



# Article Suppressed Thermocline Mixing in the Center of Anticyclonic Eddy in the North South China Sea

Yongfeng Qi <sup>1,2</sup>, Huabin Mao <sup>1,3,4,\*</sup>, Xia Wang <sup>1,2</sup>, Linhui Yu <sup>1,2</sup>, Shumin Lian <sup>1,2</sup>, Xianpeng Li <sup>1</sup> and Xiaodong Shang <sup>1,2,4</sup>

- Key Laboratory of Science and Technology on Operational Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China; yfqi@scsio.ac.cn (Y.Q.); wangxia@scsio.ac.cn (X.W.); lhyu@scsio.ac.cn (L.Y.); smlian@scsio.ac.cn (S.L.); lixianpeng@scsio.ac.cn (X.L.); xdshang@scsio.ac.cn (X.S.)
- <sup>2</sup> State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China
- <sup>3</sup> Ocean College, Zhejiang University, Zhoushan 316021, China
- <sup>4</sup> Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou 511458, China
- \* Correspondence: maohuabin@scsio.ac.cn

**Abstract**: Direct microstructure observations and fine-scale measurements of an anticyclonic mesoscale eddy were conducted in the northern South China Sea in July 2020. An important finding was that suppressed turbulent mixing in the thermocline existed at the center of the eddy, with an averaged diapycnal diffusivity at least threefold smaller than the peripheral diffusivity. Despite the strong background shear and significant wave–mean flow interactions, the results indicated that the lack of internal wave energy in the corresponding neap tide period during measurement of the eddy's center was the main reason for the suppressed turbulent mixing in the thermocline. The applicability of the fine-scale parameterization method in the presence of significant wave–mean flow interactions in a mesoscale eddy was evaluated. Overprediction via fine-scale parameterization results were consistent with microstructure observations along the eddy's periphery, where active internal waves existed. This indicates that the strong background shear and wave–mean flow interactions affected by the mesoscale eddy were not the main contributing factors that affected the applicability of fine-scale parameterization in the northern South China Sea. Instead, our results showed that the activity of internal waves is the most important consideration.

**Keywords:** fine-scale parameterization; mesoscale eddy; mixing; Richardson number; wave-mean flow interaction

# 1. Introduction

Oceanic mesoscale eddies, which play an important role in dynamical oceanography across a range of scales [1,2] and are key transporters of oceanic materials [3–7], are ubiquitous on a global scale [8]. Mesoscale eddies contain more than 90% of the ocean's kinetic energy; they play important roles in ocean energy distribution and the regulation of ocean mixing processes [7,9–12]. Turbulence microstructure observation is the most direct and effective method for studying the mixing processes of ocean mesoscale eddies; however, few microstructure observation datasets are available, which is not conducive to in-depth analyses of the interaction mechanism between mesoscale eddies and ocean-mixing. The fine-scale parameterization method is a promising alternative.

Fine-scale parameterization, built on the wave–wave interaction theory [13], facilitates exploration of the distribution of turbulent mixing in the open ocean [14–17]; hydrographic data derived by conductivity-temperature-depth (CTD) profilers are much easier to work with, compared with previous datasets. The use of fine-scale parameterization of turbulent dissipation by internal wave breaking, which consists of predictions regarding the



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). turbulent kinetic energy (TKE) dissipation rate from internal wave shear and strain on wavelengths of tens to hundreds of meters [13], has experienced explosive growth over the past 20 years [16,18–26]. Fine-scale parameterization is also one of the main methods used to study ocean mixing variation regulated by mesoscale eddies. Zhang et al. [27] applied fine-scale parameterization, together with a Richardson number (*Ri*)-based parameterization method developed by Liu et al. [11], to study latitude-dependent turbulent mixing in the west Pacific Ocean. They found that elevated diffusivities exist at 20–22°N, because of the anticyclonic eddy's inertial chimney effect. Jing and Wu [28] used fine-scale parameterization to study the modulation of turbulent diapycnal mixing by anticyclonic eddies in the sea surrounding Hawaii; they revealed that enhanced diapycnal mixing occurs under anticyclonic eddies in the upper 300–600 m, with a mean dissipation rate that is approximately half the rate present under eddy-free conditions.

However, in some instances, the application of fine-scale parameterization may be subject to restrictions. Errors in the outcomes of fine-scale parameterization may be caused by conditions such as nonlocal spectral transports associated with wave breaking, competition with wave-mean driven spectral transports, boundary conditions short-circuiting the downscale energy transfer, nonlocal spectral transports associated with resonant interactions, and stress-driven boundary layers [13]. For example, Liu et al. [11] reported that the diffusivity estimated from fine-scale parameterization considerably deviated from microstructure observations in the North Pacific's low-latitude western boundary current system, where internal wave breaking is weak. Waterman et al. [29] found that overestimates resulting from fine-scale parameterization exist with significant wave-mean flow interactions. Liang et al. [30] revealed that fine-scale parameterization fails to predict the turbulence over rough topography; this was attributed to deviation of the internal wave spectrum from the Garrett-Munk (GM) spectrum.

With respect to mesoscale eddies, which are often accompanied by strong vertical background shear and eddy-induced significant wave-mean flow interactions, there has been minimal attention toward the applicability of fine-scale parameterization. Observational and modeling studies have revealed that the South China Sea, one of the largest marginal seas in the Pacific Ocean, has abundant strong eddy and internal wave activities [7,31–35]. Thus, this area serves as an ideal testbed for investigating the fine-scale parameterization method in the context of significant wave-mean interactions and shear instability of background flows affected by mesoscale eddies.

In this study, we examined the structural characteristics of high spatial resolution turbulent microstructures, with the aim of revealing the mechanism of the spatial distribution characteristics of turbulent mixing. By comparing the results obtained through microstructure observations and fine-scale parameterization, this paper expounds on whether the fine-scale parameterization method is suitable for background flow shear and wave-mean flow interactions accompanied by mesoscale eddies. This paper is organized as follows. Field observations, including the instruments used and their setups, are described in Section 2. The main results are presented in Section 3, and a detailed discussion and summary are provided in Section 4.

#### 2. Materials and Methods

#### 2.1. Observations

The observations were carried out in the northern South China Sea between 11 and 14 July 2020. The main objective of the observations was to investigate the mixing processes of an anticyclonic eddy. In total, 50 stations were positioned over the study area (Figure 1). During the observations, one Seabird 9-11 Plus CTD was used to collect fine-scale temperature and salinity data. The CTD data were processed in accordance with standard procedures, as recommended by the instrument manufacturer, and the bin was averaged to 2 m resolution. A shipborne broadband acoustic Doppler current profiler (ADCP; 150 kHz; Teledyne RD Instruments, Poway, CA, USA) operated continuously during the cruise, providing information on the velocity of the water column in the upper layer at

approximately 400 m. The 8 m bin size was adopted for the shipboard ADCP, and the sampling interval was set to 1 min. Thus, one ensemble was captured each minute. Microstructure velocity shear data were obtained using a turbulence microstructure profiler (VMP-250). The VMP-250 was equipped with a pressure transducer, one temperature sensor, and two shear probes, thereby allowing simultaneous measurements of the pressure, temperature, and microstructure shear while free descending at a speed of 0.6–0.8 m/s.



**Figure 1.** Sea level anomaly (SLA) along with the surface geostrophic flow in the South China Sea during field observations. The SLA data were produced by SSALTO/DUACS and distributed by AVISO (with support from the Centre National d'Etudes Spatiales). Green dots indicate the observed locations, where both fine-scale and microstucture measurements were carried out; black dots indicate the anticyclonic eddy.

During the measurement period, the sea surface wind was recorded by an automatic weather station that had been mounted on the ship at approximately 15 m above the sea surface. The wind was southwesterly at <7 m/s during the observation period; thus, the sea surface wind field had little effect on our observations.

#### 2.2. Methods

# 2.2.1. Turbulence from VMP-250

The shear probes in the VMP-250 profiler measured high-frequency velocity fluctuations, which were used to calculate the local turbulent dissipation rate. The TKE dissipation rate was estimated using the following isotropic formula:

$$\varepsilon = \frac{15}{2}\nu\left(\frac{\partial u}{\partial z}\right) = \frac{15}{2}\nu\int_0^{k_{max}}\psi(k)dk,\tag{1}$$

where v is the kinematic molecular viscosity and the overline indicates a spatial mean; u is either one of the two horizontal velocity components; z is the vertical coordinate;  $\psi(k)$  is the vertical shear spectrum; and k is the vertical wavenumber [36]. The upper integration limit,  $k_{max}$ , is variable.  $k_{max}$  was calculated using the method recommended by Shang et al. [37], which applies the smallest values, in that the lowest frequency at which the shear signal is corrupted by vibrations; the wavenumber of 150 cpm owing to the shear probe spatial resolution; the cutoff frequency of the used antialiasing filter; an estimation of

4 of 16

wavenumber using the Lueck's method [38], which parses 90% of shear variance according to the Nasmyth spectrum; or the location of minimum value of spectrum determined the low-order fitting of the spectrum in the log-log space. Diapycnal diffusivity (Osborn, 1980) is calculated based on the dissipation rate ( $\varepsilon$ ) and stratification, as follows:

$$\kappa_{\rho} = \Gamma \frac{\varepsilon}{N^2},\tag{2}$$

where  $\Gamma$  is the mixing efficiency, which was set to 0.2. The stratification was calculated as  $N^2 = -\frac{g}{\rho} \frac{\partial \rho}{\partial z}$ , where *g* is the acceleration caused by gravity.

#### 2.2.2. Fine-Scale Parameterization of Turbulence

In the absence of a turbulent microstructure observation, Gregg–Henyey–Polzin (GHP) fine-scale parameterization is one of the most widely used methods for assessing ocean turbulence from the easier obtained CTD data [15,22]. The GHP scaling was first developed by Henyey et al. [39] and is based on the theory of internal wave–wave interaction. Here, the GHP parameterization was employed to qualify the diapycnal diffusivities from CTD observations for a comparison with VMP-250 observations. The GHP is expressed as follows:

$$\kappa_{\rho} = \kappa_0 \frac{\langle \xi_z^2 \rangle^2}{\langle \xi_z^2 \rangle_{GM}^2} h(R_w) j\left(\frac{f}{N}\right),\tag{3}$$

$$h(R_w) = \frac{1}{6\sqrt{2}} \frac{R_w(R_w + 1)}{\sqrt{R_w - 1}}, \text{and}$$
(4)

$$j\left(\frac{f}{N}\right) = \frac{f \operatorname{arccosh}(N/f)}{f_{30}\operatorname{arccosh}(N_0/f_{30})},$$
(5)

where  $\langle \xi_z^2 \rangle$  represents the observed fine-scale internal wave strain variance, and  $\langle \xi_z^2 \rangle_{GM}^2$  is the strain variance of the GM spectrum [40,41]. Compared with microstructure observations,  $\kappa_0 = 0.15 \times 10^{-6} \text{ m}^2/\text{s}$  was found to be most appropriate for this study; this is much smaller than the values proposed by Kunze et al. [22]. In the GM model, an open-ocean internal wave-field was assumed at a fixed buoyancy frequency ( $N_0 = 5.2 \times 10^{-3} \text{ s}^{-1}$ ) and a latitude of  $30^{\circ}$ . The functions N and f are the buoyancy and Coriolis frequencies, respectively;  $R_{\omega}$  is the variance ratio of shear/strain, which was set to a mean value of 7, as suggested by Kunze et al. [22] in the open ocean and used by Yang et al. [42] in the South China Sea. To quantify the observed strain  $\langle \xi_z^2 \rangle$ , the CTD profiles were first separated into segments of half-overlapping 300 m long, beginning from the maximum depth and excluding the data in the surface mixed layer. The strain was estimated from buoyancy frequency  $\xi_z = (N^2 - \overline{N^2}) / \overline{N^2}$ , where mean stratification  $\overline{N^2}$  is based on quadratic fits to each buoyancy frequency segment. Strain variance was obtained as  $\langle \xi_z^2 \rangle = \int_{min(k_z)}^{max(k_z)} S[\xi_z](k_z) dk_z$ . In order to calculate the strain variance, the minimum integrated wavenumber of 0.042 rad/m was used, which corresponded to the vertical wavelength of  $\lambda_z = 150$  m to be the lower wavenumber; however, this wavenumber may be influenced by strong background stratification in the pycnocline [22,28]. The maximum integrated wavenumber was set to 0.419 rad/m, corresponding to a vertical wavelength of  $\lambda_z = 15$  m. The GM strain variance was calculated over the same wavenumber band, i.e.,

$$\langle \xi_z^2 \rangle_{GM}^2 = \frac{\pi E_0 b j_*}{2} \int_{min(k_z)}^{max(k_z)} \frac{k^2}{\left(k + k_*\right)^2} dk_z,\tag{6}$$

where  $E_0 = 6.3 \times 10^{-5}$  is the dimensionless energy level; b = 1300 m is the scale depth of the thermocline;  $j_* = 3$  is the reference mode number; and  $k_* = (\pi j_* N)/(bN_0)$  is the reference wavenumber.

# 3. Results

# 3.1. Water Mass Characteristics of the Studied Eddy and Its Origin

The vessel sufficiently transited the center of the anticyclonic eddy (Figure 1) to study the eddy's structure. The observations were carried out during the summer season in which the thickness of the surface mixed layer was less than 50 m (Figure 2a,b); this was smaller than the thickness reported during the winter [10]. In an anticyclonic eddy, the warm water in the upper layer accumulates in the center; thus, the mixed layer and thermocline increase in the center of the eddy. The bottom of the thermocline had deepened by approximately 40 m. Here, the surface mixed layer was identified as the depth at which the potential temperature varied by less than 0.5 °C, and the thermocline was calculated as the depth at which the potential density varied by less than  $0.03 \text{ kg/m}^3$ .



**Figure 2.** (**a**,**b**) Observed potential temperature ( $\theta$ ) and salinity (*S*). Black solid lines indicate the surface mixed layer and dotted lines indicate the bottom of the thermocline. (**c**)  $\theta$ -*S* diagram showing the water mass within the eddy (center region) and outside of the eddy (periphery region).  $\theta$ -*S* diagrams depict the Kuroshio Current and the north South China Sea. (**d**) Sea surface wind speed measured by an automatic weather station that was mounted on the ship above the sea surface at approximately 15 m.

To determine the origin of the studied anticyclonic eddy, historical salinity and temperature data derived from the Argo Data Center for the Kuroshio Current in the northern South China Sea (17°–20° N, 114°–117° E) and the Pacific (19°–22° N, 121°–122.5° E) were compared to in situ T/S data (Figure 2c). The historical profiles of the northern South China Sea and the Kuroshio Current were derived by averaging 2443 data profiles and 654 data profiles, respectively. A comparison of the water mass characteristics from within the eddy and outside of the eddy, as well as historical data from the northern South China Sea and Kuroshio Current, revealed a notable feature—the upper layer of water within the eddy did not significantly differ from the upper layer of water outside of the eddy (both to the left and right of the eddy) or from the upper layer of water from the northern South China Sea. This indicates that the studied anticyclonic eddy originated in the northern South China Sea. In this study, the "center" of the eddy was defined as the area satisfying the criteria proposed by Chelton et al. [8]. The area outside of the "center" was designated as the periphery region. Assessment of its moving path revealed that the study anticyclonic eddy appeared at a location 100 km southwest before moving slowly to the observation position (data not shown); there were no significant differences in the in situ plots within and outside of the eddy (Figure 2c).

In the mixed layer, the salinity data showed active sub-mesoscale eddies, with a spatial scale of approximately 10 km in the periphery (Figure 2b). We will elaborate on this in another study. Here, our focus was the mixing process in the thermocline.

#### 3.2. Turbulence of the Microstructure Measurement

In open oceans worldwide, turbulence is typically enhanced in the surface mixed layer because of wave breaking, surface wind stirring, and positive buoyancy fluxes in the surface, even in the presence of calm weather conditions. It was particularly calm, with wind speed at 15 m above the sea surface less than 7 m/s during the observation (Figure 2d). This is clearly reflected by the microstructure observed turbulent dissipation rate in the surface mixed layer; notably, the strong TKE dissipation rate was confined to a depth within 10 m from the sea surface. Thus, this study concentrates on the spatial variation of turbulent mixing in the thermocline, in which the dissipation rate and the diffusivity of the center location were compared with those parameters along the periphery of the eddy.

In the thermocline, the stable density stratification suppresses the turbulence; thus, it is generally weaker than the turbulence in the mixed layer. In this study area, the vertical temperature gradient controlled the stratification (Figure 2a). The vertical salinity gradient produces negative and positive contributions below and above the maximum salinity, respectively (Figure 2b).

The observed turbulent dissipation rates and diffusivities across the section below the surface mixed layer are shown in Figure 3. To facilitate understanding of the observed mixing, flows in latitudinal (Figure 3a) and stratification (Figure 3e) at the transect are displayed, along with estimates of the shear squared (Figure 3c) and the gradient Richardson number ( $Ri = N^2/S^2$ , where  $S^2$  is the magnitude of the shear squared; Figure 3b). The zonal velocity measured by the shipborne ADCP displayed obvious eddy structure characteristics, with northward flow to the left side and southward flow to the right side of the anticyclonic eddy (Figure 3a). Based on the velocity data, the derived shear squared value and Ri were used to resolve the spatial variation characteristics. A clear relationship was evident between the enhanced turbulence and low Ri (Figure 3b,d,f). From these results, we concluded that the general features of flow stability was reflected by the estimated Ri in the study; moreover, the shipboard ADCP measured currents can be referred to during analysis of the observed characteristics of turbulence and mixing.

In terms of thermoclines, it is evident from Figure 3d,f that turbulent dissipation and mixing were both weaker at the center than in the peripheral area. The TKE dissipation rate  $\varepsilon$  mostly comprised  $O(10^{-9})$  W/kg, and the diapycnal diffusivity  $\kappa_{\rho}$  mostly comprised  $O(10^{-5})$  m<sup>2</sup>/s, which are the mean values of thermocline turbulence and mixing in oceans worldwide [43,44]. To more clearly show the characteristics of the turbulence spatial patterns, all variables in Figure 3 display the mean variation of the thermocline with longitude. Figure 4d shows that the smallest  $\varepsilon$  at the center was  $6 \times 10^{-10}$  W/kg, while the largest  $\varepsilon$  at the periphery of the eddy reached  $1 \times 10^{-8}$  W/kg. Accordingly, the smallest averaged  $\kappa_{\rho}$  at the center was  $2 \times 10^{-6}$  m<sup>2</sup>/s, while the largest  $\kappa_{\rho}$  at the edge was approximately two orders of magnitude larger. On average, the  $\varepsilon$  values at the center and in the periphery were  $1.3 \times 10^{-9}$  W/kg and  $3 \times 10^{-9}$  W/kg, respectively. The mean  $\kappa_{\rho}$  values were  $6 \times 10^{-6}$  m<sup>2</sup>/s at the center and  $2 \times 10^{-5}$  m<sup>2</sup>/s along the periphery. Similar patterns with elevated mixing at the periphery of the mesoscale eddy were found in the surface mixed layer [10]. In this study, the elevated mixing in the thermocline at the periphery of the eddy is shown.



**Figure 3.** Measured variability along the transect. (**a**–**f**) The shipborne acoustic Doppler current profiler (ADCP) measured meridional velocity (v), the inverse gradient Richardson number ( $Ri^{-1}$ ), the shear squared ( $S^2$ ), the TKE dissipation rate ( $\varepsilon$ ), the squared buoyancy frequency ( $N_2$ ), and the diapycnal diffusivity ( $\kappa_\rho$ ), respectively. Solid and dashed lines show bottom of mixed layer and thermocline, respectively.

The suppression of turbulence and mixing in the thermocline at the center is also reflected in the distribution of Ri, which is exhibited in terms of  $\log_{10}(Ri^{-1}/4)$  in Figure 3b and the mean Ri in Figure 4b. Here, the critical value of Ri, 0.25, is used to quantify the shear instability of water [43], of which the  $\log_{10}(Ri^{-1}/4)$  relates to 0. Overall, Ri was much larger than 0.25 in the thermocline at the center, usually by at least one order of magnitude; however, it decreased sharply in the periphery of the eddy, particularly along its east edge (Figure 3b), because of strong eddy-induced velocity shear (Figure 3c). This feature is displayed more clearly in the Ri and averaged squared shear (Figure 4b,c), which exhibited stronger shear and smaller Ri along the edge. There was an apparent trend whereby both  $\varepsilon$  and  $\kappa_{\rho}$  varied inversely with Ri (Figure 4b,d,f).

#### 3.3. Fine-Scale Parameterization of Turbulence under the Influence of a Mesoscale Eddy

Considering that microstructure measurements are generally scarce and difficult to obtain, fine-scale parameterization of the turbulence is the common approach used to study the mixing process of mesoscale eddies. Using the fine-scale parameterization method, studies have reported several-fold elevations of diffusivity within the anticyclonic eddy [12,45]. However, this contrasts with the results of our microstructure measurements, which indicated weak mixing at the center of the eddy. To understand the potential discrepancy, while verifying the applicability of the GHP parameterization scheme in the context of shear instability and strong wave-mean interaction, comparisons between the measurements from microstructure and estimates from fine-scale parameterization for the



averaged diapycnal diffusivity ( $\kappa_{\rho \text{ GHP}}$ ) in the thermocline at all of our observation sites were analyzed.

**Figure 4.** Averaged variability of the thermocline. (**a**–**f**) The shipborne acoustic Doppler current profiler (ADCP) measured meridional velocity (*v*), the inverse gradient Richardson number ( $Ri^{-1}$ ), the shear squared ( $S^2$ ), the TKE dissipation rate ( $\varepsilon$ ), the squared buoyancy frequency ( $N_2$ ), and the diapycnal diffusivity ( $\kappa_\rho$ ), respectively. In (**f**), the eddy center is marked.

The comparisons are shown in Figure 5. At some sites, the consistency was found between the two estimates that fall within a factor of 2; however, a considerable proportion of  $\kappa_{\rho \text{ GHP}}$  was generally biased when estimated by fine-scale parameterization, such that two stations showed overestimation by more than one order of magnitude. There were differences in the comparisons between GHP parameterization and microstructure observations of the center and periphery of the eddy. In the periphery region, the ratio of  $\kappa_{\rho \text{ GHP}}$  to  $\kappa_{\rho \text{ vmp}}$  was near the 1:1 line, whereas in the center region, the  $\kappa_{\rho \text{ GHP}}$  appeared to partially overestimate  $\kappa_{\rho \text{ vmp}}$ . This may explain the discrepancies observed in our comparisons; however, the overestimation appears to be a robust feature. Thus, fine-scale parameterization may be invalid for the within-eddy region, while it is valid along the periphery of the eddy where shear instability conditions are ubiquitous (Figure 3b).



**Figure 5.** Comparison of thermocline-averaged diapycnal diffusivity ( $\kappa_\rho$ ) between microstructure measurements and fine-scale estimates for the for all stations. Red and black dots indicate comparisons at the center and along the periphery of the eddy, respectively. Agreements within factors of 2 and 10 are specified by the gray bands. Bars in the figure present the 95% bootstrapped confidence intervals for the estimates from microstructure measurements.

## 4. Discussion

# 4.1. Potential Mechanism for Suppressed Mixing within the Eddy in the Thermocline

Our results have shown suppressed mixing in the thermocline within the anticyclonic eddy, which conflicts with the findings of previous studies [12,45]. Cyriac et al. [12] reported a larger dissipation rate and diffusivity within anticyclonic eddy than that in cyclonic eddy in the Indian Ocean. Yang et al. [45] also revealed that, compared with cyclonic eddy and background turbulence, elevated diffusivity existed within an anticyclonic eddy in the South China Sea. That means enhanced turbulence within anticyclonic eddy is recognized by many scientists. Thus, it is important to reveal why mixing is inhibited in our study. The South China Sea is a sea area with strong turbulent mixing [46,47]; an important energy source is the Luzon Strait, where the barotropic tide interacts with the bottom topography to produce a large number of internal waves [48–50]. These internal waves in the South China Sea provide an important energy source for turbulent mixing. Therefore, the intensity of mixing in the northern South China Sea is presumed to be closely related to the amplitude of the barotropic tide.

Microstructure measurements at different stations were collected at different times; thus, the measurement time may be one of the factors that affect the variability of  $\varepsilon$  in the thermocline. Strong turbulent mixing generally occurs during spring tides, while weak mixing occurs during neap tides [51]. Thus, it is possible that microstructure measurements within the eddy were collected during the neap progression. To rule out this possibility, we obtained barotropic tide data from the global inverse tide model (TPXO; [52]), which included the time information of spring–neap tides during the observation period. Only the barotropic tides at 18.5° N and 115° E were extracted, because the bias in the arrival of the spring–neap tides in different locations of the South China Sea is small ( $\leq$ 3 h). Because the amplitude of the barotropic tide in the northern South China Sea is mainly affected by the diurnal tide, only the amplitudes of K<sub>1</sub> and O<sub>1</sub> were considered. The 14-day spring–neap cycles were adequately represented in the extracted barotropic tide data (Figure 6a). The microstructure measurements were collected during the neap tide period. A comparison of averaged  $\varepsilon$  and  $\kappa_{\rho}$  in the thermocline with the extracted tides suggests that suppressed turbulent mixing in the study was closely related to the measurement period, such that the lower amplitude of the barotropic tide provided less energy for turbulent mixing.



**Figure 6.** (a) Time series of the barotropic tidal velocity (u<sub>bt</sub>) predicted from TPXO 7.1 [52] with the station symbols overlain. (b,c) The time variations in the mean dissipation rate and diffusivity in the thermocline.

The predominant propagation and degeneration of the internal wave from the LS region is the main known source of internal waves in the northern South China Sea [53–55]. The dissipation rate reportedly has a linear relationship with the available potential energy (APE) of the internal wave [56]. In our study, strong background shear and shear instability were found at the periphery of the eddy. It remains unknown whether the strong shear absorbs the energy of the mesoscale eddy, effectively destroying the abovementioned linear relationship.

To solve this problem, we examined the APE of the internal wave per unit mass,  $P_{IW} = 1/2\eta_{th}^2 \langle N_{th}^2 \rangle$ . Although the APE calculation is based on the linear theory of internal waves [57], it has been successfully applied in many nonlinear internal wave studies [58]. The wave displacements  $\eta_{th}^2$  were calculated as the root mean square of the density disturbances  $\rho'(z) = \rho'(z) - \tilde{\rho}(z)$  divided by the mean density gradients in selected layers of the pycnocline [59]. Here,  $\tilde{\rho}(z)$  is the low-pass density profile filtered with a cutoff wavelength of 40 m [56]. Figure 7a shows the change in observed  $P_{IW}$  with longitude.  $P_{IW}$  was weak at the center of the eddy and increased towards the periphery. This change in the trend is consistent with spatial changes in the dissipation rate and diffusivity (Figure 4d,f), as well as the change in the internal tide amplitude (Figure 6a). Thus, there is an approximate linear relationship between  $P_{IW}$  and the averaged  $\varepsilon$  in the thermocline, indicating that the breaking of internal waves directly provides an energy source for dissipation at both the periphery and center of the study mesoscale eddy.



**Figure 7.** (a) Spatial variation in the available potential energy (APE) of internal waves ( $P_{IW}$ ) in the thermocline. (b) Averaged dissipation rate in the thermocline vs.  $P_{IW}$ . Black dashed line in (b) indicates linear regression.

In the ocean, the sub-mesoscale dynamic process is an important bridge between the mesoscale eddy and turbulence. Elevated mixing in the surface mixed layer at the periphery of the eddy is usually found and supplied by sub-mesoscale eddies [10], which develop from the baroclinic instability of the mixed layer [60]. However, it is difficult to observe the sub-mesoscale eddy in the thermocline. The activity of the sub-mesoscale eddy can be identified by analyzing the horizontal wavenumber spectrum of velocity (spectrum slope using a scale rate of -2) and the Rossby number [ $Ro \sim O(1)$ ]. In this study, the slope of the horizontal wavenumber spectrum of velocities in the thermocline was approximately -3, and the Rossby number was much smaller than 1 in both the periphery and center of the eddy (data not shown). Our findings indicated that the elevated turbulent mixing in the thermocline in the periphery of the eddy was not furnished by the sub-mesoscale eddy.

# 4.2. Relationship between the Fine-Scale Parameterization Results and Wave–Mean Flow Interactions

As mentioned in the Introduction, the use of fine-scale parameterization under specific conditions may cause some deviation. In this study, the GHP results tended to overestimate the microstructure measurements in the center of the eddy (Figure 5). That overestimation is most likely related to specific background flow characteristics; thus, the wave–mean flow interaction plays a significant role in fine-scale overprediction.

The Froude number,  $Fr = \overline{U_z}/N$ , was calculated to explore the relationship between the fine-scale parameterization results and wave-mean flow interactions. In the spectral energy transmission in vertical wavenumber space, Fr can weigh the wave-mean flow interactions relative to the nonlinear wave-wave interactions [29]. Here,  $\overline{U_z}$  is the vertical shear estimated from the shipborne ADCP data that were smoothed by a sliding polynomial fit on a vertical scale of 100 m. The overprediction of fine-scale parameterization shows a systematic correlation with the value of Fr in the thermocline, comprising a larger Frwith larger overprediction (Figure 8a). The tendency for fine-scale overprediction to be associated with Fr of O(0.1) and greater, and the positive linear trend of the  $\kappa_{\rho}$  ratio, suggest that wave-mean flow interactions play a supporting role in the observed overpredition of fine-scale parameterization in the center region of this study. Although the Fr in the center of the eddy is in the order of 0.1, this order of magnitude is sufficiently large for wave-mean flow interactions to play a significant role in the wave dynamics [13,29].



**Figure 8.** (a) Ratio of fine-scale parameterization estimated diffusivity ( $\kappa_{\rho \text{ GHP}}$ ) to VMP-250 observed diffusivity ( $\kappa_{\rho \text{ vmp}}$ ) vs. the Froude number (*Fr*). (b) Spatial-variation of *Fr*.

Notably, *Fr* was larger along the periphery of the eddy than in the center (Figure 8b), indicating that wave–mean interactions were more significant. However, a positive correlation linear trend of the  $\kappa_{\rho}$  ratio with respect to *Fr* could not be resolved in the periphery region. Therefore, it is reasonable to infer that, although the wave–mean flow interaction is strong, the GHP parameterization method retains the ability to calculate the correct diffusivity in the region where the internal wave is sufficiently active, similar to the scenario involving the periphery region in our measurements. When the internal wave is inactive, the influence of wave–mean flow interactions on the GHP parameterization method will be highlighted, similar to the center region in the present study. The fundamental reason for these findings is that the GHP method was developed based on the theoretical basis of the wave–wave interaction [22].

#### 4.3. Scaling Thermocline Mixing with the Richardson Number

The results of the present study suggest that weak background mixing in the center of the anticyclonic eddy is preserved by the reduced internal waves breaking with weak APE during the neap tide period (Figures 6 and 7). The mixing may elevate locally because of strong shear; this is presumably associated with the prominent dynamic features of the eddy and cannot be ignored. As mentioned earlier, a clear relationship was established between the enhanced (inhibited) turbulence and low (high) *Ri*; this was demonstrated in Figure 4b,d,f. According to Liu et al. [11], who modeled the observed diffusivity  $\kappa_{\rho}$  with *Ri*:

$$\kappa_{\rho} = \kappa_0 + \kappa_m \left( 1 + \frac{Ri}{Ri_c} \right)^{-1},\tag{7}$$

where  $Ri_c = 0.25$  is the critical Ri value due to shear instability,  $\kappa_0$  is the background diffusivity, and  $\kappa_m$  is the maximum diffusivity corresponding to a vanishing Ri. Both  $\kappa_0$  and  $\kappa_m$  are determined from the data. Although the original data were scattered, the bin-averaged data showed an obvious decreasing tendency of  $\kappa_\rho$  with increasing Ri (Figure 9). Application of a nonlinear least squares regression to the bin-averaged data provided values of  $\kappa_0 = 5.1 \times 10^{-6} \text{ m}^2/\text{s}$  and  $\kappa_m = 1.4 \times 10^{-4} \text{ m}^2/\text{s}$ . This  $\kappa_0$  was larger than the value estimated by Liu et al. [11], who derived  $\kappa_0 = 2.1 \times 10^{-6} \text{ m}^2/\text{s}$  in the low latitudes of the Pacific Ocean. It is not difficult to understand, because our observations were performed at a higher latitude. The  $\kappa_m$  in this study was slightly smaller. The 95% confidence intervals of the model predictions are also shown in Figure 9 as red dots. Here, a majority of the bin-averaged data fall within the confidence intervals, meaning that the above analytical model adequately approximated the observations. Furthermore, the estimated value of  $\kappa_0$  was similar to the observed background diffusivity from VMP-250 (Figure 4).



**Figure 9.** Microstructure observed diffusivity ( $\kappa_{\rho}$ ) versus *Ri* for all estimates in the thermocline, with original (gray symbols) and bin-averaged samples (black symbols). Red solid line shows the nonlinear least squares regression to the bin-averaged data, with 95% confidence intervals indicated by red dotted lines.

# 5. Conclusions

This study reports on turbulence microstructure measurements of turbulent mixing across an anticyclonic eddy in the northern South China Sea. Thermocline turbulence and mixing were found to be weak at the center of the eddy, with a mean TKE dissipation rate of  $1.3 \times 10^{-9}$  W/kg and a diapycnal diffusivity of  $6 \times 10^{-6}$  m<sup>2</sup>/s. Elevated mixing was found at the periphery, with a diffusivity threefold larger than the diffusivity at the center. The spatial variation of the mixing was positive, consistent with the change in the APE of the internal wave and the change in the background shear. From these findings, we conclude that the lack of internal wave energy in the corresponding neap tide period during the center eddy measurements is the main reason for the spatial structure of mixing in the thermocline.

Under the influence of an anticyclonic eddy, *Fr* (the ratio of the background shear to the buoyancy frequency) indicated that the wave–mean flow interactions both in the center and in the periphery of the eddy have significant roles in the wave dynamics. These significant wave–mean flow interactions may lead to error in the outcomes of fine-scale parameterizations. In the thermocline, overprediction of fine-scale parameterization outcomes existed at the eddy center when and where the internal waves were inactive; however, the results were consistent with microstructure observations along the eddy's periphery in the vicinity of active internal waves. Thus, the strong background shear and wave–mean flow interactions affected by the mesoscale eddy were not responsible for effects on the applicability of fine-scale parameterization. Instead, the activity of the internal wave was the most important factor. Concerning the error of fine-scale parameterization, the Richardson number-based model proposed by Liu et al. [11] is another alternative for parameterizing the thermocline turbulence in the center of the eddy.

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