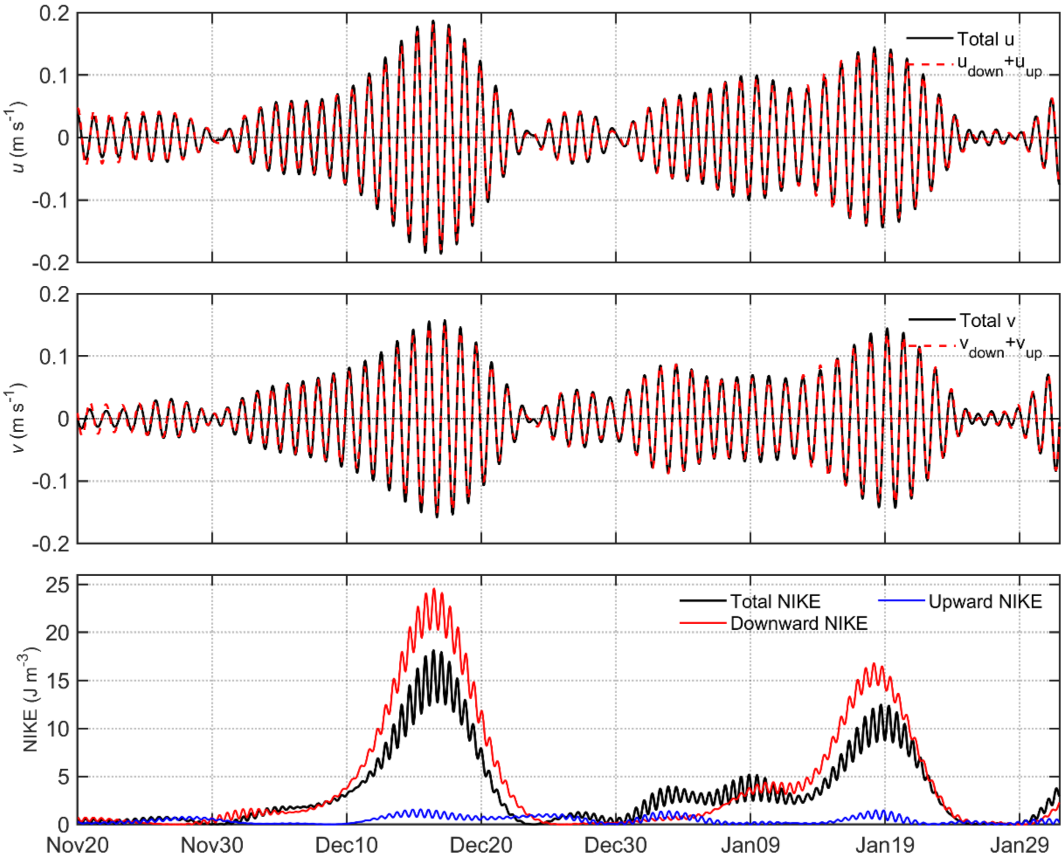

Figure R1. Comparison of the total near-inertial velocity and the reconstructed velocity obtained by summing the downward- and upward-propagating components at 150 m depth. (a) Zonal near-inertial velocity. (b) Meridional near-inertial velocity. The black lines represent the total near-inertial velocity, and the red dashed lines represent the sum of the downward- and upward-propagating components. (c) Comparison of total NIKE, downward propagating NIKE, and upward propagating

NIKE at 150 m depth.

14) ***Line 182-184: Please clarify how to estimate decay time here. Is the decay time defined as the time it takes for the energy propagating along a ray path determined by the group velocity to decrease to one-tenth of its maximum? It might be helpful to understand if the authors indicate the time and depth of 1) the maximum NIKE and 2) the one-tenth of maximum NIKE in Fig. 5c.***

Response:

Thank you very much. The decay time is defined as the time it takes for the near-inertial energy to decrease from its maximum value to one-tenth of the maximum value along the downward propagation path. The blue and brown circles in Fig. 5c indicate the time and depth of the maximum NIKE and one-tenth of the maximum NIKE, respectively. For WS1, the maximum NIKE is located at 120 m depth, and the one-tenth maximum NIKE is located at 300 m depth, corresponding to a decay time of approximately 8 days. For WS2, the maximum NIKE is located at 220 m depth, while the one-tenth maximum NIKE is located at 300 m depth, corresponding to a decay time of approximately 5 days. **(Lines 196-198)**

We have clarified the definition of the decay time and marked the time and depth of the maximum NIKE and the one-tenth of maximum NIKE in the revised manuscript Fig. 5c.

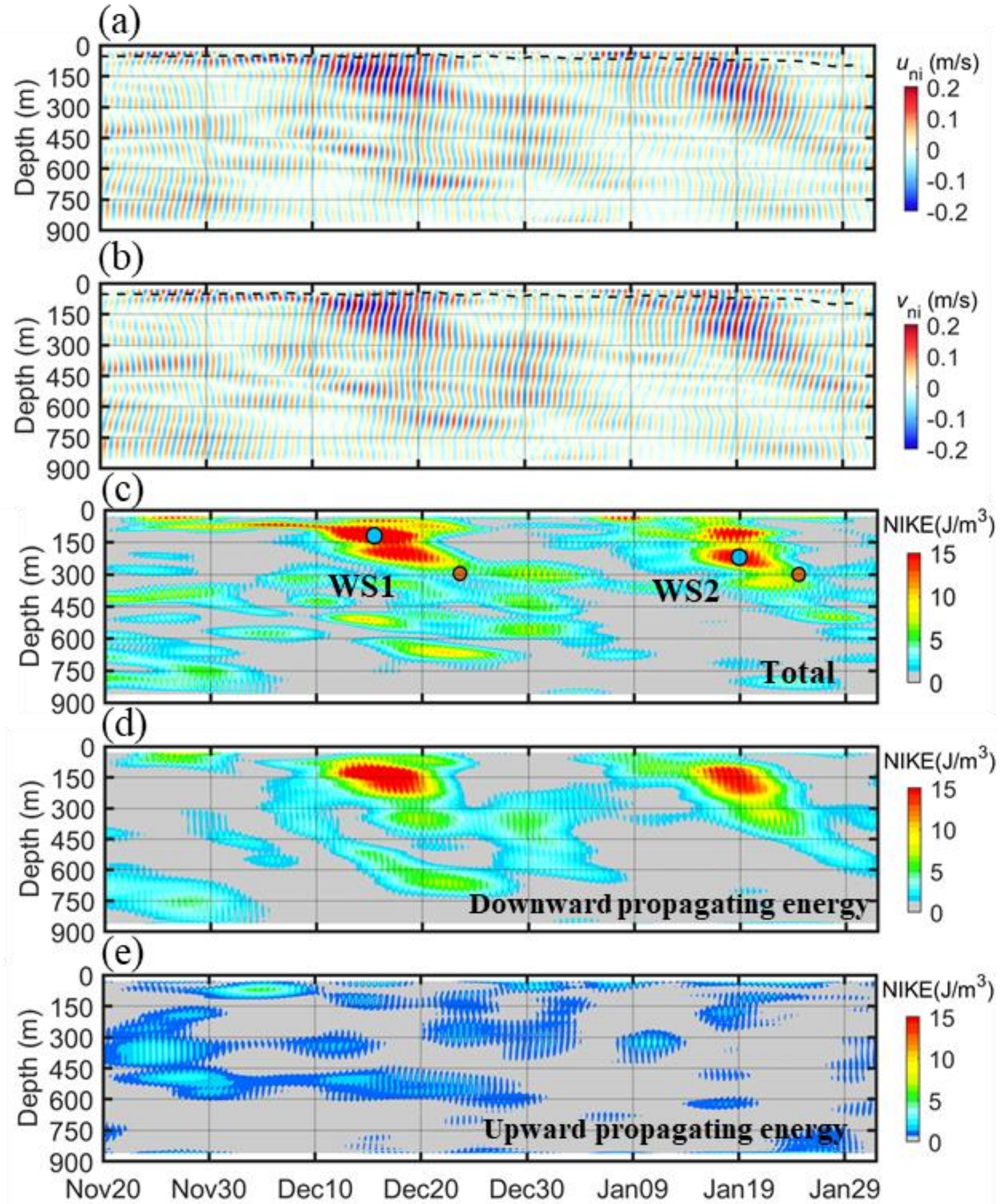

Figure 5 in the revised manuscript. Depth-time plots of near-inertial velocities and near-inertial kinetic energy, NIKE, from 20 November 2017 to 30 January 2018. (a) Zonal near-inertial velocity, $\boldsymbol{u_{ni}}$. (b) Meridional near-inertial velocity, $\boldsymbol{v_{ni}}$. (c) Depth-time plot of NIKE. (d) and (e) are the same as (c), but for the downward-propagating and upward-propagating NIKE, respectively. The black dashed line in (a) and (b) indicates the mixed layer depth (MLD). The blue and brown circles in (c) indicate the time and depth of the maximum NIKE and one-tenth of the maximum NIKE for each NIW event, respectively.

(15) ***Line 201: Please consider indicating the values of 1.01f_0 and 0.98f_0 as vertical lines in Fig. 6. I would like to check whether the red-shifted near-inertial peak shown in Fig. 6c corresponds to 0.98f_0.***

Response:

Thank you very much. We have added vertical dashed lines to indicate 0.98f_0 and 1.01 f_0 in Fig. 6.

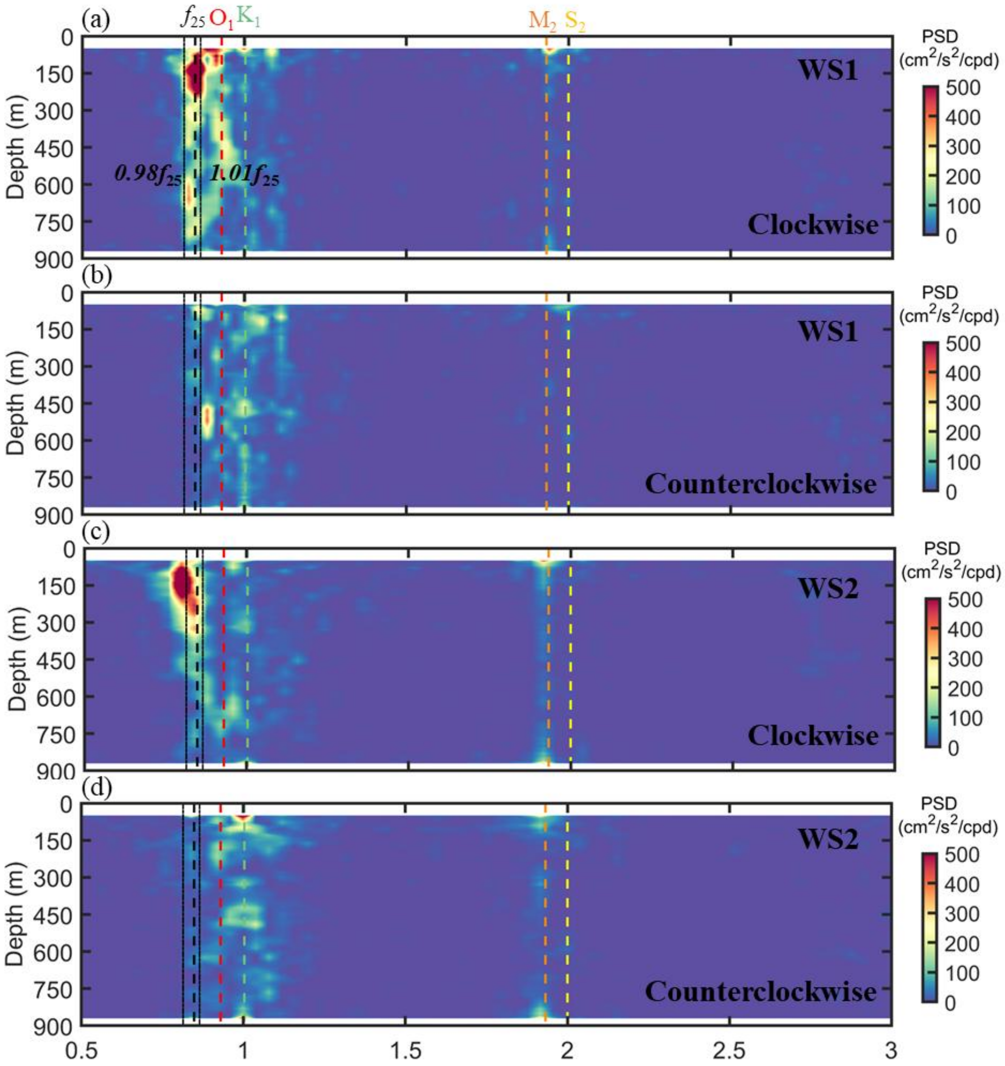

Figure 6 in the revised manuscript. Rotary frequency spectra of raw velocities observed from ADCPs during WS1 (a and b) and WS2 (c and d). Clockwise and anticlockwise polarizations of velocities are shown in (a-d). The vertical dashed lines in panels represent the local inertial frequency, f_0, 0.98 f_0, 1.01 f_0, diurnal tidal frequency, O1 and K1, and semidiurnal tidal frequency, M2 and S2, respectively.

(16) ***Line 208-210: How is the vertical wavenumber (or vertical wavelength) estimated in the present study? Is the wavenumber estimated as m=d(atan(uni/vni))/dz, same as in Chen et al. (2023)? Please clarify it.***

Response:

Thank you very much. In the present study, the vertical wavenumber m is calculated as

$$m = \partial(\mathrm{atan}(u_{\mathrm{ni}}/v_{\mathrm{ni}}))/\,\partial \mathrm{z}. \tag{6}$$

We have added this definition in Section 2 of the revised manuscript.

(17) ***Table 1: How are the errors (±) in Table 1 estimated?***

Response:

Thank you very much. Due to the depth-varied stratification and background current within the wave packet range, the estimated wave packet parameters have an error range. The errors (±) are obtained using one standard deviation of wave packet parameters.

(18) ***Line 252-253: Why does the Fig 9a show the estimated P "within" the mixed layer, rather than "below" the mixed layer, where near-inertial internal waves can freely propagate? Does the author assume that the energy transfer between the near-inertial motions and eddies within the mixed layer is dominant for the net energy budget throughout the water column?***

Response:

Thank you very much for this insightful comment. In this study, Fig. 9a shows the temporal variation of the depth averaged energy transfer rate within the mixed layer. It was aimed to identify the sign and intensity of wave-eddy energy transfer during the two NIW events. To further examine the subsurface variation of energy exchange, we further estimated the energy transfer rate below the mixed layer. As shown in Figs. 9c-d, significant energy transfer mainly occurs in the upper approximately 200 m depth.

(19) ***Line 256-257: Please consider showing the definition of the OW parameter used***

in the present study.

Response:

Thank you very much. We have added the definition of the Okubo-Weiss (OW) parameter in the revised manuscript. Specifically, the OW parameter is defined as $\mathrm{OW} = S_n^2 + S_s^2 - \zeta^2$, where S_n, S_s, and ζ represent the normal strain, shear strain, and relative vorticity, respectively. **(lines: 292-296)**

(20) ***Line 264-265: Please also show the time-integrated energy transfer rate*** $\iint \rho P dz dt$ ***during WS1 and WS2 and compare them with the time-integrated energy flux*** $\int F dt$.

Response:

Thank you very much. We have calculated the time-integrated energy transfer $\iint \rho P dz dt$ during WS1 and WS2 and compared it with the time-integrated wind-generated near-inertial energy flux $\int F dt$. The results show that the time-integrated wind-generated near-inertial energy flux is -2.9 kJ/m^2 and 0.8 kJ/m^2 during WS1 and WS2, respectively. The time-integrated energy transfer is -1.3 kJ/m^2 and 0.5 kJ/m^2 during WS1 and WS2, respectively. We have added the time-integrated results to the revised manuscript. **(Lines: 285-289)**

(21) ***Line 268: I understand that it is not possible to estimate the vertical variation of relative vorticity from the data obtained by the single mooring site. However, I am concerned about whether there is any reason why and can be used in P in Eq. (4) but are not used to estimate relative vorticity?***

Response:

Thank you very much. The depth-temporal variation of relative vorticity can be calculated from the reanalysis data. It also shows that, during WS1, relative vorticity changed from positive to negative, whereas during WS2 it was predominantly negative. We have added this result to Figure 11(f) in the revised manuscript.

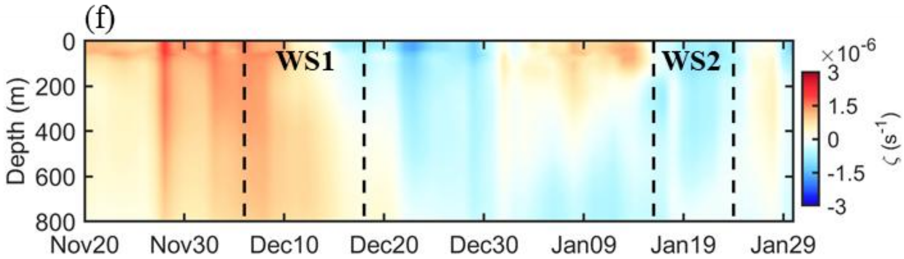

Figure 11(f) in the revised manuscript. Depth-time distribution of relative vorticity $\zeta = V_x - U_y$ derived from the reanalysis velocity fields near the mooring site from 20 November 2017 to 31 January 2018.

(22) ***By presenting an equation, please clarify how the authors estimate the modal projection of wind-induced energy flux following Raja et al. (2022).***

Response:

Thank you very much. Following the reviewer's recommendation, we have added the equation used to estimate the modal projection of wind-generated near-inertial energy flux in the revised manuscript. According to Raja et al. (2022), the wind-generated near-inertial energy flux projected onto the nth vertical mode is calculated as $F_n(t) = \tau(t) \cdot v_{ni,n}$, where τ is the wind stress vector and $v_{ni,n}$ is the nth-mode near-inertial velocity at 50 m depth. We have added this equation in Section 4.3 of the revised manuscript. **(Lines: 353-354)**

Reference:

Bieli, M., Sobel, A. H., Camargo, S. J., and Tippett, M. K.: A Statistical Model to Predict the Extratropical Transition of Tropical Cyclones, Weather and Forecasting, 35, 451-466, 10.1175/waf-d-19-0045.1, 2020.

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