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Tropical storm-forced near-inertial energy dissipation in the southeast continental shelf region of Hainan Island

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Near-inertial motion is an important dynamic process in the upper ocean and plays a significant role in mass, heat, and energy transport across the thermocline. In this study, the dissipation of wind-induced near-inertial energy in the thermocline is investigated by using observation data collected in July and August 2005 during the tropical storm Washi by a moored system at (19°35′N, 112°E) in the continental shelf region off Hainan Island. In the observation period, the near-inertial part dominated the observed ocean kinetic energy and about 80% of the near-inertial energy dissipated in the upper layer. Extremely strong turbulent mixing induced by near-inertial wave was observed in the thermocline, where the turbulent energy dissipation rate increased by two orders of magnitude above the background level. It is found that the energy loss of near-inertial waves in the thermocline is mainly in the large-scales. This is different from the previous hypothesis based on "Kolmogorov cascade" turbulence theory that the kinetic energy is dissipated mainly by small-scale motions.

tropical storm Washi, continental shelf region of Hainan Island, near-inertial energy dissipation in thermocline

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Near-inertial motions are commonly observed in the ocean. Wind forcing over the ocean surface is believed to be responsible for the generating the near-inertial motions, which is more efficient under the forcing wind in half the local inertial frequency than in other situations (Pollard, 1970). Near-inertial waves are not only the carrier for wind kinetic energy being transported into the interior ocean (Zhou et al., 2005), but also the driver for heat being fluxed into deeper ocean (D'Asaro, 2003; Sriver et al., 2007) .

Diapycnal mixing processes in the thermocline of the ocean interior are believed to play an important role in sustaining global thermohaline circulations (Munk et al., 1998). Although the near-inertial energy propagation from the upper to deep ocean has been qualitatively well documented (D'Asaro, 1985; Zervakis et al., 1995; Alford, 2001; Garrett, 2001; Moehlis et al., 2001; Watanabe et al., 2002; Jiang et al., 2005; Shearman, 2005; Plueddemann et al., 2006; Alford et al., 2007; Furuichi et al., 2008; Silverthorne et al., 2009; Alford et al., 2012; Xu et al., 2013), the physical mechanism of near-inertial energy dissipation in thermocline remains poorly understood.

Recent studies suggested that wind-forced near-inertial waves can propagate into the deep ocean (Alford et al., 2007; Silverthorne et al., 2009; Xu et al., 2013). The deeply penetrated near-inertial motions may cause mixing in the deep water, and observations indicated that there was high variability in the mixing processes. Therefore, it is of great significance to better understand the mixing in strong stratified continental shelf ocean (Zhang et al., 2014. In this pa-

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per, the observation data from a moored system reflecting the ocean responses to tropical storm Washi in the continental shelf region off Hainan Island in summer are first analyzed to elucidate the near-inertial energy dissipation process in the thermocline. It is found that about 80% of the near-inertial energy was dissipated in the upper layer, and the near-inertial energy dissipation in the thermocline is associated mainly with large-scale near-inertial waves.

1 Data and methods

A moored observation system was deployed at (19°35′N, 112°E) with water depth of 130 m on the northwest continental shelf of the South China Sea by the Institute of Oceanology, Chinese Academy of Sciences (Figure 1). The observations had been implemented from July 28 to August 2, 2005. For the moored system, a downward-looking 190 kHz Acoustic Doppler Current Profiler (ADCP) was used to measure current velocity at 51 levels from 14 to 114 m with depth interval of 2 m and time interval of 10 min. Temperature data were also collected by a chain of temperature sensors at 15 levels from 4 to 75 m with depth interval of 1 m and time interval of 10 min.

The tropical storm Washi was a fast-motion and weak-wind storm, first formed as a cyclone in northwestern South China Sea (18.4°N, 112.6°E) at about 16:00 on July 28, 2005. It became a tropical storm on July 29, reached its maximum wind speed of 23.1 m s^{-1} on July 30, and then reduced to a cyclone and made a land fall on northeast part of Vietnam (20.5°N, 104.5°E) on July 31 (Figure 1). The storm moved slowly in its first 18 hours (<2.5 m s^{-1}), and then accelerated to a relatively higher translational speed (>3 m s^{-1}). The storm track data used in this study were obtained from the Unisys Weather Web site (http://weather.unisys.com/hurricane/w_pacific/), based on the best hurricane track data issued by the Joint Typhoon Warning Center. The data include the maximum sustained surface wind speeds and the locations of the hurricane center every 6 hours. The moored system was about 130 km away from the nearest center of tropic storm Washi (Figure 1).

The wind stress is calculated by $\tau = \rho_a C_D \vec{U}_{10}(\vec{U}_{10} - \vec{U}_{ocean})$, where $\rho_a, C_D, \vec{U}_{10}, \vec{U}_{ocean}$ are the air density, drag coefficient, 10-m high wind speed and ocean surface velocity. Baroclinic velocity profiles with 2-m interval are derived from the ADCP observations by subtracting the vertical mean velocities as the barotropic component. The near-inertial velocity $\vec{u}_{in}$ and near-inertial wind stress $\vec{\tau}_{in}$ are obtained from baroclinic velocity profiles and wind stress within [0.8 f − 1.25 f] by means of a second-order Butterworth filter applied in the time domain respectively.

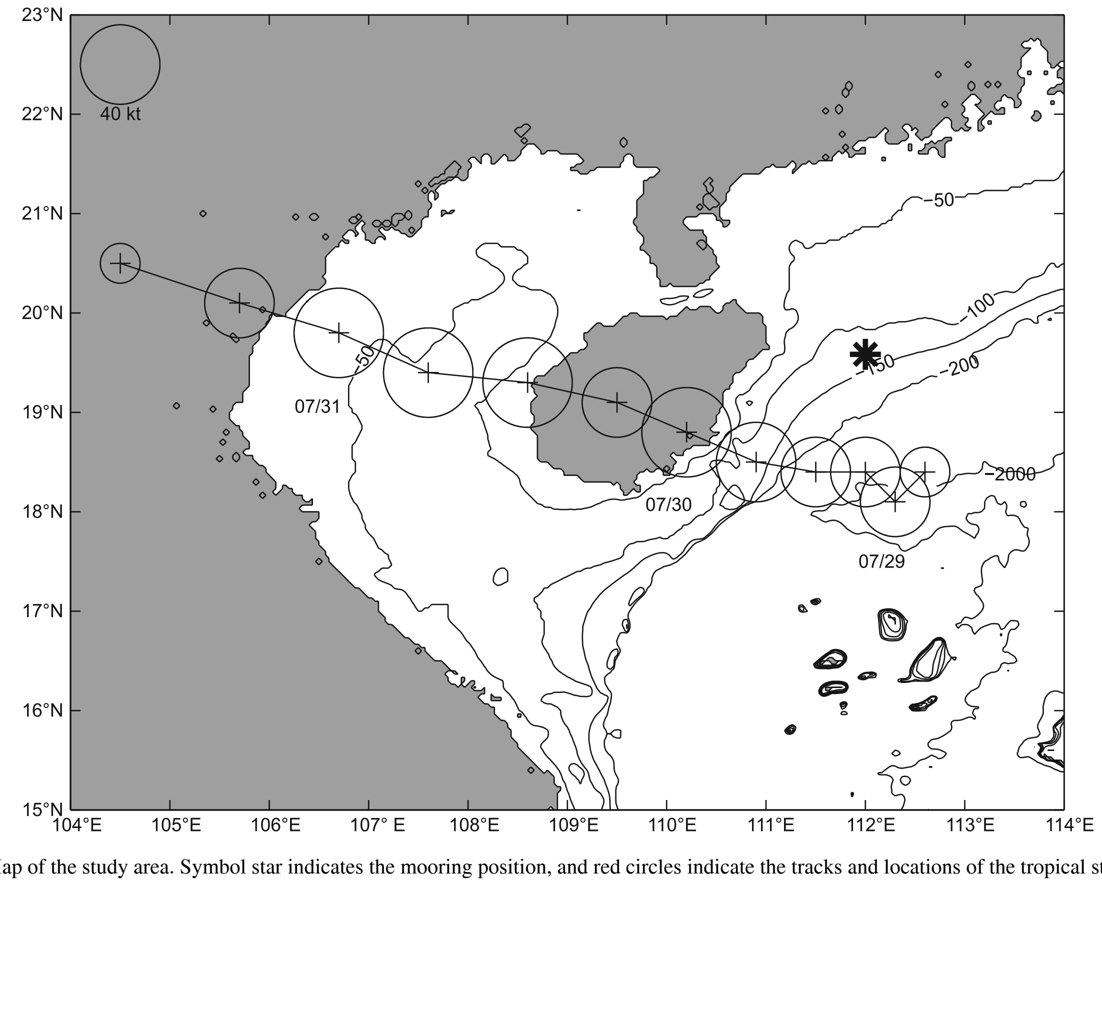

Figure 1 Map of the study area. Symbol star indicates the mooring position, and red circles indicate the tracks and locations of the tropical storm Washi.

The filter is applied twice, once forward and once backward to minimize distortion of phase. The wind energy input into the ocean and near-inertial waves can be calculated respectively by

$$E = \vec{\tau} \cdot \vec{u}\ , \tag{1}$$

$$E_{\text{in}} = \vec{\tau}_{\text{in}} \cdot \vec{u}_{\text{in}}\ , \tag{2}$$

where $\vec{u}$ is the mixed layer velocity.

The near-inertial kinetic energy is calculated by using the bandpass filtering method, and given by

$$EK_{\text{in}} = \frac{1}{2}\rho_0 (u_{\text{in}}^2 + v_{\text{in}}^2)\ , \tag{3}$$

where ρ_0 is the reference density of sea water (here defined as 1024 kg m^{-3}), $\vec{u}_{\text{in}} = (u_{\text{in}}, v_{\text{in}})$ is the near-inertial oscillation current.

Without microstructure measurements, turbulent kinetic energy dissipation rate could be inferred from fine-scale parameterization, which relates the characteristics of the internal wave field to energy dissipation. We use the parameterization proposed by Mackinnon et al. (2003) for continental shelf:

$$\varepsilon = \varepsilon_0 (N / N_0)(S_{\text{lf}} / S_0)\ , \tag{4}$$

where N is the buoyancy frequency calculated from observation data, and S_{lf} is the low frequency shear of background velocity from large-scale waves, ε_0= 0.69 nW kg^{-1} and $N_0 = S_0 = 3\ \text{h}^{-1}$.

2 Results

The surface wind speed around the moored system was about 5 m s^{-1} prior to July 29, increased significantly to about 18.9 m s^{-1} on July 30 as the storm passed by, and then dropped below 10 m s^{-1} after the storm (Figure 2(a)).

During the mooring observation period, the baroclinic energy had dominated the record, and the maximum baroclinic energy in the whole water depth was at the near-inertial frequency with a period of 35 hours and maximum velocity above 0.2 m s^{-1} (not shown here). Wind energy input to the ocean was increasing from July 29 to July 30 with the maximum value of 0.35 W m^{-2}, and then decreasing after July 30 (Figure 2(b)). In contrast to the wind energy input to the ocean, wind energy into the near-inertial waves showed periodic fluctuations, with maximum value of 0.027 W m^{-2} on July 30 (Figure 2(c)). It is noted that about 31.8% of the total wind energy into the ocean is inputted to near-inertial waves. A time-depth near-inertial kinetic energy image from 28 July to 3 August corresponding to the passage of storm Washi is shown in Figure 2(d). Similar to the previous investigation in the Gulf of Mexico by Zheng et al. (2006) revealing the upper ocean response to the Hurricane Georges in 1998, this study shows that there appear dual peaks of the near-inertial kinetic energy caused by the tropical storm Washi. One appeared above 14 m with a peak value of 0.05 m^2 s^{-2}, and the other at about 80 m with a peak value of 0.005 m^2 s^{-2}. In between, there was a transitional layer from 30 to 60 m corresponding to the thermocline with extremely low near-inertial kinetic energy. This

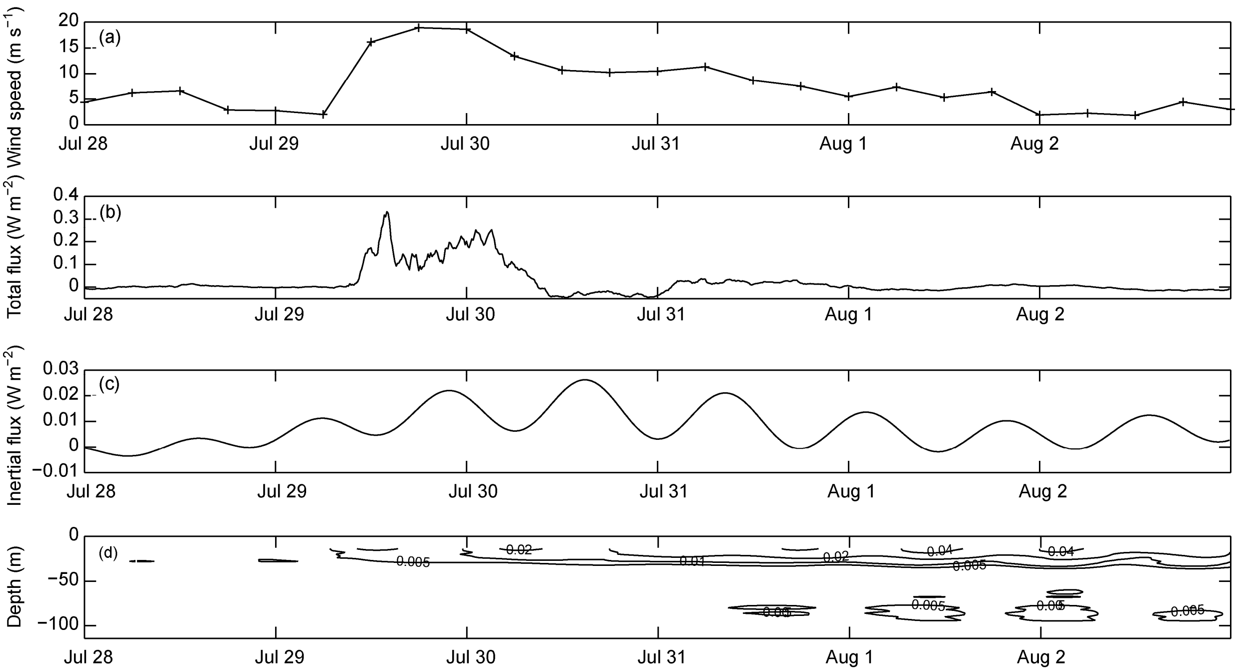

Figure 2 Temporal variations of wind speed (a), wind energy input to ocean (b), wind energy input to near-inertial band (c), and temporal and vertical distribution of near-inertial kinetic energy (d).

implies that the near-inertial waves could propagate through the thermocline, but in the thermocline, the near-inertial kinetic energy was pretty weak, about one order of magnitude smaller than that in the mixed layer.

The near-inertial oscillation induced by winds in the mixed layer can excite baroclinic shear instability at the bottom of the mixed layer, and then drives vertical entrainment mixing in thermocline (Gardner et al., 2001; Mac Kinnon et al., 2005). As shown in Figure 3, the kinetic energy of near-inertial waves significantly decreased at the base of the thermocline. The substantial difference between the kinetic energy of near-inertial waves in mixed layer and in the thermocline suggests that a large amount of the near-inertial energy should be dissipated in the thermocline.

The near-inertial energy dissipation rate ε is calculated by using near-inertial shear in parameterization eq. (4). Figure 4 shows that strong turbulent mixing induced by the near-inertial waves is observed in the thermocline, where turbulent kinetic energy dissipation rates ε increased to the magnitude of $O(10^{-6}\ \mathrm{W\ kg^{-1}})$, about two orders of magnitude above the background level.

The horizontal motion of near-inertial waves is induced by the coriolis force. On a scale of β plane, the coriolis force drives the near-inertial waves propagating from the near-surface region to equatorward. Within a fairly small distance of mixed layer, however, the effect of coriolis force on the near-inertial waves can be neglected. Figure 5 shows difference between the power spectra of near-inertial wave

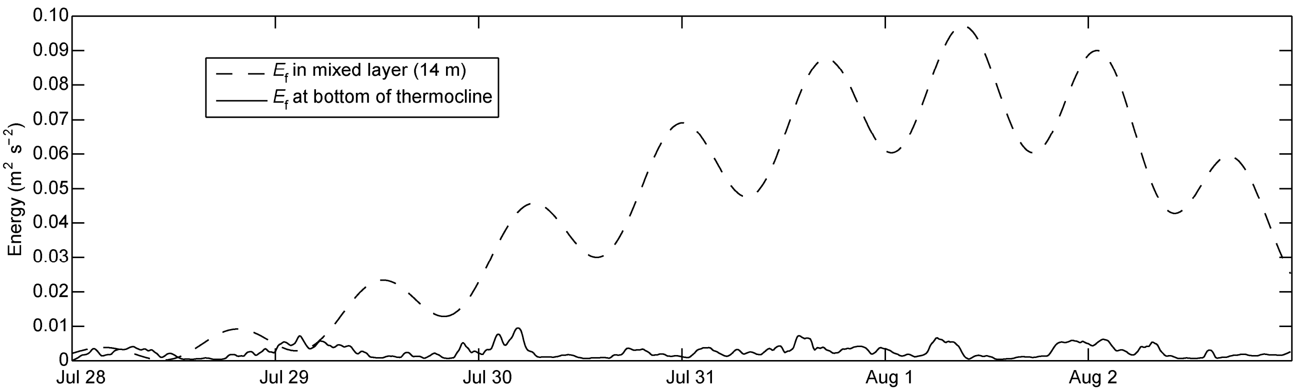

Figure 3 Temporal variations of near-inertial kinetic energy in mixed layer and at the base of thermocline.

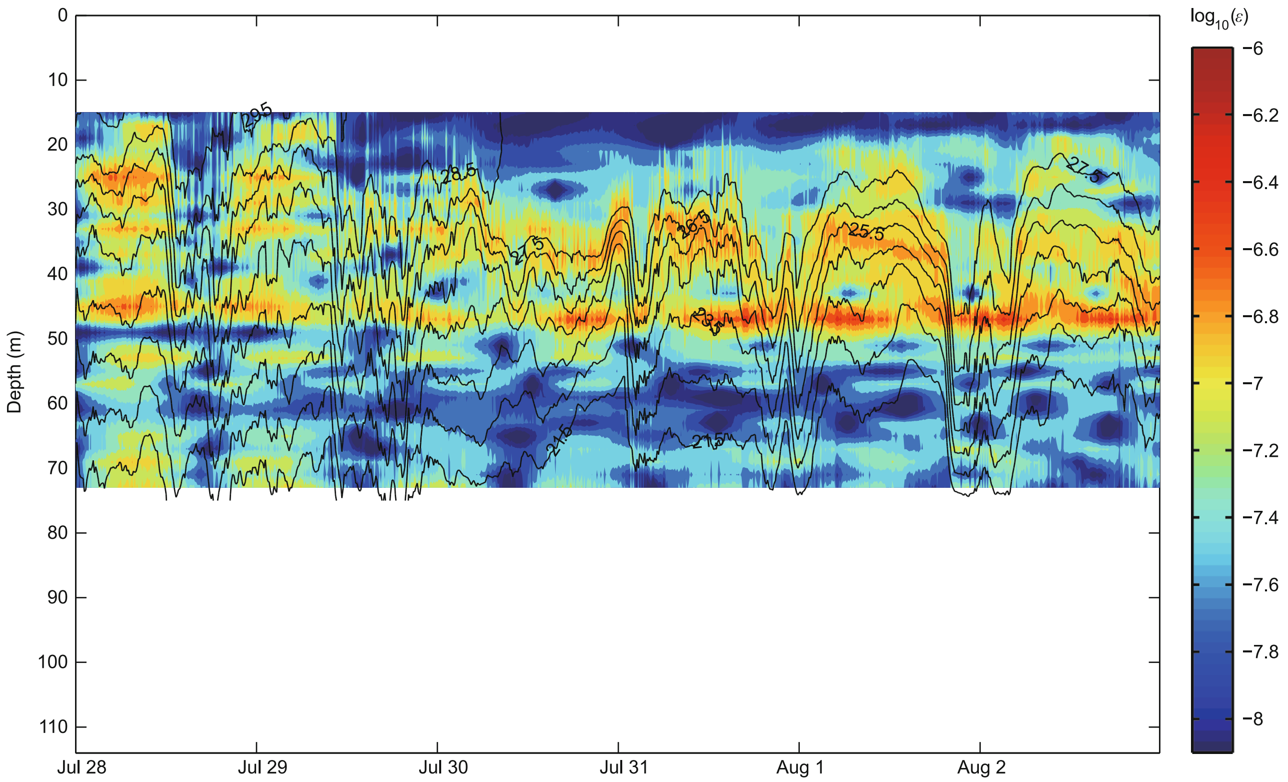

Figure 4 Contour plot of depth vs time of turbulent kinetic energy dissipation rate ε. Isotherms are also overlaid, with lines every 1°C.

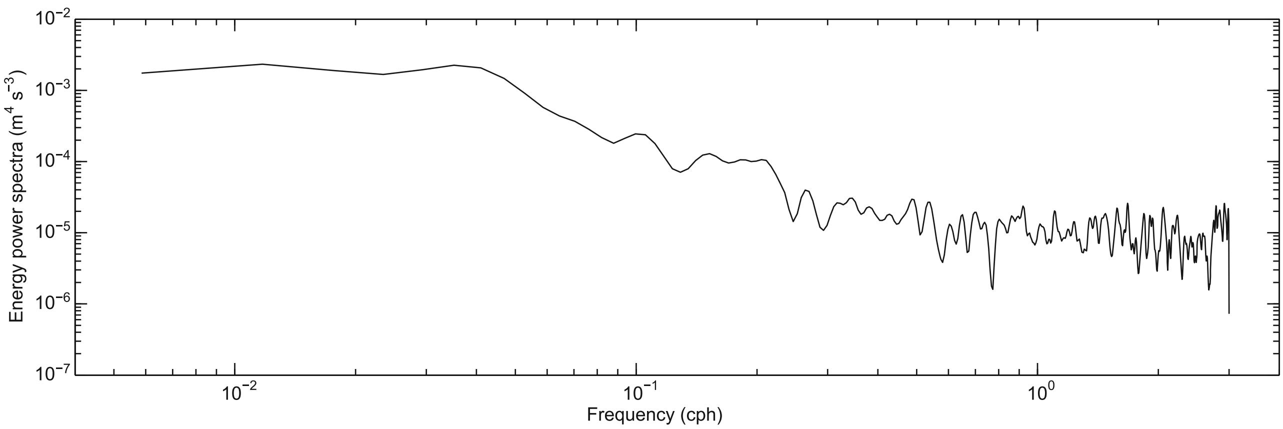

Figure 5 Energy power spectra difference between near-inertial wave in mixed layer and in thermocline.

energy in the mixed layer and in the thermocline. It indicates that the major energy loss in thermocline was caused mainly by the large-scale near-inertial waves. Although the energy loss existed in small-scales, it was found insignificant, compared with that in the large-scale of near-inertial waves.

3 Discussion and conclusions

In this paper, we present an analysis of observation data from a moored system in the continental shelf region off Hainan Island, which reflects the ocean response to a weak tropical storm. Moored ADCP observations indicate that strong near-inertial oscillations were excited by the tropical storm Washi, and wind energy input to the near-inertial band was 31.8% of the total wind energy into the ocean.

According to "Kolmogorov cascade" hypothesis, the kinetic energy enters the cascade at the large scales. Those large scale motions transport their energy down to somewhat smaller scales. The smaller motions experience the break-up process and energy is dissipated by inviscid processes. This is called the energy cascade process. During the passage of tropical storm Washi, however, strong turbulent mixing induced by the near-inertial waves is observed in the thermocline. The intensified turbulent mixing in the thermocline is caused mainly by large-scale near-inertial waves. This offers no support for the hypothesis of "Kolmogorov cascade" in wind-generated near-inertial waves analogous to that in flow turbulence.

It is well known that near-inertial waves are a ubiquitous feature of the ocean and an important source of energy for turbulent mixing in the upper ocean. Near-inertial turbulent mixing processes in the ocean are believed to play an important role in sustaining the global thermohaline circulation and increasing fluxes of nutrient-rich deep waters into the low enphotic zone in the upper layer. Therefore a better understanding of their resultant mixing mechanism is needed. In summer season, the thermocline in the continental shelf region off Hainan Island is strongly stratified and as an impermeable barrier for the mass, heat and energy exchange between the upper mixed layer and the lower layer waters. As the large-scale near-inertial waves penetrating across the stratified water, they become susceptible to instability and break (Gardner et al., 2001; MacKinnon et al., 2005). This may be the possible mechanism for the intensified turbulent mixing in the thermocline during the tropical storm Washi. Moreover, our observation represents a quantitative link between near-inertial waves and mixing and indicates that shear instability of the near-inertial wave leads to the intensified turbulent mixing in the thermocline.

During the period of strong mixing, we observed that, in total, 80% of the near-inertial energy was dissipated in the upper layer. This is consistent to the numerical study by Furuichi et al. (2008), which suggested that 85% of the near-inertial energy deposited into the mixed layer by the wind is dissipated in the upper 150 m. Therefore, it is reasonable to conclude that most of the large-scale near-inertial wave energy is likely dissipated in the upper ocean of stratified continental shelf sea.

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