

## Referee #1

The paper deals with an interesting and important problem, namely the mechanism(s) responsible for oceanic mixing in a topographically-complex region. The data have been processed satisfactorily and they show some interesting features, though the interpretation of these features is not straightforward. My principal difficulty with the paper lies in the analysis of the data and the validity of the conclusions drawn from such an analysis. The heart of the analysis is the correlation of observed features of the diapycnal diffusivity patterns with the main causes of mixing identified by the authors. Many of the correlations claimed by the authors seem to be based either on visual inspection of the data plots or analysis based upon ratios of the energy fluxes associated with each of the driving agencies (e.g Fig 4) . I did not find these analyses convincing and I would have appreciated some more quantitative and rigorous data correlation procedures carried out to justify the conclusions. Figs 6, 7 and 8 are very difficult to interpret. Overall, I found the data analysis to be rather superficial and, in consequence, the conclusions unjustified by the evidence of the data analysis.

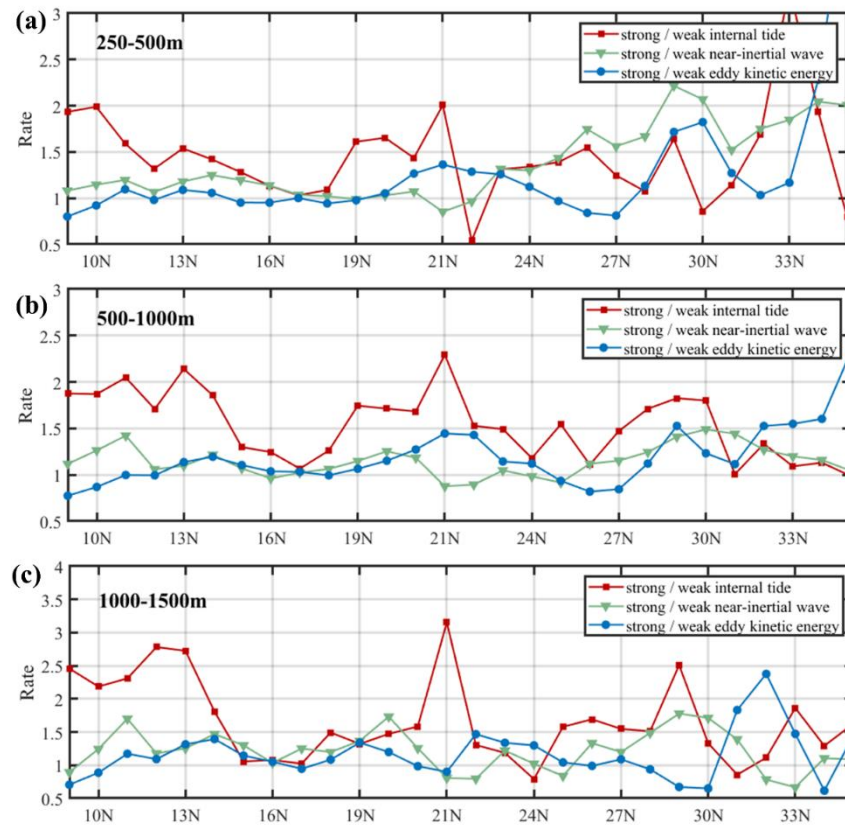
## Response:

*Thank you for your time and constructive comments. The convincing verifications of both the methods and results are crucial for a scientific paper. According to your helpful suggestions, we have thoroughly made the validation of the analysis methods used in present manuscript. The detailed descriptions and discussions were added to section 3.3.1 (Fig. 4 and Fig. 5), section 3.3.2 (Fig. 6 and Fig. 7) and section 3.4 (Fig. 8). Based on the verified methods and the comparison to other studies, the conclusions that have been drawn are found to be reliable and convincing.*

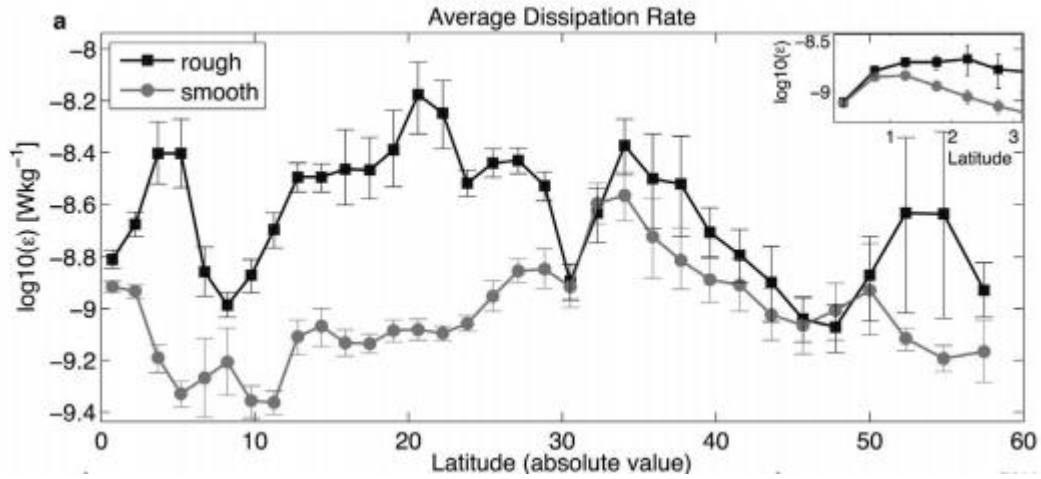
*1. As for the parameterization method itself, it is widely used in the studies of ocean mixing. The most beneficial point is that there are amount of observations of temperature and salinity by ARGO among the global ocean, with good spatial and temporal coverage. The parameterization method was used to estimate global or regional distributions of diapycnal mixing, which can supplement the scarcity of direct turbulence observations. The parameterization analysis seems not straightforward but effective in mixing investigation through several statistical analysis and correlation analysis with other impact factors (e.g. Wu et al., 2011; Whalen et al., 2012; Kunze et al., 2017; Chanona et al., 2018).*

*2. As for the statistical and correlation analysis methods*

a. To address the relative contributions to the mixing from possible factors, we showed Fig. 4 and Fig. 5. Each  $1^\circ$  latitude band was separated into two regions with weak or strong internal tides (or other factors). Here we define the strong or weak internal tides as the internal tide conversion rate larger or smaller than the median internal tide conversion rate of the Philippine Sea (for the details see section 3.3.1). The diapycnal diffusivities in these two kinds of regions were then averaged. The similar method has been used to analyze the effect of topography and different frequency-bands internal waves on ocean interior shear and mixing (eg. Whalen et al., 2012; Zhang et al., 2018). For a more direct representation, the ratios of diapycnal diffusivities above the strong internal tides to weak internal tides were shown. The ratio larger than 1 means that the diapycnal diffusivities are significantly higher in the regions of strong internal tides. The similar analysis were used for the analysis of wind and EKE effects.



**Figure 4** Ratios of diapycnal diffusivities between areas over strong (greater than median) and weak internal tide (red lines), strong (greater than median) and weak near-inertial wave (green lines) and strong (greater than median) and weak eddy kinetic energy (blue lines) for each  $1^\circ$  latitude bands in the depth range of (a) 250-500 m, (b) 500-1000 m and (c) 1000-1500 m, Which averages for each bands containing more than 10 estimates.



(Whalen et al., GRL, 2012, Figure 3a ) E.g. Global mean dissipation rate for 3\_x0005\_half-overlapping latitudinal bands in the depth range 250–1,000 m over rough (variance greater than global mean) and smooth topography with 90% bootstrapped confidence intervals.

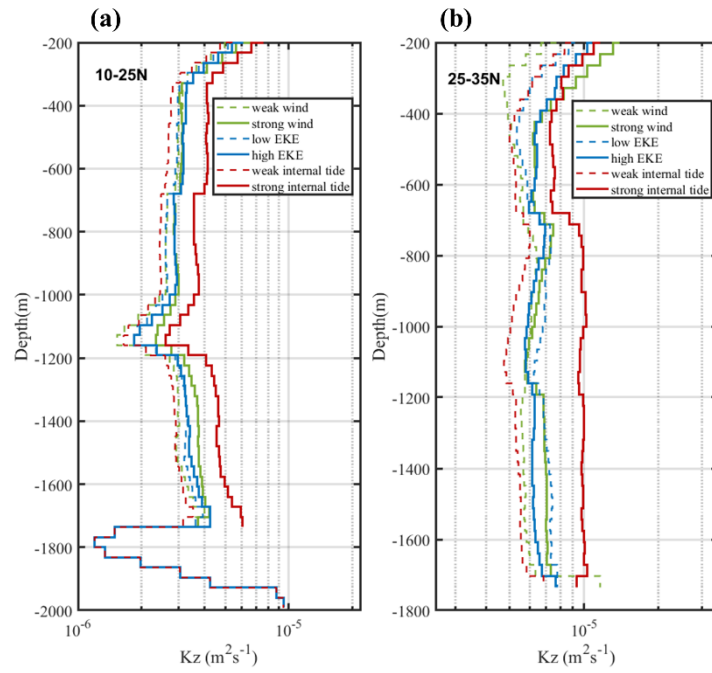
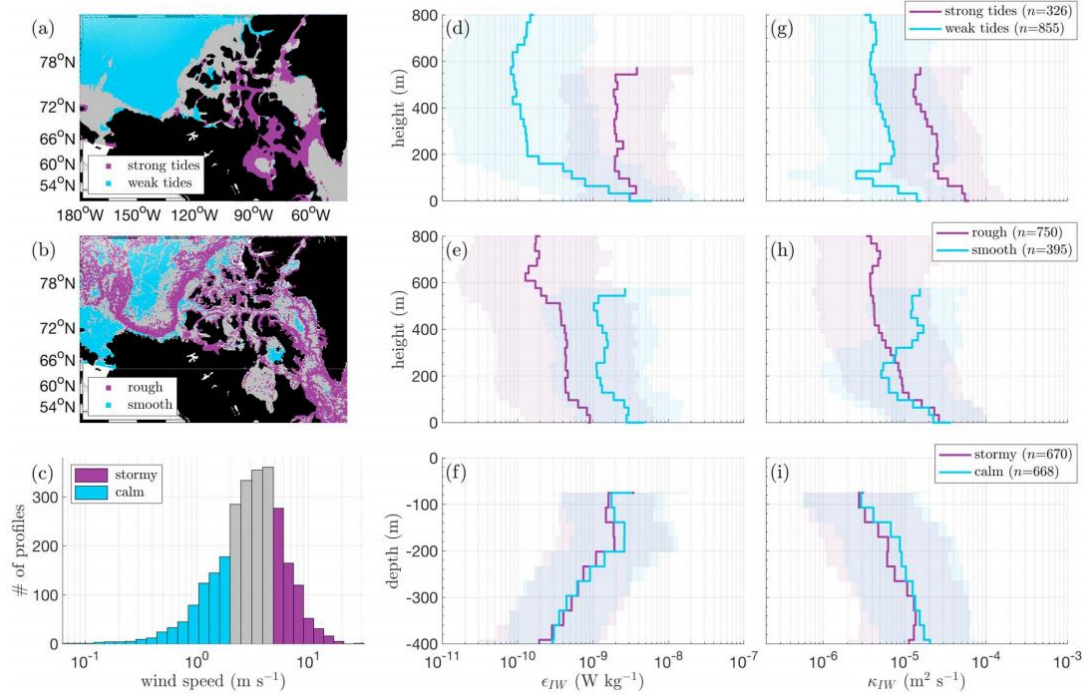
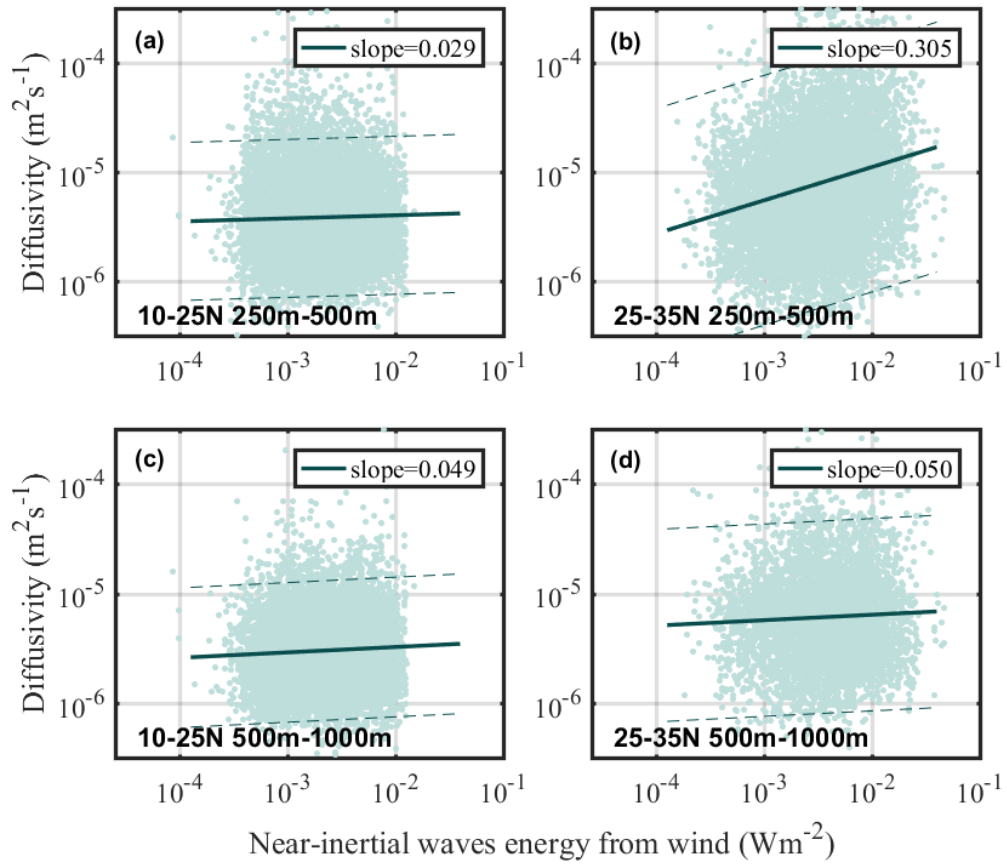


Figure 5 Vertical structures of geometric averaged diapycnal diffusivities  $K_z$  with weak and strong wind (green), low and high EKE (blue) and weak and strong internal tide (red) in the (a) low-latitude and (b) middle latitudes.

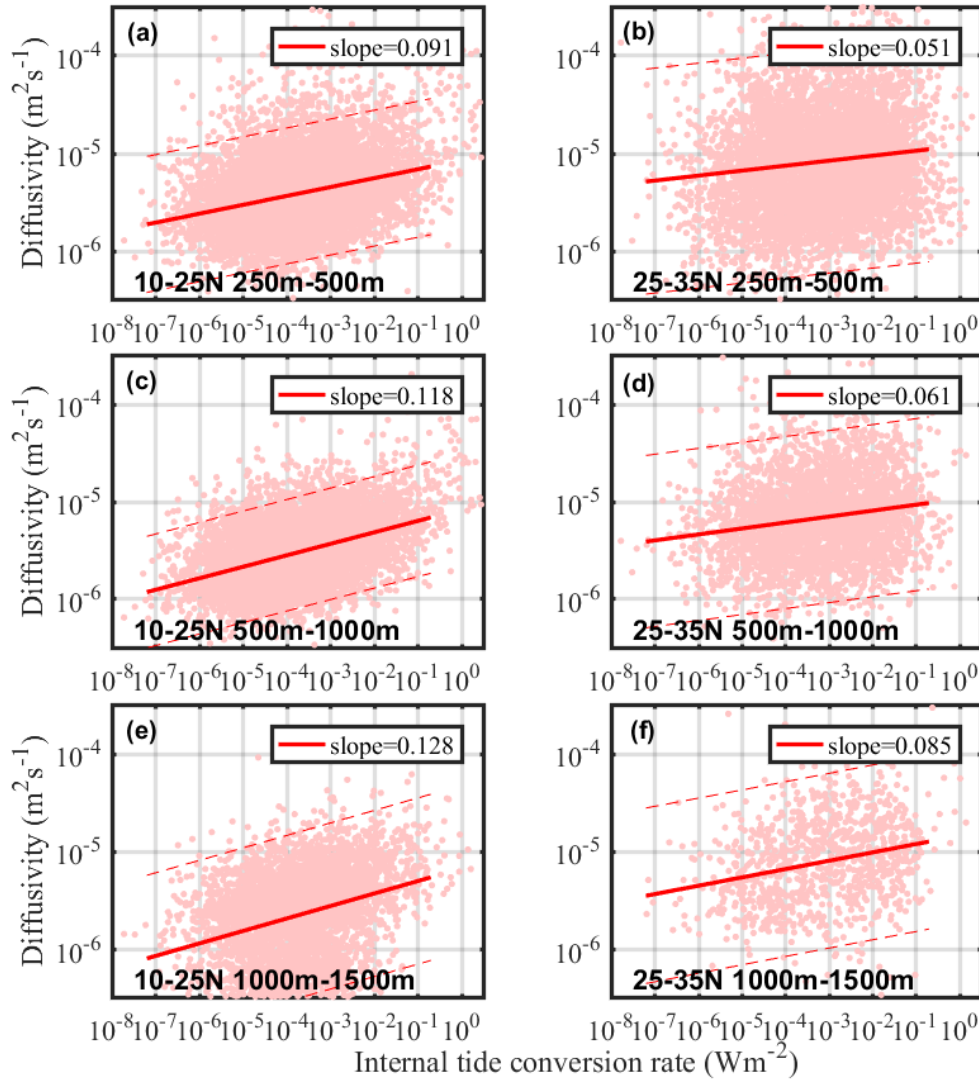


(Chanona et al., JGR, 2018, Figure 11 ) E.g. (a) Spatial distribution of strong (purple) and weak (blue) barotropic tidal speeds (b) spatial distribution of rough (purple) and smooth (blue) topography as determined by topographic roughness, and (c) log-scale histogram of stormy (purple) and calm (blue) 10 m wind speeds, associated with each conductivity-temperature-depth profile. High/low bin cutoffs for each parameter are defined by the upper/lower quartile limits of their corresponding distributions; gray regions indicate interquartile values not included in our analysis. Average vertical profiles of  $\epsilon_{IW}$  (middle column) and  $K_{IW}$  (right column) are binned accordingly for (d, g) strong/weak tidal speeds, (e, h) rough/smooth topography, and (f, i) stormy/calm wind speeds. The number of profiles comprising each vertical average is given by  $n$  and shading indicates the associated geometric standard deviations.

*b. In order to further verify our results of Fig. 4 and 5, the Fig. 6 and Fig. 7 were plotted using another direct correlation analysis method. The same conclusion can be drawn from the two kinds of analysis methods. The linear regression is a popular method for statistics analysis of the correlation between two factors (eg. Wu et al., 2011; Jing et al., 2014; Jeon et al., 2018; Zhao et al., 2019). The regression coefficient can represent the response of mixing to wind (eg. Qiu et al., 2012) or other factors. Another reviewer also gave some advises for comparing and interpreting these figures. Noted that Fig. 6 and Fig. 7 have been revised according to the suggestions from both reviewers.*



**Figure 6** Scatter of log-scale  $K_z$  versus log-scale near-inertial energy flux from wind in 250-500 m between (a)  $10^\circ\text{N}$  - $25^\circ\text{N}$  and (b)  $25^\circ\text{N}$ - $35^\circ\text{N}$ , and in 500-1000 m between (c)  $10^\circ\text{N}$ - $25^\circ\text{N}$  and (d)  $25^\circ\text{N}$ - $35^\circ\text{N}$ . The best-fit slopes are denoted by the solid line, the 95% confidence interval is indicated by dash lines.



**Figure 7** Scatter of log-scale  $K_z$  versus log-scale internal tide conversion rate in 250-500 m (row 1), 500-1000 m (row 2), 1000-1500 m (row 3) and the best-fit slopes are denoted by the red line. Columns 1 and 2 are 10°N-25°N and 25°N -35°N latitude bands, the 95% confidence interval is indicated by dash lines.

### 3. As for the conclusions

*The main conclusions in this paper include: 1. internal tides played a significant role in mixing the whole water column in the Philippine Sea. 2. the energetic mesoscale environment increases the internal tidal mixing.*

*We believe our conclusions are reliable and convincing, with several reasons:*

*a. The methods used are reasonable. The statistical methods have all passed the significance test.*

*b. We used different methods for the analysis and come to the same conclusion (eg. Figs. 4,5 and Figs. 6,7; Fig. 8 and Fig. 9). The results from different methods can support each other.*

*c. Some conclusions can be supported by previous studies. For example, according to Fig. 4 and Fig. 5, we can get the following three messages: 1. Wind and EKE play important roles on mixing the upper ocean in the mid-latitudes; 2. Strong internal tides are easier to enhance mixing in the deeper ocean. 3. Internal tides played a significant role in turbulent mixing not only in the low latitudes, but also in the mid latitudes with strong winds. The points 1 and 2 are consistent with some previous works (e.g. Waterhouse et al., 2014; Mackinnon et al., 2017; Whalen et al., 2018). The point 3 can be explained by some theoretical and numerical studies. For example, the eddy flows can increase vertical shear and subsequently internal tide energy dissipation rate (eg. Chavanne et al., 2010, Dunphy, 2014).*

*Therefore, we carefully considered your comments, checked and verified our methods and results again. We believe our methods used are valid and our main conclusions are reliable and reasonable.*

There are a few typographic and/or grammatical errors but, in general, the standard of English is satisfactory. The main error is to use "rates" instead of "ratios" in the correlation analyses (line 250 and elsewhere). The use of "slopes" instead of "ratios" (e.g line 319 and elsewhere) is misleading also (if I have understood the text correctly). In equation (3) I assume that "acrcosh" should be "arccosh"?

**Response:**

*Thank you for your comments, the “rates” (line 250 and elsewhere) was misused in this paper, and it has been corrected. The Figs. 7 and 8 used the linear regression approach, so we think the “slopes” is more suitable here. And the error in equation (3) has been corrected.*

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# Enhanced ~~i~~Internal ~~t~~Tidal ~~m~~Mixing in the Philippine Sea ~~m~~Mesoscale ~~e~~Environment

Jia You<sup>1, 3, 4</sup>, Zhenhua Xu<sup>\*1, 2, 3, 4</sup>, Qun Li<sup>5</sup>, Robin Robertson<sup>6</sup>, Peiwen Zhang<sup>1, 3, 4</sup>,  
Baoshu Yin<sup>1, 2, 3, 4</sup>

<sup>1</sup>CAS Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of  
Sciences, Qingdao, China

<sup>2</sup>Pilot National Laboratory for Marine Science and Technology, Qingdao, China

<sup>3</sup>Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China

<sup>4</sup>College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China

<sup>5</sup>Polar Research Institute of China, Shanghai, China

<sup>6</sup>China-Asean College of Marine Science, Xiamen University Malaysia, Sepang, Malaysia

*\*Corresponding author: Zhenhua Xu, Institute of Oceanology, Chinese Academy of Sciences; Email:  
[xuzhenhua@qdio.ac.cn](mailto:xuzhenhua@qdio.ac.cn).*

## Abstract.

Turbulent mixing in the ocean interior is mainly ~~attributed to~~~~contributed by~~ internal wave breaking; however, the mixing properties and the modulation effects of mesoscale environmental factors are not well-known. Here, the spatially inhomogeneous and seasonally variable diapycnal diffusivities in the upper Philippine Sea were estimated from ARGO float data using a strain-based finescale parameterization. Based on a coordinated analysis of multi-source data, we found that the driving processes for diapycnal diffusivities mainly included the near-inertial waves and internal tides. Mesoscale features were important in intensifying the mixing and modulating its spatial pattern. One interesting finding was that, besides near-inertial waves, internal tides also contributed significant diapycnal mixing ~~for~~~~in~~ the upper Philippine Sea. The seasonal cycles of diapycnal diffusivities and their contributors differed zonally. In the mid-latitudes, wind-mixing dominated and was strongest in winter and weakest in summer. In contrast, tidal-mixing was more predominant in the lower-latitudes and had no apparent seasonal variability. Furthermore, we provide evidence that the mesoscale environment in the Philippine Sea played a significant role in regulating the intensity and shaping the spatial inhomogeneity of the internal tidal mixing. The magnitudes of internal tidal mixing ~~was~~~~ere~~ greatly elevated in regions of energetic mesoscale processes. ~~The a~~~~Anticyclonic~~ mesoscale features were found to enhance diapycnal mixing more significantly than ~~did~~-cyclonic ones.

**Keywords:** Mixing, Internal tides, Mesoscale, the Philippine Sea

## 1. Introduction

Turbulent mixing can alter both the horizontal and vertical distributions of temperature and salinity gradients. These then modulate the ocean circulation variability, both globally and regionally. Many studies have shown the existence of a complicated spatiotemporal pattern of diapycnal mixing in the ocean interior. Such mixing inhomogeneity can influence the hydrological characteristics, ocean circulation variability and climate change. The breaking of internal waves is believed to be the main contributor to the ocean's diapycnal mixing (eg. Liu et al., 2013, Robertson R., 2001). Thus, clear understanding of the spatial patterns and dissipation processes of broad-band internal waves is necessary to clarify and depict the global ocean mixing climatology.

The long-wavelength internal waves in the ocean ~~are~~occur mainly in the form of near-inertial internal waves (NIWs) and internal tides (eg. Alford and Gregg, 2001; Cao et al., 2018; Klymak et al., 2006; Xu et al., 2013), and the internal solitary waves evolved from them also can trigger mixing (eg. Deepwell et al., 2017; Grimshaw, et al., 2010; Shen et al., 2020). The wind-input NIW energy to the mixing layer is about 0.3-1.4 TW (eg. Alford, 2003; Liu et al., 2017; Rimac et al., 2013; Watanabe and Hibiya, 2002). The NIW energy propagate downward, mainly dissipate and drive energetic mixing within the upper ocean (Wunsch and Ferrari, 2004). Barotropic tidal currents flowing over rough topographic features can generate internal tides (eg. Robertson R., 2001; Xu et al., 2016), with the global energy of 1.0 TW (Egbert and Ray, 2001; Jayne and St. Laurent, 2001; Song and Chen, 2020). Near the generation sources, the internal tidal mixing intensify above the bathymetries, meanwhile, in the remote area, the tidal mixing ~~is~~ becomes distributed throughout the water column due to the multiple reflection and refraction processes. Therefore, the relative contributions to the upper-layer diapycnal diffusivities by NIWs and the spatial variability of internal tides ~~should differ regionally, which~~ deserves further investigation.

In mid-latitudes, NIWs dominated the upper ocean mixing, as a result of the presence of westerlies and frequent storms (eg. Alford et al., 2016; Jing et al., 2011; Whalen et al., 2018). However, from the global view, the upper ocean mixing geography is inconsistent with the global wind field distribution. For example, in low-latitudes, upper ocean mixing hotspots are located nearer to rough topographic features, regardless of the wind conditions. This indicates that upper ocean mixing might be attributed to non-wind-driven internal waves, such as internal tides. In order to better understand the ocean mixing patterns and modulation mechanisms, we need to clarify the relative contributions between the wind

and tidal energy.

Internal tides are generally considered to be important to ocean mixing in the deep ocean, ~~beyond~~<sup>low</sup> the influence of winds (Ferrari and Wunsch, 2009; Munk et al., 1998; MacKinnon et al., 2017). Many factors influence the spatial pattern and energy transfer of internal tides. Higher-mode internal tides break more easily near their sources, while the low-mode internal tides propagate long distances, even thousands of kilometers. Propagating internal tides will be limited by several factors, such as topography, stratification and turning latitude (eg. Vlasenko et al., 2013; Song and Chen, 2020; Hazewinkel & Winters, 2011). Wave-wave interaction in the ocean also influences the spatiotemporal variability of internal tides. For example, PSI (parametric subharmonic instability) is a potential avenue to transfer internal tidal energy to other frequencies (Ansong et al., 2018). Moreover, stratification and background flows also contribute to internal tidal spatial and temporal variability (eg. Karry et al., 2016; Huang et al., 2018; Chang et al., 2019). Due to the complicated multi-scales of the background flows, it is still unclear about how the background flow modulates the internal tides, their energy dissipation and ocean mixing.

Recent research suggests that the mesoscale environment is a key factor influencing ocean mixing. There is evidence that mesoscale eddies can enhance wind-driven mixing and internal tidal dissipation. This enhancement will be more significant in the presence of an anticyclonic eddy (eg. Jing et al., 2011; Whalen et al., 2018). Likewise, regional studies indicate that mesoscale features modulate the generation and propagation of internal tides. Mesoscale currents can also broaden the range undergoing internal tide critical latitude effects and enhance the energy transfer from diurnal frequencies to semidiurnal or high frequencies (Dong et al., 2019). Mesoscale eddies are found to modulate internal tide propagation (Rainville and Pinkel, 2006; Park and Watts, 2006; Zhao et al., 2010) and enable the internal tide to lose its coherence (Nash et al., 2012; Kerry et al., 2016; Ponte and Klein, 2015). Numerical simulation results support these observations (Kerry et al. 2014), indicating that the patterns of internal tides ~~is~~<sup>are</sup> largely modulated by the position of eddies. An idealized numerical experiment shows that the energy of internal tides shows bundled beams after passing through an eddy (Dunphy and Lamb, 2014). And the mode-1 internal tide<sup>les</sup> interactions with eddies will trigger higher-mode signals. Up to now, research ~~about~~<sup>on</sup> mesoscale–internal tide interactions has ~~been-been~~ primarily focused on the propagation pattern or 3-D structure of internal tides and has ignored their energy dissipation and mixing effects. The latter ~~is~~<sup>are</sup>

91 more important for [altering impacts on](#) the ocean circulation variability and climate change.

92 The Philippine Sea, located in the Northwestern Pacific Ocean, is one of the most energetic internal  
93 tidal regimes in the world. In this region, powerful internal tides significantly enhance ocean mixing, as  
94 shown by numerical simulations (Wang et al., 2018). The importance of sub-inertial shear to ocean  
95 mixing has been hypothesized from observations (Zhang et al., 2019), and the importance of internal  
96 tides to mixing is supported through parameterization techniques (Qiu et al., 2012). On the other hand,  
97 the Philippine Sea is an area with frequent typhoons, which make significant contributions to ocean  
98 mixing. [Consequently, M](#)multiple factors and mechanisms impact the turbulent mixing distribution in  
99 the Philippine Sea (Wang et al., 2018). To date, it is unclear what the dominant factors are and how these  
100 factors modulate the ocean mixing properties. Moreover, the role of mesoscale environment in regulating  
101 ocean mixing is still not well understood.

102 [At p](#)Presently, coupled numerical models are basically able to accurately simulate the generation and  
103 propagation of internal tides. The internal tide dissipation and induced mixing are found to be important  
104 for the determination of correct mixing parameterizations in numerical models (Robertson and Dong,  
105 2019). Some existing studies focus on the simulations of internal tidal breaking and tidally induced  
106 mixing (Kerry et al., 2013; Kerry et al., 2014; Muller, 2013; Wang et al., 2018). It is difficult to provide  
107 a complete spatial and temporal picture from direct observations of turbulence. This is due to the scarcity  
108 of observations and their patchy distribution in time and space. Multisource data covering multiple tidal  
109 cycles or preferably a spring-neap cycle, as well as a broad domain, are necessary to acquire the  
110 spatiotemporal distribution and few of these have been collected. The development and application of  
111 parameterization methods provide greater possibility of characterizing a broad-regional mixing  
112 distribution and variability. A global pattern of ocean mixing has been provided using these  
113 parameterization methods (Whalen et al. 2012; Kunze 2017). Furthermore, sensitivity studies have been  
114 performed investigating the dependence of several factors to global mixing, such as bottom roughness,  
115 internal tides, wind and background flows (eg. Whalen et al. 2012; Waterhouse. 2014; Kunze and Eric.  
116 2017; Whalen et al. 2018; Zhang et al. 2019). At present, parameterization is the most effective method  
117 to investigate the modulation of tidal mixing by mesoscale background flows.

118 The spatial pattern and temporal variability of diapycnal diffusivities in the Philippine Sea are  
119 examined in this paper. We provide evidence to verify the importance of tidal mixing in the upper layer  
120 of this region. Moreover, we illustrate the modulation of mesoscale environment in tidal mixing

properties and distributions. Our data and methods are detailed in Section 2. Results and analysis, including the spatial patterns and seasonal cycle of mixing, contributions of influencing factors and internal tide-mesoscale interrelationships, are shown in Section 3. Finally the summary and discussion are given in Section 4.

## 2. Method and Data

### 2.1 ARGO and Fine-scale parameterization method

The ARGO Program is a joint international effort involving more than 30 countries and organizations and having deployed over 15,000 freely drifting floats since 2000. The accumulated total of collected profiles exceeds 2 million profiles of eConductivity, tTemperature, dDepth (CTD) along with other geobiochemical parameters. The ARGO program has become the main data source for many research and operational predictions of oceanography and atmospheric science (<http://www.ARGU.ucsd.edu>). We screened the profiles from the Philippines Sea with quality control and estimated diapycnal diffusivity and dissipation rate from them using a finescale parameterization.

The diapycnal diffusivity and turbulent kinetic energy dissipation rate can be estimated from a fine-scale strain structure. This is based on a hypothesis that the energy can be transported from large to small scales. In such scales, waves break due to shear or convective instabilities by weakly nonlinear interactions between internal waves (Kunze et al., 2006). Presently, this method has been widely used for the global ocean (eg. Wu et al., 2011; Kunze et al., 2017; Whalen et al., 2012; Fer et al., 2010; Waterhouse et al., 2014). The dissipation rate  $\varepsilon$  can be expressed as

$$\varepsilon = \varepsilon_0 \frac{\overline{N^2} \langle \xi_z^2 \rangle^2}{N_0^2 \langle \xi_{z_{GM}}^2 \rangle^2} h(R_\omega) L(f, \overline{N}) \quad (1)$$

where  $\varepsilon_0 = 6.73 \times 10^{-10} W/kg$  and  $N_0 = 5.24 \times 10^{-3}/s$ , and  $\overline{N^2}$  represents the averaged buoyancy frequency of the segment.  $\langle \xi_{z_{GM}}^2 \rangle$  and  $\langle \xi_z^2 \rangle$  are strain variance from the Garrett-Munk (GM) spectrum (Gregg and Kunze, 1991) and the observed strain variance, respectively. The angle brackets indicate integration over a specified range of vertical internal wavenumbers (see equations 4 and 5). The function  $h(R_\omega)$  accounts for the frequency content of the internal wave field and  $R_\omega$  represents shear/strain variance ratio.  $R_\omega$  is fixed at 7, which is a global mean value (Kunze et al., 2006).

$$h(R_\omega) = \frac{1}{6\sqrt{2}} \frac{R_\omega(R_\omega+1)}{\sqrt{R_\omega-1}} \quad (2)$$

The function  $L(f, \bar{N})$  corrects for a latitudinal dependence, here  $f$  is the local Coriolis frequency, and  $f_{30}$  is the Coriolis frequency at  $30^\circ$ , and  $\bar{N}$  is the vertically averaged buoyancy frequency of the segment.

$$L(f, \bar{N}) = \frac{f \operatorname{arccosh}(\frac{\bar{N}}{f})}{f_{30} \operatorname{arccosh}(\frac{\bar{N}}{f_{30}})} \quad (3)$$

strain  $\xi_z$  was calculated from each segment,

$$\xi_z = \frac{N^2 - N_{ref}^2}{N^2} \quad (4)$$

$$\langle \xi_z^2 \rangle = \int_{k_{min}}^{k_{max}} S_{str}(k_z) dk_z \leq 0.2 \quad (5)$$

We derived  $N$  from 2 to 10 dbar-processed temperature, salinity, and pressure data according to the ARGO float resolution.  $N_{ref}$ , as a smooth piece-wise quadratic fit to the observed  $N$  profile, is fitted to 24 m. Here we remove segments that vary in the range of  $\langle N^2 \rangle > 5 \times 10^{-4} s^{-2}$  or  $\langle N^2 \rangle < 1 \times 10^{-9} s^{-2}$  since the strain signal at these levels is dominated by noise (Whalen et al., 2018). By applying a fast Fourier transform (FFT) on half-overlapping 256 m segments along each vertical  $\xi_z$  profile, we computed the spectra  $S_{str}(k_z)$  and integrated them to determine the strain variance. We integrated these spectra between the vertical wavenumbers  $k_{min} = 0.003 \text{ cmp}$  and  $k_{max} = 0.02 \text{ cmp}$  according to typical global internal tidal scales and equation 5, respectively. Substituting  $\langle \xi_z^2 \rangle$  into equation (1) ultimately yields 32 m resolved vertical profiles of each observed profiles. The dissipation rate  $\varepsilon$  is related to the diapycnal diffusivity  $K_z$  by the Osborn relation

$$K_z = \Gamma \frac{\varepsilon}{N^2} \quad (6)$$

where the flux coefficient  $\Gamma$  is fixed at 0.2 generally.

## 2.2 ERA-Interim and Slab-model

The near-inertial energy flux for each observation profile was calculated using the 10 m wind speed product from ERA-Interim (<https://www.ecmwf.int/en/forecasts/datasets>), which is 6-hourly wind speed on a grid of  $0.75^\circ \times 0.75^\circ$ . We selected the mean near-inertial flux of 30-50 days before the time of each diapycnal diffusivity estimation as our measure of the near-inertial flux, with the consideration of the propagation of NIWs.

The wind-drive NIW energy flux can be directly estimated using a slab model, which assumes that the

inertial oscillations in the mixed layer do not interact with the background fields. The mixed layer current velocity can be described by

$$\frac{dZ}{dt} + (r + if)Z = \frac{T}{\rho H} \quad (7)$$

where  $Z = u + iv$  is the mixed layer oscillating component of full current, and  $i$  is an imaginary number to indicate the latitudinal component.  $T = (\tau_x + i\tau_y)$  is the wind stress on the sea surface,  $f$  is the local Coriolis parameter,  $r$  is the frequency-dependent damping parameter, which was fixed at  $0.15 f$  for these calculations.  $\rho$  is sea water density and fixed at  $1024 \text{ kg/m}^3$ .  $H$  is the mixed-layer depth and was set to a constant 25 m. We can calculate the oscillating component of full velocity from equation 7 and obtain the near-inertial component through a bandpass filter of  $[0.85, 1.25] f$ . The near-inertial energy flux is calculated as

$$EH(\Pi) = Re(Z \cdot T^*) \quad (8)$$

the asterisk (\*) indicates the complex conjugate of a variable.

### 2.3 AVISO and Eddy kinetic energy

The eddy kinetic energy is estimated based on geostrophic calculation as:

$$EKE = \frac{1}{2} (U_g'^2 + V_g'^2) \quad (9)$$

$$U_g' = -\frac{g}{f} \frac{\Delta \eta'}{\Delta y} \quad V_g' = -\frac{g}{f} \frac{\Delta \eta'}{\Delta x} \quad (10)$$

where  $U_g'$  and  $V_g'$  are the geostrophic velocities in the east-west and north-south directions, respectively. They are taken from the AVISO (<http://www.aviso.altimetry.fr/duacs/>) geostrophic velocity product.  $\eta'$  indicates sea level anomaly (SLA).

### 2.4 Internal tidal conversion rates

The internal tidal conversion rate was provided by SEANOE (<https://www.seanoe.org/data/>, C.de Lavergne et al., 2019), including 8 main tidal constituents. We used the mode-summed internal tidal conversion rates of  $M_2$  and  $K_1$ , and integrated 8 main tidal constituents in present study.

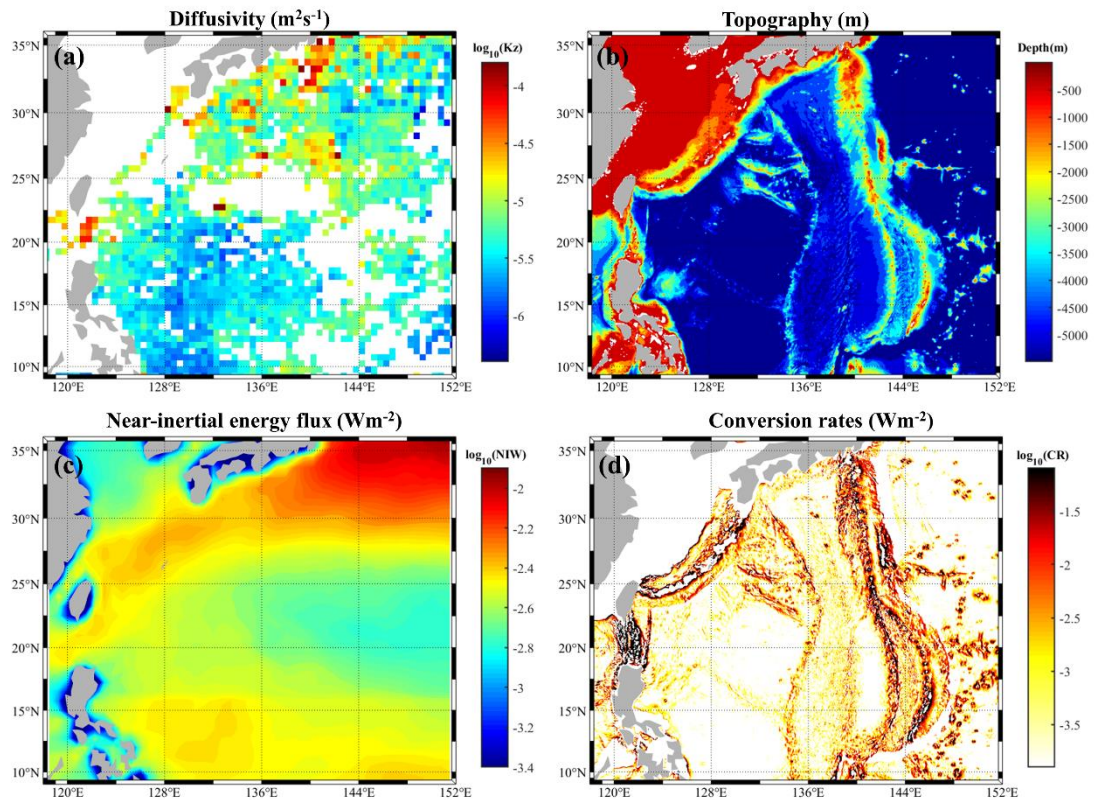
## 3. Results

### 3.1 Spatial pattern of diapycnal mixing in the upper Philippine Sea

The diapycnal diffusivities were used as indicators of ocean diapycnal mixing. The pattern averaged within 250-500 m is shown in Fig.1a. The  $K_z$  was estimated from the ARGO profiles, with an average



on each cell of  $0.5^\circ \times 0.5^\circ$ . The magnitude of diapycnal diffusivities increased with latitude, reaching  $10^4 \text{ m}^2 \text{ s}^{-1}$  in the northern part of this area ( $30^\circ \text{N}$ - $36^\circ \text{N}$ ). The mean value of  $K_z$  was about  $O(-6)$ - $O(-5)$  in lower latitude. While, it was remarkable that the magnitude of  $K_z$  also increased significantly in some low-latitude regions, reaching  $O(-4)$  or higher. These regions include Izu Ridge (Nagasawa et al., 2005; Tanaka et al., 2018) and, such as Luzon Strait (Xu et al., 2014). Reviewing the influence of topography, wind and internal tide (Fig.1b-d) on ocean mixing, it was found that the latitudinal-zonal variability of  $K_z$  was consistent with the wind intensity distribution. Upper ocean mixing was significantly enhanced at mid-latitudes due to the presence of westerlies. In addition,  $K_z$  was also enhanced near several key internal tide sources, such as the Luzon Strait, Bonin Ridge, Izu Ridge, Dadong Ridge, etc. At these sites, the magnitude of  $K_z$  was obviously larger than other areas at the same latitude, indicating a significant role of internal tides. Additionally, the enhancement of deep ocean mixing at these sites was even more obvious (not shown).

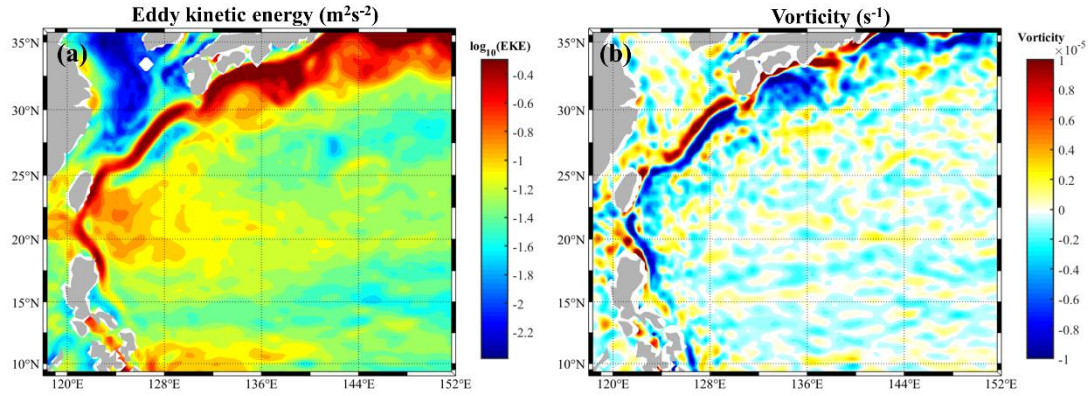


**Figure 1** Maps of (a) log-scale averaged diapycnal diffusivities  $K_z$  ( $\text{m}^2 \text{s}^{-1}$ ) estimated from ARGO profiles, (b) topography, (c) log-scale long-term averaged near-inertial energy flux from wind ( $\text{Wm}^{-2}$ ), and (d) log-scale M2 internal tide conversion rates ( $\text{Wm}^{-2}$ ).

It can be noted that the pattern of diapycnal diffusivities was not completely consistent with those of



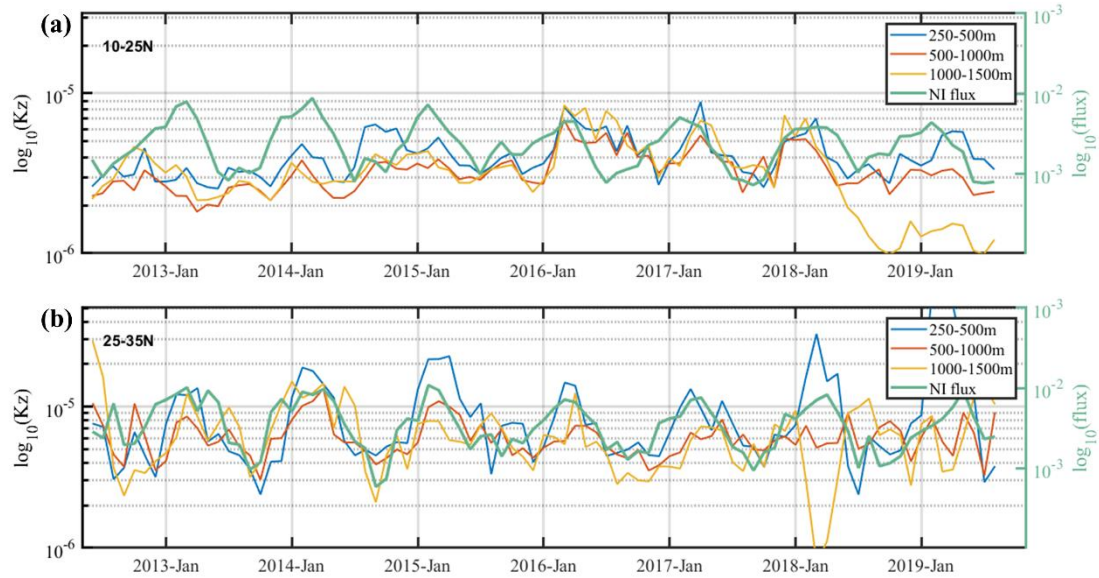
either internal tides or winds. This suggests that the ocean mixing was modulated by other factors than tides and winds. The magnitudes of  $K_z$  also vary for internal tide source sites. Considering that the Philippine Sea is a region with energetic mesoscale motions (Fig.2), the influences of mesoscale features in turbulent mixing should be taken into account. The existence of mesoscale features can alter the propagation and dissipation of internal tides. Therefore, the Philippine Sea is an ideal region to study the modulation of background flows on turbulent mixing associated with strong internal tides.



**Figure 2 Maps of (a) log-scale long-term averaged eddy kinetic energy and (b) long-term averaged vorticity.**

### 3.2 Seasonal variability of mixing at different latitudes

The seasonal cycle for diapycnal diffusivities also differs zonally. Here, we divided the Philippine Sea into two portions: low-latitude (10°N-25°N) and mid-latitude (25°N-35°N). The diapycnal diffusivities  $K_z$  were averaged in each latitude band (Fig.3). At the depth of 250-500 m in the mid-latitude, the diapycnal diffusivities had a significant seasonal trend as strong in winter and weak in summer. This is consistent with the seasonal fluctuation of near-inertial energy from wind. Such a seasonal cycle could also be found at 500-1000 m and 1000-1500 m in the mid-latitudes, but it was relatively weaker, especially after 2016. In the lower latitudes, the NIW energy was still strong in winter and weak in summer, but a seasonal dependence of turbulent mixing was not obvious, even in the upper ocean. Consequently, the wind was found to play a significant role in driving turbulent mixing at mid-latitude, but was insignificant at low latitudes. Other factors drove and modulated turbulent mixing in low latitudes.



**Figure 3** Seasonal cycles in diapycnal diffusivities (colorful line) and near-inertial energy flux from wind (green) extends to 250-500 m, 500-1000 m and 1000-1500 m in (a) 10°N -25°N and (b) 25°N-35°N, which is averaged in each month and all water column.

### 3.3 Impact factors

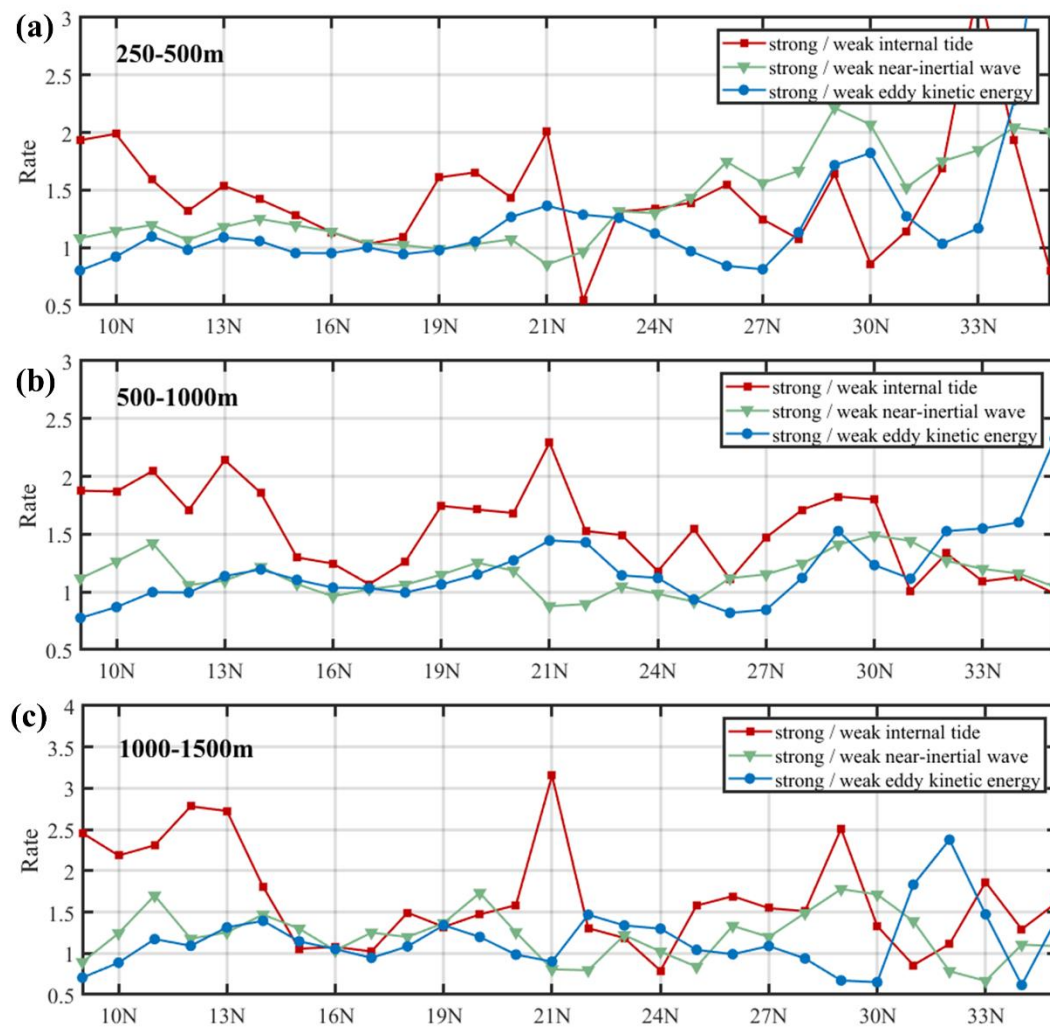
#### 3.3.1 Relative contributions

The turbulent mixing of the Philippine Sea displayed an obvious ~~latitudinal~~latitudinal dependence, so the latitudinal influence was examined for several factors: internal tides, wind and eddy kinetic energy (Fig.4).

The diapycnal diffusivities in the regions of weak internal tides and strong internal tides were averaged in each 1° latitude band. Each 1° latitude band was separated into two regions with weak or strong internal tides (or other factors). Here we define the strong or weak internal tides as the internal tide conversion rate larger or smaller than the median of the Philippine Sea. The diapycnal diffusivities in these two kinds of regions were then averaged. The similar method has been used to analyze the effect of topography and different frequency-bands internal waves on ocean interior shear and mixing (eg. Whalen et al., 2012; Zhang et al., 2019). A similar method has been used to analyzed the effect of topography or different frequency bands waves on mixing (eg. Whalen et al., 2012; Zhang et al., 2019). For a more direct representation, the ratios of diapycnal diffusivities above the strong internal tides to weak internal tides were shown. The ratio of diapycnal diffusivities above the strong internal tides to weak internal tides are shown. The ratio larger than 1 means that the diapycnal diffusivities are significantly higher in the regions

of strong internal tides. This ratio larger than 1 means that the diapycnal diffusivities is higher in the regions of strong internal tides than above weak internal tide in this latitudinal band. The larger this ratio is, the more important the internal tidal induced mixing. Similarly, the contributions of near-inertial wave and eddy kinetic energy were analyzed by this statistical method. The strong near-inertial wave or eddy kinetic energy is the locations where this parameter exceeds the regional median.

The rates of diapycnal diffusivities in regions of weak/strong internal tides, weak/strong NIW energy, and high/low eddy kinetic energy were calculated in each  $1^\circ$  latitude, respectively. If the rate was close to 1, the influence of this factor was insignificant, while a larger rate indicated a greater contribution.



**Figure 4 Ratios of diapycnal diffusivities between areas over strong (greater than median) and weak internal tide (red lines), strong (greater than median) and weak near-inertial wave (green lines) and strong (greater than median) and weak eddy kinetic energy (blue lines) for each  $1^\circ$  latitude bands in the depth range of (a) 250-500 m, (b) 500-1000 m and (c) 1000-1500 m, Which averages for each bands containing more than 10 estimates.**

At depths of 250-500 m, the ~~ratio~~<sup>rate</sup> associated with internal tide increased significantly at 10°N, 21°N and 33°N. These latitudes correspond to Guap seamount, Luzon Strait and Izu Ridge, which are main internal tide<sup>al</sup> source sites. It reached 2 near these three latitudes, indicating that strong internal tides triggered the enhancement of  $K_z$  twice as much compared to the regions of weak internal tides. In addition, north of 23~~3~~°N, the ~~ratio~~<sup>rate</sup> in related to NIW in the upper ocean increased significantly with latitude. ~~And it exceeded the internal tidal contribution north of 25°N,~~ which indicated that the wind plays a more important role in mixing at this latitude band. This results is basically consistent with the previous studies (Whalen et al., 2018), which suggested that the mixing is dominated by wind in the mid-latitude. Taking the wind as the driving factor better explains the seasonal cycle of diapycnal diffusivities in Fig.3, since the winds have an apparent seasonal dependence. The obvious seasonal trend of  $K_z$  due to the important contribution of wind occurs between 25°N-35°N. In contrast, the ~~ratio~~<sup>rate</sup> for wind is ~1 at lower latitudes, indicating that the wind-driven mixing is insignificant here with the absence of wind-driven seasonal cycle.

The ~~contribution of~~ wind contribution to turbulent mixing is significantly reduced in the depth ranges of 500-1000 m and 1000-1500 m (Fig.4 b and c). The ~~ratio~~<sup>rate</sup> only increased slightly at mid-latitudes, less than 2 anywhere. In contrast, the enhancement of mixing triggered by internal tides at these depth ranges was more significant, with the ~~ratio~~<sup>rates</sup> exceeding 3.5 at some latitudes. This suggested that internal tides played a more important role in deep ocean mixing. Furthermore, internal tides significantly enhanced  $K_z$  around 13°N, 21°N, and 29°N, corresponding to the sources of Mariana Trench, Luzon Strait and Bonin Ridge, respectively. Such enhancement was not obvious at the Izu Ridge possibly due to the shallower depth and paucity of deep data, or the turning latitude effects in this area.

Combined with the analysis of relative contributions of different factors in different layers, it was concluded that the contribution of internal tides in turbulent mixing is more important in low latitudes of the Philippine Sea. In this area, the wind and mesoscale features did not significantly enhance  $K_z$ . At mid-latitudes, internal tides still played an important role, but the wind contribution was more significant in the upper ocean. The wind drove turbulent mixing even at the depths of 500-1000 m and 1000-1500 m. The mid-latitude region not only corresponds to westerlies, but also features energetic mesoscale motions. Therefore, the mesoscale features might be a potential factor for the enhanced turbulent mixing. The modulation of mesoscale environments in the wind-induced mixing are discussed by some previous studies (eg. Jing et al., 2011; Whalen et al., 2018), while the impact of mesoscales features in tide-induced

mixing and in lower latitudes were not be considered.

The Philippine Sea was separated into two latitude bands. The vertical structures of diapycnal diffusivities in the regions with strong and weak internal tides were compared (Fig.5). This result can directly reveal the enhancement of internal tide on mixing at different depths. A similar analysis was used for wind and EKE. In the low latitudes,  $K_z$  did not increase in the regions of high eddy kinetic energy or strong near-inertial energy, whereas, it increased significantly in the regions of strong internal tides. This enhancement was more obvious below 400 m (Fig.5 a). And in the mid-latitudes,  $K_z$  in the upper ocean increased significantly corresponding to strong winds with compared to weak winds (Fig.5 b). Meanwhile,  $K_z$  was also larger in the regions of strong internal tides and high EKE in the upper ocean. The enhancement of wind or EKE to turbulent mixing significantly weakened below 600 m, while the enhancement of internal tides increased with depth. Here, these results conveys several information: 1. Wind and EKE plays an important roles on mixing in the upper ocean in the middle latitudes; 2. Strong internal tides is easier to facilitate and enhance mixing in the deeper ocean. These two conclusions is are consistent with previous researchers (eg. Jing et al., 2011; Whalen et al., 2012; Waterhouse et al., 2014; Mackinnon et al., 2017; Whalen et al., 2018-). This In addition, our results indicates that, in the Philippine Sea, internal tides played a significant role in turbulent mixing not only in the low latitudes, but also in the mid latitudes, and not only in the deeper ocean, but also in the upper ocean, with their strong winds.

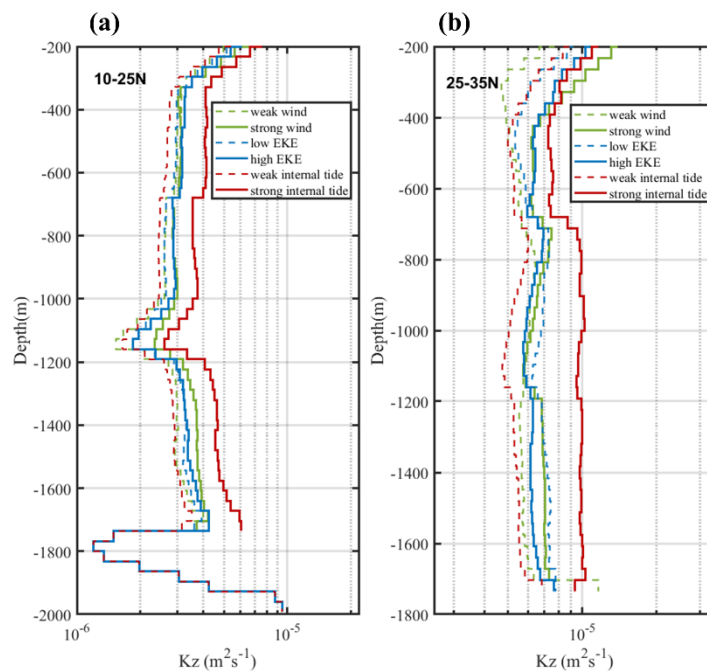
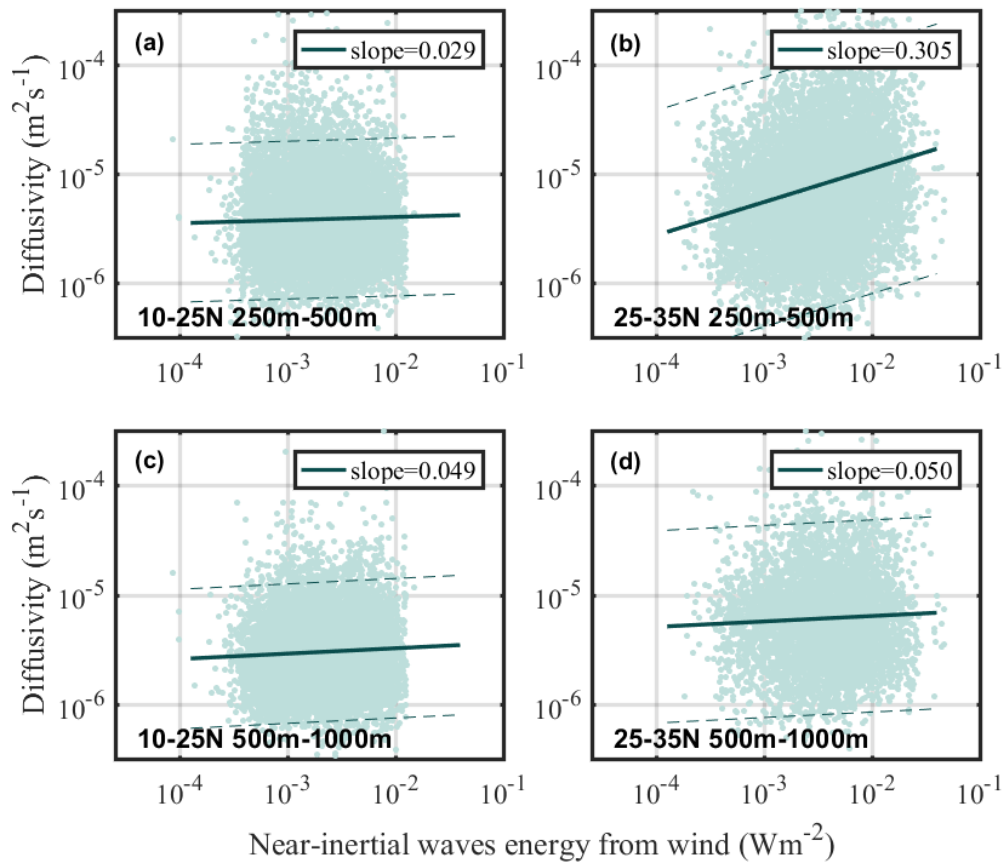


Figure 5 Vertical structures of geometric averaged diapycnal diffusivities  $K_z$  with weak and strong wind (green), low and high EKE (blue) and weak and strong internal tide (red) in the (a) low-latitude and (b) middle latitudes.

### 3.3.2 Wind

We adopted the linear regression approach and obtained the correlation between diapycnal diffusivities and wind. This approach is generally used to statistics the correlation between two factors (eg. Wu et al., 2011; Jing et al., 2014; Jeon et al., 2018; Zhao et al., 2019). The least squares linear fit slopes regression coefficient is able to of  $K_z$  to NIW energy from wind represent the mixing response to wind (eg. Qiu et al., 2012). Here, the Philippine Sea is divided into  $10^{\circ}\text{N}$ – $15^{\circ}\text{N}$ ,  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$  and  $25^{\circ}\text{N}$ – $35^{\circ}\text{N}$  (Fig.6). At the depth of 250-500 m, the slope is the largessignificant largeert in  $25^{\circ}\text{N}$ – $35^{\circ}\text{N}$  (~0.305), followed by that in  $10^{\circ}\text{N}$ – $15^{\circ}\text{N}$  (~0.133), and the smallest in  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$  (~0.04329). The wind driven turbulent mixing was most significant between  $25^{\circ}\text{N}$ – $35^{\circ}\text{N}$ , but was insignificant between  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$ . At the depth of 500-1000 m, the wind influence on turbulent mixing was weakened in the mid-latitudes. This was consistent with the results of Fig.3 and Fig.4. It proved that the contribution of wind has a latitudinalzonal dependence, which was significant at the mid-latitudes, but insignificant at low latitudes. In addition, the response of turbulent mixing to wind weakened quickly with depth, indicating that the dominant factor of mixing in the deeper water column was not wind. Accordingly, it was difficult for wind to drive mixing below 1000 m, so we do not show the results at the depth of 1000-1500 m (Fig.4).





**Figure 6** Scatter of log-scale  $K_z$  versus log-scale near-inertial energy flux from wind in 250-500 m between (a)  $10^\circ\text{N}$ - $12.5^\circ\text{N}$ , (b)  $15^\circ\text{N}$ - $25^\circ\text{N}$  and (c)  $25^\circ\text{N}$ - $35^\circ\text{N}$ , and in 500-1000 m between (d)  $10^\circ\text{N}$ - $12.5^\circ\text{N}$ , (e)  $15^\circ\text{N}$ - $25^\circ\text{N}$  and (f)  $25^\circ\text{N}$ - $35^\circ\text{N}$ . The best-fit slopes are denoted by the solid line, the 95% confidence interval is indicated by dash lines.

### 3.3.3 Tide

The slopes of  $K_z$  to internal tide conversion rates represent the mixing response to internal tides. As discussed above, the mixing significantly responded to the internal tides over the entire Philippine Sea (Fig.7). The relationship was depth dependent. The slopes did not reach 0.1 at the depth of 250-500 m, but increased significantly at 500-1000 m and 1000-1500 m, and exceeded 0.1 for the deepest depth band. The response of mixing to internal tides was more significant in the deeper ocean. Focusing on different latitude bands, the slopes of  $K_z$  to internal tides is smaller at mid-latitudes. This is because the wind contribution increased in this region, which led to a weakening relative contribution of internal tides. Compared with the internal tide conversion rates, the pattern of  $K_z$  was inconsistent with internal tides, even at lower latitudes. It can be inferred that the turbulent mixing was not only affected by the internal tides, but also by other factors. There is a strong western boundary flow, Kuroshio, and an active

mesoscale environment in this region. Some researchers have shown that the existence of mesoscale environment will alter the internal tide features, so we reasonably infer that the tidal induced turbulent mixing in this area was modulated by the mesoscale features.

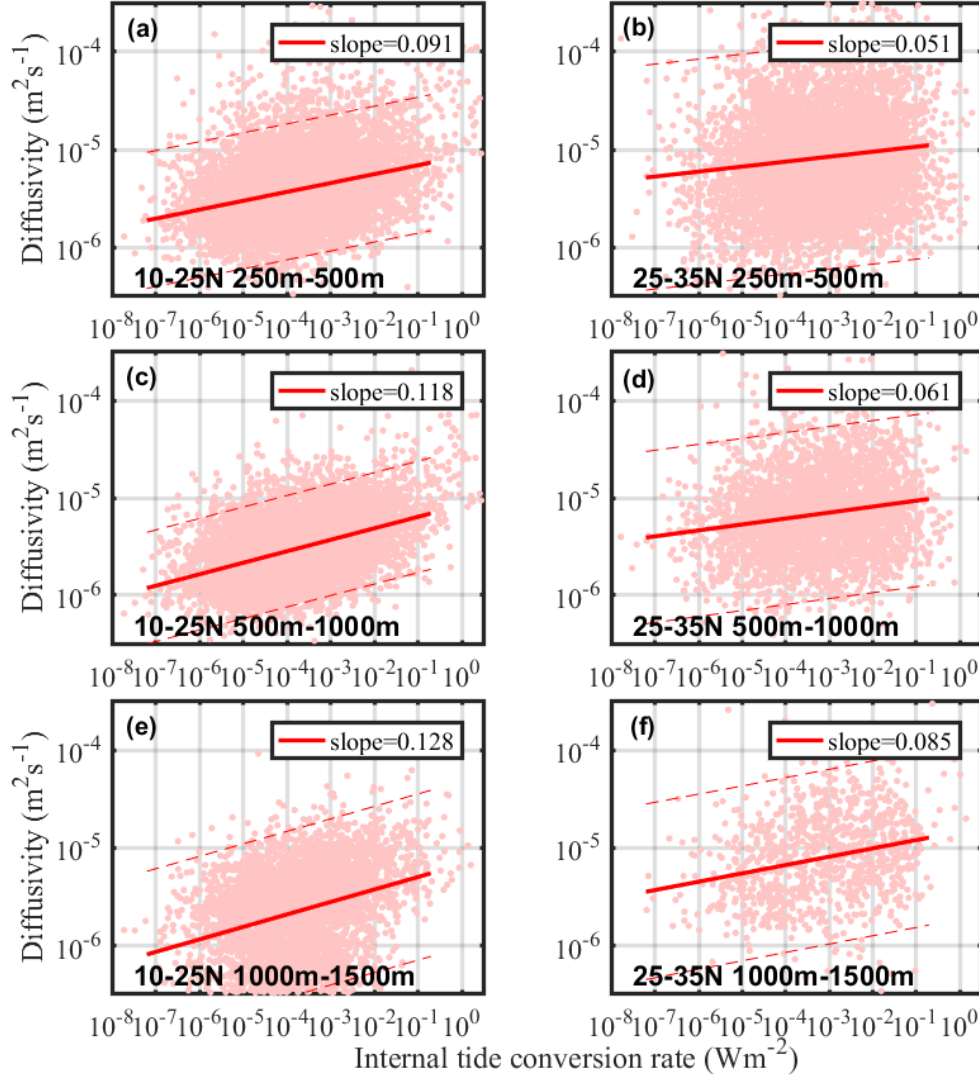


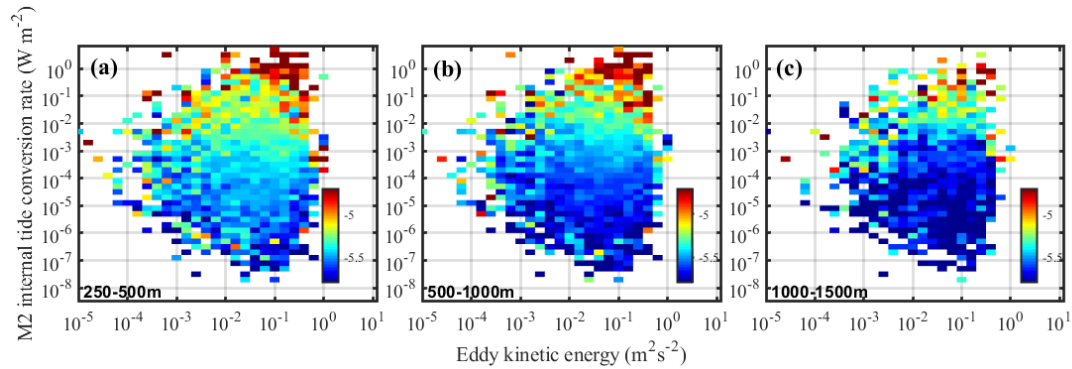
Figure 7 Scatter of log-scale  $K_z$  versus log-scale internal tide conversion rate in 250-500 m (row 1), 500-1000 m (row 2), 1000-1500 m (row 3) and the best-fit slopes are denoted by the red line. Columns 1 and 2 are 10°N-25°N, 25°N-35°N latitude bands, the 95% confidence interval is indicated by dash lines, respectively.

### 3.4 Role of Mesoscale features in tidal mixing

Focusing on the low latitudes, where tidal mixing is dominated, the diapycnal diffusivities,  $K_z$ , related to internal tides and eddy kinetic energy are shown in (Fig.8). The combined influences of mesoscale features and internal tides on mixing are indicated. The increasing internal tide conversion

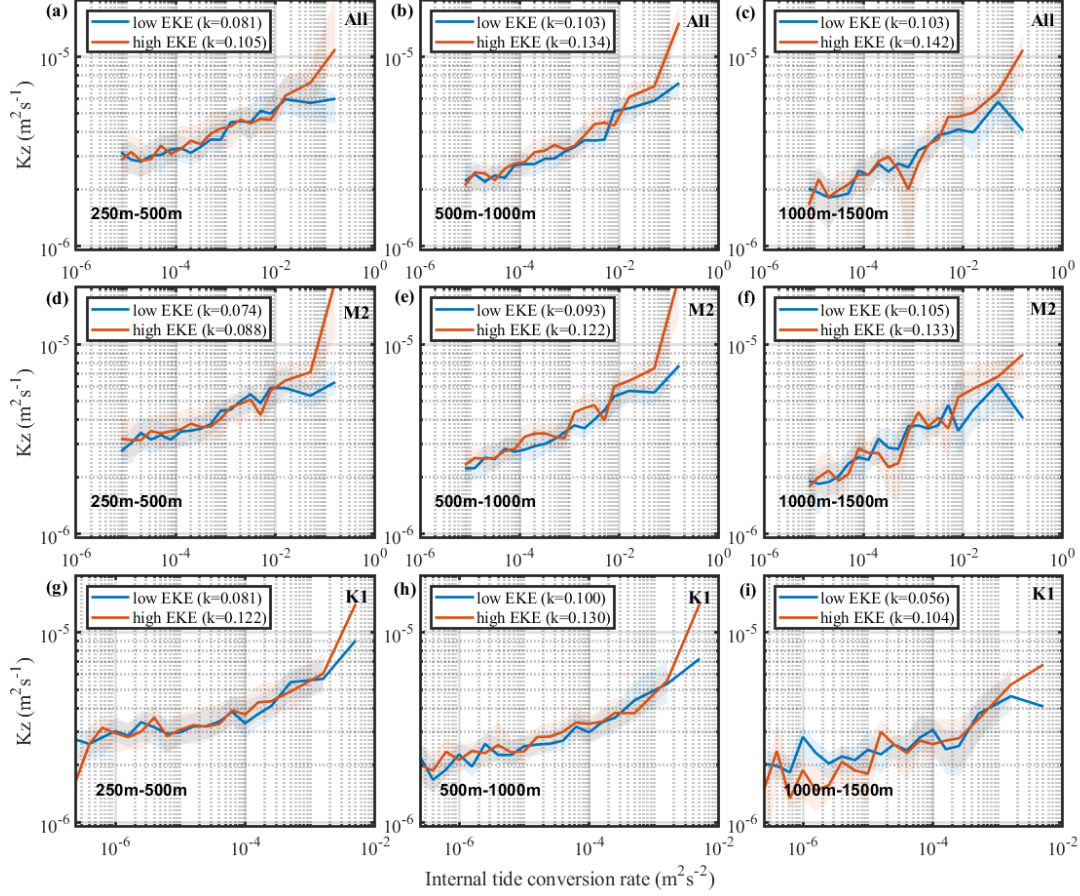


rates significantly enhanced turbulent mixing. We find a correlation between elevated eddy kinetic energy and the averaged diapycnal diffusivities for a given internal tide conversion rate level. The increasing internal tide conversion rates significantly enhanced turbulent mixing. When the conversion rate was  $10^{-3} \text{ Wm}^{-2}$ , the magnitudes of  $K_z$  were about  $3 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ ,  $3 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ ,  $1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$  at the depth of 250-500 m, 500-1000 m and 1000-1500 m, respectively. When the internal tide conversion rates reached  $O(-1)-O(0)$ ,  $K_z$  reached  $10^{-5} \text{ m}^2 \text{ s}^{-1}$  at both depths of 250-500 m and 500-1000 m, even exceed  $10^{-4} \text{ m}^2 \text{ s}^{-1}$  at some internal tide source sites. In addition, there was a positive correlation between eddy kinetic energy and diapycnal diffusivities. A higher eddy kinetic energy can further increase  $K_z$  under the same magnitude of internal tide conversion rate. Such enhancement was more significant with strong internal tide conversion rates greater than  $10^{-3} \text{ Wm}^{-2}$ .



**Figure 8** Averaged diapycnal diffusivities as a function of EKE and internal tide conversion rates between (a) 250-500 m, (b) 500-1000 m and (c) 1000-1500 m.

$M_2$  and  $K_1$  tidal constituents were analyzed to clarify the response of  $K_z$  to internal tides in the regions of high eddy kinetic energy (EKE is larger than the regional average value) and low eddy kinetic energy (Fig.9). The results integrating 8 main tidal constituents (Fig.9 a, b and c) showed that the slopes in a weak (strong) mesoscale field were smaller (larger), 0.081 (0.105), 0.103(0.134) and 0.103 (0.142) at the depth of 250-500 m, 500-1000 m, 1000-1500 m, respectively. The turbulent mixing was more sensitive to the internal tide magnitude in the presence of an energetic mesoscale field. Moreover, such response was more obvious in the region with strong internal tides (such as  $>10^{-2} \text{ Wm}^{-2}$  conversion rate). In some regions with weak internal tides, such as with internal tide conversion rates less than  $10^{-3} \text{ Wm}^{-2}$ , the modulation of mesoscale eddies was less significant.

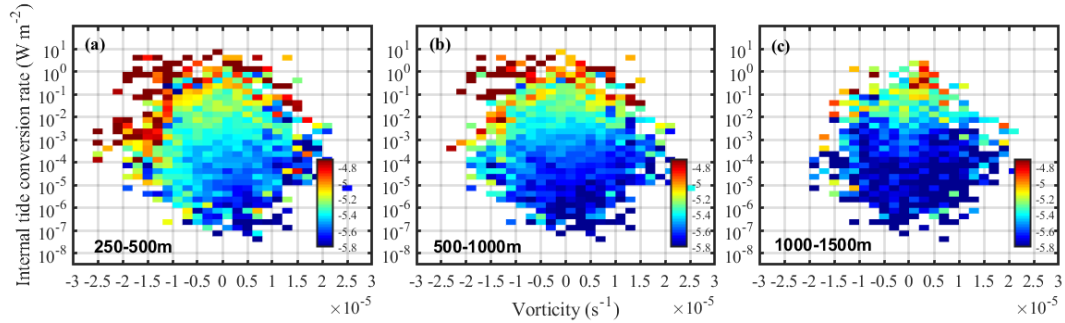


**Figure 9** The averaged diffusivity between depths of (a, d, g) 250 m-500 m, (b, e, h) 500 m-1000 m and (c, f, i) 1000 m-1500 m in high (greater than the median) and low (less than the median) eddy kinetic energy. The shade indicate the 1 deviation. Rows 1,2 and 3 are related to 8 main tidal constituents,  $M_2$  internal tide and  $K_1$  internal tide, respectively.

A similar conclusion can be drawn only considering  $M_2$  or  $K_1$ . In regions of high eddy kinetic energy, the change in diffusivities in response to internal tides was significant. And the increase was more sensitive to  $M_2$  internal tide. The enhancement related to  $M_2$  internal tide was more significant below 500 m (Fig.9 d and e), while enhancement of the  $K_1$  internal tide was similar at all depths. This may be due to different features and structures of  $M_2$  and  $K_1$  internal tides. In this area, the modal structure and propagation path of  $M_2$  internal tide are more complicated and more prone to breaking, but those of  $K_1$  were relatively stable. And this area includes the  $K_1$  critical latitude range, which can be broadened by mesoscale currents (Robertson and Dong, 2019).

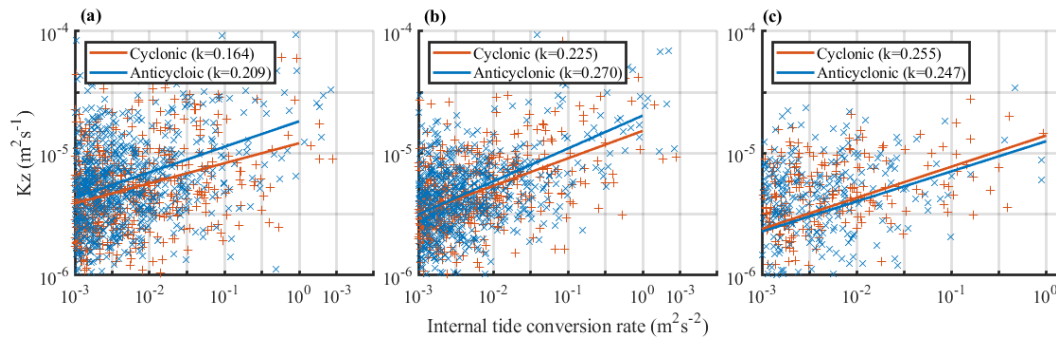
The modulation of cyclonic and anticyclonic eddies on tidal mixing also differ. The increase of  $K_z$  by internal tides in regions with cyclonic eddies ( $\text{vorticity} > 3 \times 10^{-6} \text{ s}^{-1}$ ) and anticyclonic eddies ( $\text{vorticity} < -3 \times 10^{-6} \text{ s}^{-1}$ ) are both shown (Fig.10 and Fig.11). Under the same magnitude of internal tides,

the  $K_z$  increase more significantly in the presence of anticyclonic eddies, which is obvious in 250-500 m, and can also be seen in 500-1000 m. Below 1000 m, there ~~isare~~ no significant differences between the regions with cyclones and anticyclones.



**Figure 10** The averaged diapycnal diffusivities as a function of vorticity and internal tides conversion rate between (a) 250-500 m, (b) 500-1000 m and (c) 1000-1500 m

Considering mixing driven by eddies is relatively significant in regions where the tidal mixing is very weak, we only analyze the cases of internal tides conversion rates larger than  $10^{-3} \text{ W m}^{-2}$ . When the conversion rates become larger than this value, the diapycnal diffusivities at the presence of high eddy kinetic energy increase faster with internal tides (Fig. 9). It was found that the response of turbulent mixing to internal tides was more sensitive in the presence of anticyclones above 1000 m. While below 1000 m, the influence of cyclones is slightly ~~higher~~**stronger** than that of anticyclones.



**Figure 11** ~~s~~**Scatter** of log-scale  $K_z$  versus log-scale internal tide conversion rate with Cyclone (red) and anticyclone (blue) in (a) 250-500 m, (b) 500-1000 m, and (c) 1000-1500 m. The best-fit slopes are denoted by the red and blue solid line.

#### 4. Summary

The spatial pattern and seasonal variability of the diapycnal diffusivities in the Philippine Sea were estimated using a fine scale parameterization. The main conclusions ~~are as~~ follows.

The seasonal fluctuations of mixing in this area were zonally dependent. Seasonal variability was strong in winter and weak in summer at mid-latitudes, with the seasonal fluctuations more obvious in the upper ocean. This was attributed to the Westerlies, and the wind plays a more significant role in turbulent mixing here. However, the seasonal cycle of mixing in the low latitudes was not obvious, indicating that the wind-driven mixing was not dominant here. As opposed to wind-driven mixing, tidal mixing was more significant in the deeper ocean.

Evidence that the mixing was modulated by internal tides was seen in regions of both high and low eddy kinetic energy, and it was more significant with high eddy kinetic energy. The presence of high eddy kinetic energy enhanced the response of  $K_z$  to internal tides, especially for the  $M_2$  internal tide. The increased rate of  $K_z$  with internal tides in the high EKE field was higher than that in the weak EKE field. The existence of mesoscale features changed the vertical structure of internal tides, and transferred the internal tides energy from low modes to higher modes. It was more likely to cause internal tide breaking (Dunphy and Lamb 2014). The enhancement by mesoscale motions to tidal mixing was more significant for  $M_2$  internal tides. Anticyclonic eddies were more likely to increase tidal mixing in the upper ocean. While the influence of cyclonic eddies to tidal mixing was slightly higher than that of anticyclonic ones in the deep ocean.

There are several mechanisms that might explain the elevated tidal mixing in the presence of energetic mesoscale environment. The vertical scales of internal tide can be reduced and the energy of internal tide can be amplified near the surface in the presence of energetic mesoscale features. When internal tide passes through mesoscale eddy, the energy of mode-1 internal tide can be refracted and transmitted to higher-mode waves (eg. Ferrari and Wunsch, 2008, Henning and Vallis, 2004). The eddy flows can also directly increase vertical shear and subsequently internal tide energy dissipation rate (eg. Chavanne et al., 2010, Dunphy, 2014). The anticyclones induce higher tidal mixing than do cyclones probably because of the Chimney effects associated with distinct vorticities (Jing and Wu, 2011).

This paper explores the modulation of the mesoscale environments on tide-induced mixing statistically through ARGO float observations by some observed dataset. Theoretical clarification of the driving mechanisms is needed. Some previous numerical studies can explain our conclusion to some extent. However, how and to which extent the vorticity alter internal tide evolution and induced mixing have not been clearly explained in theory. Moreover, the latitude range from 9°N to 36°N are discussed in this work due to the limitations of the fine scale parameterization method in equatorial areas. The influence

of the equatorial background flows on ocean mixing remains to be solved.

**Code and data availability.** The ARGO data (<ftp://ftp.argo.org.cn/pub/ARGO/global/>) set were made available by China Argo Real-time Data Center (Li Zhaoqin et al., 2019). The near surface 10 m wind speed was product by ERA-Interim dataset (<https://www.ecmwf.int/en/forecasts/datasets>). The geostrophic velocity were taken from the AVISO (<http://www.aviso.altimetry.fr/duacs/>). The internal tidal conversion rate was provided by SEANOE (<https://www.seanoe.org/data/>, C.de Lavergne et al., 2019). The corresponding data and codes are available on request to Zhenhua Xu by email.

**Author contribution.** The concept of this study was developed by Zhenhua Xu and extended upon by all involved. Jia You implemented the study and performed the analysis with guidance from Zhenhua Xu, Qun Li and Robin Robertson. Peiwen Zhang and Baoshu Yin collaborated in discussing the results and composing the manuscript.

**Competing interests.** The authors declare that they have no conflict of interest.

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