Elevated Mixing in the Periphery of Mesoscale Eddies in the South China Sea

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ABSTRACT

Direct microstructure observations across three warm mesoscale eddies were conducted in the northern South China Sea during the field experiments in July 2007, December 2013, and January 2014, respectively, along with finestructure measurements. An important finding was that turbulent mixing in the mixed layer was considerably elevated in the periphery of each of these eddies, with a mixing level 5–7 times higher than that in the eddy center. To explore the mechanism behind the high mixing level, this study carried out analyses of the horizontal wavenumber spectrum of velocities and spectral fluxes of kinetic energy. Spectral slopes showed a power law of $k^{-2}$ in the eddy periphery and of $k^{-3}$ in the eddy center, consistent with the result that the kinetic energy of submesoscale motion in the eddy periphery was more greatly energized than that in the center. Spectral fluxes of kinetic energy also revealed a forward energy cascade toward smaller scales at the wavelength of kilometers in the eddy periphery. This study illustrated a possible route for energy cascading from balanced mesoscale dynamics to unbalanced submesoscale behavior, which eventually furnished turbulent mixing in the upper ocean.

1. Introduction

The South China Sea (SCS) is a large marginal sea located west of the tropical Pacific Ocean. There is significant, high-level turbulent mixing compared with its neighboring Pacific Ocean; hence, the SCS has a remarkable effect on modifications of water mass and circulation both locally and remotely in the Pacific Ocean (Tian et al. 2009; Zhao et al. 2014; Yang et al. 2016). Many studies were carried out to explore the ocean processes that are responsible for this intensified mixing in the SCS.

Various processes are known to provide energy for mixing in the SCS from shallow shelf to deep water. Convection caused by solar radiation is mainly responsible for diurnal variability of mixing in the mixed layer (e.g., Yang et al. 2014b). There are many internal solitary waves in the northern SCS (e.g., Zhao et al. 2004; Klymak et al. 2006; Lien et al. 2014), which contribute to mixing in the shallow continental shelf of the SCS. In the deep water, internal solitary waves do not break; so, they do not directly provide energy for mixing. When propagating westward to the shelf of the SCS, these solitary waves become dissipative, exhibit strong shear, and generate vigorous turbulence due to shear instability (e.g., St. Laurent et al. 2011; Xu et al. 2012). St. Laurent et al. (2011) reported that the turbulent kinetic energy (TKE) dissipation rate was elevated to $1 \times 10^{-4}$ W kg$^{-1}$ in the trailing edge of
an internal solitary wave captured by their direct microscale observations.

At depth, internal tides play a key role in furnishing high-level mixing in the SCS (Jan et al. 2008; Tian et al. 2009). In the northern SCS, internal tide mostly comes from the generation site of the Luzon Strait (Zhao 2014). The energy of these tides was estimated at ~10 GW based on field experiments (Tian et al. 2009) and numerical simulations (Niwa and Hibiya 2004; Jan et al. 2007; Jan et al. 2008). In addition, lee waves, generated by the interaction between barotropic tidal current (or geostrophic current) and unique complex bathymetry, were considered to play an important role in supporting high-level mixing in the deep water of the SCS (Buijsman et al. 2012).

In contrast to the processes mentioned above, we know much less about mesoscale eddies and their effects on mixing, although mesoscale eddies are abundant in the SCS (Wang et al. 2008). Yang et al. (2014a) examined influences of both warm and cold eddies on mixing in the SCS. They found that warm eddies generated a negative relative vorticity and resulted in a lower effective Coriolis frequency, which reinforced downward-propagating, near-inertial waves and promoted the occurrence of strong mixing. By comparison, cold eddies reduced the downward propagation and thus inhibited strong mixing. Their results were based on comparison of parameterized diffusivity values, and the authors did not study the mechanisms at work. Using McLane Moored Profiler observations in the northern SCS, Sun et al. (2016) suggested that the generation of near-bottom, near-inertial waves through the interaction of mesoscale eddies and unique bottom topography was a main cause for the intense turbulent mixing in the region.

In the present study, we found mixing was considerably elevated in the periphery of warm mesoscale eddies based on measurements from three cruises in the SCS, each capturing a warm eddy. We also investigated potential mechanisms behind the high-level mixing. In the text that follows, the field observations, including the instruments used and their setups, are described in section 2. The main results are presented in section 3. A detailed discussion and summary are given in section 4.

2. Field observations

Aimed at understanding the effects of mesoscale eddies on turbulent mixing in the SCS, three cruises (Fig. 1) set out in August 2007, December 2013, and January 2014, respectively, after careful inspection of satellite images. During 31 July and 5 August 2007, 35 stations located west of Luzon Island were sampled. The spacing of these stations was planned to be half a degree; however, measurements at a few stations were not obtained successfully. During this period, a prominent warm eddy existed west of Luzon Island, which spanned 2° in both meridional (16°–18°N) and zonal (118°–120°E) directions. This warm eddy remained in this area from 10 July to 10 September based on satellite images, with its location and size almost unchanged. The maximum sea level anomaly (SLA) of this warm eddy exceeded 30 cm at its center. There was also a weak warm eddy to the west of this strong warm eddy. The stations were designed only for

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**Fig. 1.** Sea level anomaly in the South China Sea during three field experiments. The data were produced by the SSALTO/DUACS and distributed by the AVISO, with support from the CNES. The black dots in each panel indicate station locations, where both finescale and microscale measurements were carried out.
studying the strong warm eddy, which cut through the eddy in both zonal and meridional directions.

During 4–5 December 2013, only a zonal section was surveyed, which cut through a warm eddy from the east to the west. There were 11 stations in all, with a spacing of ~25 km. This strong warm eddy occurred west of the Luzon Strait and had an elliptical shape. The SLA at the eddy center reached 35 cm. Unlike the stationary eddy in August 2007, this eddy moved westward continuously since its generation on 10 November based on satellite images.

During 14–16 January 2014, a high spatial resolution section was surveyed, which cut through a warm eddy meridionally from 18.5° to 21.5°N. There were 28 microstructure stations and 85 temperature stations along the 300-km-long section, resulting in an average spacing between two adjacent stations being as short as ~3.5 km. This warm eddy had a diameter of ~28 and was, in fact, the same eddy as that observed in December 2013 based on satellite images, which propagated westward to this new location.

At all stations, hydrographic measurements were sampled by deploying both conductivity–temperature–depth system (CTD 911plus, Sea-Bird Electronics) and acoustic Doppler current profiler (300-kHz ADCP, Teledyne RD Instruments) to the seafloor. Microscale velocity shear was obtained using two microstructure probes named Turbulence Ocean Microstructure Acquisition Profiler (TurboMAP-L, JFE Advantech Co. Ltd.) and MSS-90L (Sea and Sun Technology). TurboMAP and MSS were loosely tethered, free-falling instruments ballasted to fall at a speed of 0.5–0.7 m s⁻¹, and their depth ranges were limited to 500 m from the surface. The sampling frequencies were 256 and 512 Hz for TurboMAP and MSS, respectively. The microstructure data were analyzed, and the TKE dissipation rate was estimated following Wolk et al. (2002). A shipboard broadband ADCP (75 kHz, Teledyne RD Instruments) worked all the time during the three cruises, providing velocity information for the water column in the upper 500 m (Figs. 2a–c). The bin size of the shipboard ADCP was set to 16 m, and the sampling interval was 1 min; so we can get one ensemble per minute. This resulted in velocity measurements taken across each eddy center with a horizontal resolution of ~300 m, since the average ship speed was 9–10 kt (1 kt = 0.51 m s⁻¹; Figs. 2d–f). This spatial resolution is high enough to explore submesoscale processes, which have a scale on the order of kilometers (Callies et al. 2015).

3. Results

a. TKE dissipation rates along five sections

Figure 3 shows the distributions of TKE dissipation rate ε along the five sections of the three cruises. The dissipation levels along the three sections in August 2007 were mostly on the order of 10⁻⁹ W kg⁻¹. Some elevated values of ε ranging from 10⁻⁸ to 10⁻⁷ W kg⁻¹ occurred in the upper 100 m of the water column. The distributions of TKE dissipation rate along the two sections in December 2013 and January 2014 were significantly different from those in August 2007,
with higher dissipation values between $10^{-7}$ and $10^{-6}$ W kg$^{-1}$, much more pronounced in the upper 200 m. The difference could come from two factors. The first factor is latitudinal difference. The two sections surveyed in December 2013 and January 2014 were located north of 18°N, and the three sections surveyed in August 2007 were south of 18°N. Turbulence in the SCS generally becomes weaker from the north to the south (Liu and Lozovatsky 2012; Yang et al. 2016), since its energy source mainly comes from internal tides, which are generated in the Luzon Strait and propagate southwestward into the central SCS. The energy flux of internal tides becomes weaker from the north to the south along the propagating path. For example, Zhao (2014) pointed out that the M$_2$ internal tide was hardly detected south of 16°N. Our results here show a consistent spatial pattern, which was about one order weaker from north of 18°N to south of 18°N. The second factor is seasonal variability, caused by seasonal variations of wind and internal tide. Wind is generally stronger in winter than in summer in the SCS and so is internal tide. Liu et al. (2015) observed enhanced internal tides in winter in the northern SCS. Although the observation periods in this study were short, we

FIG. 3. Spatial distributions of TKE dissipation rate (W kg$^{-1}$: logarithmic scale) along the sections surveyed in (a)–(c) August 2007 (18.5°, 18.0°, and 17.5°N), (d) December 2013, and (e) January 2014.
could infer that the turbulence in winter was more active than that in summer in the SCS (Sun et al. 2016). Based on the Osborn (1980) model, eddy diffusivity is calculated by taking mixing efficiency as a constant. Here, we use 0.2, as in some studies of frontal regions (e.g., St. Laurent et al. 2012; Sheen et al. 2013). The associated diffusivity values with these TKE dissipation rates ranged from $10^{-4}$ to $10^{-2}$ m$^2$s$^{-1}$, consistent with previous studies (e.g., Liu and Lozovatsky 2012; Yang et al. 2014b).

b. TKE dissipation rate in the mixed layer

Here, we focus on spatial variation of TKE dissipation rate; specifically, we compare the rate in the eddy center with that in the eddy periphery. Based on the velocity data measured by the shipboard ADCP, we defined the center and periphery for each eddy first. We examined the velocity component perpendicular to the section. For example, we examined the $u$ component for the meridional section in January 2014 and found the velocity across the eddy increased from zero at 20.00°N to maximum values of −1.0 m s$^{-1}$ at 19.50°N and 0.9 m s$^{-1}$ at 20.45°N (Fig. 4a). For the eddy in December 2013, the $v$ component of velocity increased from zero at 118.50°E to maximum values of −1.5 m s$^{-1}$ at 117.8°E and −1.4 m s$^{-1}$ at 119.30°E (Fig. 4b). Although the velocity across the eddy in August 2007 was weak, its variation trend was the same as those in December 2013 and January 2014 (Fig. 4c). We defined the eddy center as the area where the velocity increased outward until it reached its maximum. So, the enclosed SLA contour passing through the two locations with maximum velocities was the outer edge of the eddy center. We defined the range from the maximum velocity to the outermost enclosed SLA contour as the eddy periphery. These definitions are consistent with the features in the cross-track gradient of potential density based on high spatial resolution sampling (Fig. 4a). Sharp potential density gradient corresponded to the locations of velocity maxima well. This density gradient was not examined for the eddies surveyed in December 2013 and August 2007 because we did not have as high-resolution measurements as those in January 2014.

The center and periphery for the three eddies are shown in Figs. 4d–f, respectively. With this definition, there were 15 profiles in the eddy periphery, and 17 profiles in the eddy center. For each eddy, the dissipation profiles were averaged over the eddy periphery and the eddy center, respectively (Fig. 5). The results show that the mean values of TKE dissipation rate in the upper layer were obviously elevated in the eddy periphery for all three eddies, being 5–7 times larger than those in the eddy center. Thicknesses of these layers with high TKE dissipation rate ranged from 70 to 80 m for these three eddies, which were consistent with the mixed layer depths based on the vertical profiles of temperature and potential density (Fig. 6). Here, we defined the bottom of the surface mixed layer using the difference from the surface density greater than 0.125 kg m$^{-3}$ (e.g., Rimac et al. 2016). We conclude that the turbulent mixing in the mixed layer was elevated in the periphery of each warm mesoscale eddy surveyed.

FIG. 4. (a)–(c) Horizontal velocity component along the cruise track shown in Fig. 2 and (d)–(f) the defined eddy center and periphery. Sea level anomaly (cm) is shown in color in the bottom panels, from left to right, the dates are January 2014, December 2013, and August 2007. The light blue curve in (a) is the horizontal gradient of potential density along the cruise track.
4. Discussion and summary

a. Wind and buoyancy flux

It is important to understand what kind of dynamic process in the mixed layer could drive such elevated turbulent mixing in the periphery of these mesoscale eddies. The two most obvious candidates are wind and buoyancy flux, which are the basic driving force of mixing in the mixed layer. Hence, we examined observation dates and times and wind and buoyancy flux for dissipation profiles in the eddy center and periphery, respectively (Table 1). Visually, nearly all profiles in the eddy periphery were collected in the daytime, except for one profile sampled at an early morning (0559 local time (LT) on 15 January 2014). In contrast, half of the profiles...
in the eddy center were collected at night. The wind during each observation period varied only slightly. To quantify the contributions of wind and buoyancy flux to the TKE dissipation rate in the mixed layer, we estimated wind energy flux $E_{10}$ and buoyancy flux $J_{b}$. Here, $E_{10}$ is given by

$$E_{10} = \rho_a C_D U_{10}^{3},$$

where $\rho_a$ is air density (1.2 kg m$^{-3}$), drag coefficient $C_D = 1.14 \times 10^{-3}$ (Large and Pond 1981), and $U_{10}$ is the wind speed at 10-m height above the sea surface. The procedure for calculating $J_{b}$ can be found in Shay and Gregg (1986), which requires a total of 15 parameters. Among them, seven parameters were constants, five parameters were taken from the shipboard meteorological measurements, and the rest (three parameters) were obtained from the daily ERA-Interim dataset, at a time interval of 6h. We assumed a fraction of 1%, as in Oakey and Elliott (1982), for the wind energy flux that entered the mixed layer to support turbulent dissipation. Based on this assumption, the mean dissipation level caused by both wind and buoyancy flux during the survey periods of the profiles shown in Table 1 was about $1.4 \times 10^{-7}$ W kg$^{-1}$. This value was comparable to the mean TKE dissipation rate of these three eddies in the eddy center of $2.1 \times 10^{-7}$ W kg$^{-1}$, but only about 16% of the mean dissipation value of $8.7 \times 10^{-7}$ W kg$^{-1}$ in the eddy periphery. This large difference indicates that other process contributed to the active turbulence in the periphery of the three mesoscale eddies.

b. Submesoscale motion

Both numerical simulations and satellite observations suggest that submesoscale motions are frequently created from mesoscale eddies and can be detected clearly in the eddy periphery (e.g., Capet et al. 2008a; Gaultier et al. 2014). Submesoscale motion provides a dynamic conduit for energy transfer toward microscale dissipation and diapycnal mixing (McWilliams 2016). We
suspect the submesoscale process existed in the periphery of these eddies, which can explain the elevated TKE dissipation rates observed. To verify this hypothesis, we examined the horizontal wavenumber spectra of shipboard ADCP-measured velocities in the eddy periphery and eddy center, respectively (Fig. 7). When performing spectral calculation, the ADCP data were horizontally interpolated to a unified spacing of 500 m from its original resolution of ~300 m. The horizontal wavenumber spectra were then obtained by applying fast Fourier transform to the interpolated ADCP-measured velocities for each individual layer and finally averaged over the mixed layer depth range. The spectra in the eddy periphery and center exhibited a marked slope difference (Figs. 7d–i). In the eddy center, the spectrum followed a power law of $k^{-3}$ in small wavenumbers; in the eddy periphery, however, the spectrum followed a power law of $k^{-2}$ in larger wavenumbers (with a wavelength of kilometers). This difference indicates that submesoscale motion was more energetic in the eddy periphery than in the eddy center (Callies and Ferrari, 2013). Large potential energy stored in the mesoscale eddy can be released easily to this submesoscale motion (Capet et al. 2008b). Another piece of supporting evidence came from the Rossby number Ro, the ratio of relative vorticity $\zeta$ to ambient vorticity $\bar{f}$ based on the uniformly interpolated ADCP-measured velocities (Fig. 8). The results show a clear pattern that the small Rossby number existed in the eddy center, but they were significantly elevated with Ro values reaching 1 in the eddy periphery. The bands with high Ro values in the eddy periphery were indicators for active submesoscale motions. In addition, the positive Ro values dominated over the negative Ro values in the eddy periphery. This asymmetry was mainly caused by the inertial instability, as reported by Capet et al. (2008a). In the eddy periphery, the ageostrophic balance could be in the form of vortex filaments with a scale of...
kilometers, which could be detected from remote sensing images. A composite sea surface temperature map over 3–5 December 2013 from the MODIS level-2 product revealed this kind of filaments around the eddy periphery (Fig. 9).

We also investigated the kinetic energy distribution of both mesoscale and submesoscale motions along the transection using our cruise data. The mesoscale and submesoscale velocities were obtained by applying 20-km low-pass and high-pass filters to the shipboard ADCP-measured velocities, respectively. The kinetic energy was defined as $KE = \frac{1}{2} \int_{-\text{MLD}}^{0} \rho (\vec{u}^2 + \vec{v}^2) \, dz$, where MLD is mixed layer depth. The results suggest that submesoscale motion was significant in the eddy periphery but relatively weak in the eddy center. The kinetic energy of submesoscale motion accounted for up to 74% in the eddy periphery and was only about one-quarter in the eddy center in January 2014 (Fig. 10). Although the high-pass-filtered data may include the
information of internal waves and tides, the energy variation at the order of kilometers caused by these waves and tides is likely not significant. Similar results were obtained for the other two eddies. For the eddy observed in January 2014, the submesoscale motion was greatly energized in the northern part of the eddy periphery. This was likely related to the presence of Dongsha Island there, since the island favors the generation of submesoscale motion (Zheng et al. 2008).

To identify the direction of energy cascade, we estimated the spectral flux of kinetic energy $\Pi$, which is defined as the integral of the local horizontal advective term in the kinetic energy equation from wavenumber $k$ to the largest wavenumber $k_s$, corresponding to the grid size:

$$\Pi(k) = \int_k^{k_s} -\text{Re}[\mathbf{u}_h^* \cdot (\mathbf{u}_h \cdot \nabla_h \mathbf{u}_h)](k) \, dk,$$

where $\mathbf{u}_h = (u, v)$ denotes the horizontal velocity vector measured from the shipboard ADCP, and $\nabla_h$ is the horizontal gradient operator. The structure $\cdot$ represents

![Fig. 10. Distributions of kinetic energy of submesoscale and mesoscale motions along the section in (a) January 2014, (b) December 2013, and (c) August 2007. Kinetic energy is normalized by its maximum value. The dashed lines in each panel separate the eddy center and the periphery, and the percentage of kinetic energy in each area is also shown.](image-url)
the horizontal spectral transform, and \((\cdot)^*\) stands for complex conjugate, with \(\text{Re}(\cdot)\) indicating the real part. Computationally, \[\hat{\mathbf{v}}_h^*(\mathbf{u}_h \cdot \nabla_h \mathbf{u}_h)\] is estimated as 
\[
\text{fft}(u)^*\text{fft}(ud/dx + vd/dy) + \text{fft}(\nu)^*\text{fft}(ud\nu/dx + vd\nu/dy),
\]
where \(\text{fft}\) represents fast Fourier transform. For a meridional section observed in January 2014 or August 2007, \[\hat{\mathbf{v}}_h^*(\mathbf{u}_h \cdot \nabla_h \mathbf{u}_h)\] is simplified as 
\[
\text{fft}(u)^*\text{fft}(ud\nu/dy) + \text{fft}(\nu)^*\text{fft}(ud\nu/dy).
\]
The spectral flux was calculated individually for each layer within the mixed layer, and depth-averaged flux was used to examine the direction of flux transport. From the definition of spectral flux of kinetic energy, for a given wavenumber a positive (negative) flux value indicates a forward (inverse) kinetic energy cascade. The spectral fluxes of kinetic energy in the eddy center and periphery for these three eddies are shown in Fig. 11. The positive values around larger wavenumbers (at wavelength of kilometers) occurred in the eddy periphery, indicating a forward energy cascade toward smaller scales. This suggests that submesoscale motions in the eddy periphery could be a key factor leading to the enhanced mixing. In contrast, the energy flux in the eddy center was transferred backward toward large scales. However, submesoscale motion cannot directly provide energy for turbulent mixing because its characteristic length is several orders larger than that for turbulent dissipation to occur. Submesoscale motion acts as a bridge, which decreases the scale gap between mesoscale and microscale processes, and expedites the occurrence of turbulent mixing.

c. Summary

To summarize, direct microstructure observations across three warm mesoscale eddies were obtained in the northern SCS during field experiments, along with finestructure measurements. An important finding is that the turbulent mixing in the mixed layer was considerably elevated in the periphery of the three eddies, where the mixing level was 5–7 times larger than that in the eddy center. To explore the mechanism behind the elevated mixing, we carried out analyses of the horizontal wavenumber spectrum and spectral fluxes of kinetic energy. The spectral slope showed a power law of \(k^{-2}\) in the eddy periphery and of \(k^{-3}\) in the center, which was consistent with the results that the kinetic energy of submesoscale motion in the warm eddy periphery was more greatly energized than that in the eddy center. Spectral fluxes of kinetic energy also revealed a forward energy cascade toward smaller scales at wavelength of kilometers in the eddy periphery. These results illustrate a route for energy cascading from balanced mesoscale dynamics to unbalanced submesoscale behavior, which eventually furnishes turbulent mixing. However, the eddies studied in this study were all warm ones. Generation of submesoscale motion depends on mixed layer depth. Warm (cold) eddies can deepen (shallow) the mixed layer depth, which is beneficial (detrimental) for developing submesoscale motion (Callies et al. 2015). Therefore, the submesoscale process is more likely to
be generated when encountering a warm eddy than a cold eddy. As a result, high-level mixing is expected to occur in the periphery of a warm eddy. In the coming days, systematic observations involving multiscale processes are planned to examine the impacts of warm and cold eddies on turbulent mixing in detail and to reveal their associated energy cascade routes.

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