Dear Dr. John M. Huthnance,

We appreciate your very nice help to our paper. We have checked our paper very carefully and corrected all syntax errors and addressed the comments accordingly. Please find our responses and the revised manuscript in the attached files.

Thank you again.

There is one reviewer comment; in the Introduction, first paragraph, please add your aim stated near the end of the Introduction "Whether high frequency . . is the main purpose of this study." [I think you can keep this sentence where it is as well].

Reply: Thanks for the nice comment. We have rephrased these statements as shown in lines 119-121.

Introduction

Paragraph 1, sentence 2. "Previous studies show that the South China Sea (SCS) . ."

Paragraph 2, first sentence. Omit "South China Sea" and "(", ")". [To define SCS when first used].

Reply: Thanks for the nice comment. We have corrected it, as shown in lines 64-65 and line 68.

Equations (2) and (3). Usually Xw < Xe so I would expect the integration to be from Xw to Xe and not as written.

Reply: Thanks for the nice comment. We have checked and corrected it, as shown lines 144-148.

Section 3.

First sentence; better ". . from 1 January . ."

Reply: Thanks for the nice comment. We have corrected it, as shown in line 173.

Same paragraph, 6th line from end. "sub-inertial frequencies" or "periods longer than inertial".

Reply: Thanks for the nice comment. We have corrected it, as shown in line 186.

Paragraph 3, 5th line from end. Here you mention the Pacific but there is nothing about near-inertial Pacific variability in the paper anywhere else so it is not clear what you refer to.

Reply: Thanks for the nice comment. We have checked these references (Komori et al., 2008; Blaker et al., 2012; Sévellec et al., 2013) very carefully and delete these statements about near-inertial Pacific variability in the paper,as shown in lines 230-233.

Discussion

Paragraph 1, sentence 4. ". . A mooring . .". [I assume that this is the first reference to the mooring. At present with "The" it reads as though it was Yuan et al.'s mooring which is obviously impossible]

Reply: Thanks for the nice comment. We have corrected it, as shown in line 265.

Last paragraph, 5th line from end. This is a bit vague – what are the two states? It would read better as “. . intrusion changes state (Nan et al. . .),” and better still if there were a short description of the different states.

Reply: Thanks for the nice comment. We have checked and corrected it, as shown in lines 309-310.

Last paragraph, 3rd line from end. Better “in relation to” rather than “about the”?

Reply: Thanks for the nice comment. We have corrected it, as shown in line 311.

Last paragraph, last line. “. . in a future study.”

Reply: Thanks for the nice comment. We have corrected it, as shown in line 314.

On the near-inertial variations of meridional overturning circulation in the South China Sea

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Abstract

We examine near-inertial variability of the meridional overturning circulation in the South China Sea (SCSMOC) using a global 1/12° ocean reanalysis. Based on wavelet analysis and power spectrum, we suggest that deep SCSMOC has a significant near-inertial band. The maximum amplitude of the near-inertial signal in the SCSMOC is nearly 4Sv. The spatial structure of the signal features regularly alternating counterclockwise and clockwise overturning cells. It is also found that the near-inertial signal of SCSMOC mainly originates from the region near the Luzon Strait and propagates equatorward with the speed of 1-3 m/s. Further analyses suggest that the near-inertial signal in the SCSMOC is triggered by high-frequency wind variability near the Luzon Strait, where geostrophic shear always exists due to Kuroshio intrusion.

Key words: SCSMOC; near-inertial variability; Kuroshio.

1 Introduction

Near-inertial internal waves have been considered to be an important energy source for the diapycnal mixing in the ocean required to maintain the meridional overturning circulation (MOC, Munk et al., 1998). Previous studies show that the South China Sea (SCS) acts as a mixing mill that mixes the surface and deep waters and returns the mixed waters out of the Luzon Strait at an intermediate depth (Yuan, 2002; Tian et al., 2009; Yang et al., 2013, 2014).

The widest and deepest channel in the SCS is the Luzon Strait, which has a sill depth of about 2400m, and is the main passage connecting the SCS and the northwestern Pacific Ocean (Qu et al., 2006). Based on field observations, studies confirm the hypothesis that the Luzon Strait transport (LST) has a sandwiched vertical structure, which shows a westward flow in the upper layer (<500 m) and in the deeper layer (>1500 m), and an eastward flow in the intermediate layer (500–1500 m, Tian et al., 2006; Yang et al., 2010). The corresponding circulation in the SCS is consistent with the potential vorticity constraint (Yang et al., 2000 and 2007), which suggests that the mixing-induced circulation inside the SCS should be cyclonic gyres at the surface and at the bottom (Chao et al., 1996; Li et al., 2006; Wang et al., 2011; Lan et al., 2013; Xu et al., 2014), and an anti-cyclonic gyre at an intermediate depth (Isobe et al., 2001; Yuan, 2002). Note that the upper-layer SCS circulation is also affected by the seasonally reversing monsoon, exhibiting a cyclonic circulation over the whole SCS basin in winter, and in summer a strong anti-cyclonic circulation in the southern SCS and a weak cyclonic circulation in the northern SCS (Wrytki, 1961; Chu et al., 1999; Chu and Li, 2000; Qu, 2000; Hu et al., 2000; Liu et al., 2001; Wang et al., 2003; Su, 2004).

In the context of the strong mixing in the SCS and the sandwiched vertical structure of the Luzon Strait transport, Wang et al. (2004) proposed that the shallow meridional overturning in the SCS (SCSMOC) is semi-enclosed, transporting waters from north to south at the depth of about 500m (200 m) and returning waters to north at surface in winter (summer). The shallow SCSMOC hints at a transport path such that intermediate water enters the SCS from the northwestern Pacific Ocean (Wang et al., 2004; Xie et al., 2013). Zhang et al. (2014)[1] further show that the shallow SCSMOC consists of downwelling in the northern SCS, a southward subsurface branch supplying upwelling in the southern SCS and a northward return flow of surface water. Based on the high-resolution global reanalysis data (GLBa0.08), Shu et al. (2014) found that the whole SCSMOC also has a sandwiched structure driven by the Luzon Strait transport, consisting of a stronger semi-enclosed clockwise overturning circulation in the upper layer, a weaker counterclockwise overturning circulation in the intermediate layer, and a weaker clockwise overturning circulation in the deep layer.

The SCSMOC variability spans a wide range of time scales. On a decadal time scale, the intermediate water of the SCS was fresher in the 1980s than that in the 1960s, caused by the deep SCSMOC decreasing from the 1960s to the 1980s according to an ocean reanalysis (Liu et al., 2012). On the interannual scale, the Luzon Strait transport shows a remarkable inter-annual variability associated with El Niño-Southern Oscillation (ENSO, Qu et al., 2004). The upper LST correlates with the local wind stress while the lower LST shows a statistically significant correlation with Nino3.4 index (Qu et al., 2005; Wang, D. et al., 2006; Wang, Y. et al., 2006), indicating that the shallow SCSMOC also has an interannual variability related with ENSO. On a seasonal scale, the seasonal variability of the shallow SCSMOC mostly controls the strength of seasonal intrusions of the North Pacific Water into the SCS (Liu et al., 2008). Moreover, the deep overflow through the Luzon Strait is strong in summer while weak in winter, driving the seasonal variability of the deep SCSMOC (Lan et al., 2015).

The existence of near-inertial (several days) variability of the Atlantic meridional overturning circulation (AMOC) has been recently reported by using a high-resolution oceanic general circulation model (Blaker et al., 2012). This variability is associated with equatorward-propagating near-inertial gravity waves (NIGWs). However, there is no study so far for shorter time-scale variability (especially for near-inertial

[1] Zhang, N., Lan, J., and Cui, F.: The shallow meridional overturning circulation of the South China Sea, Ocean Sci. Discuss., 11, 1191–1212, doi:10.5194/osd-11-1191-2014, 2014.

variation) of the SCSMOC. In this paper, we examine the near-inertial variations of the SCSMOC and identify the generation processes behind the variations using a realistic high-resolution ocean reanalysis. The rest of the paper is organized as follows. The data and methods are introduced in Sect. 2. The results are presented in Sect. 3. Sections 4 and 5 give discussion and conclusion.

2 Data and Method

The product of Hybrid Coordinate Ocean Model+Navy Coupled Ocean Data Assimilation (HYCOM+NCODA) global 1/12° Reanalysis (GLBu0.08, http://hycom.org/dataserver/glb-reanalysis) provided by the Naval Research Laboratory is used in this study. As a dynamical model, HYCOM 2.2 is configured for the global ocean with the bathymetry derived from the 30 arc-second GEBCO (General Bathymetric Chart of the Oceans) dataset. The K-Profile Parameterization (KPP) mixing scheme is adopted for the vertical diffusion of momentum, temperature, and salinity (Thoppil et al., 2011). The model is forced by the hourly wind stress and heat fluxes derived from National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) with horizontal resolution of 0.3125°. Note that there is no tidal forcing during the integration. It is initialized using temperature and salinity from the 1/4° Generalized Digital Environmental Model (GDEM4) climatology in January. The NCODA assimilates available satellite altimeter observations, satellite and in-situ sea surface temperature (SST) as well as available in-situ vertical temperature and salinity profiles from XBTs, Argo floats and moored buoys using a 3-D variational scheme (Cummings, 2005). The model output is stored every 3 h.

Based on the equation of continuity, the meridional overturning streamfunction can be defined as (Endoh et al., 2007):

$$\frac{\partial \psi(y,z,t)}{\partial z} = -\int_{x_w}^{x_e} v(x,y,z,t)dx \qquad (1)$$

$$\frac{\partial \psi(y,z,t)}{\partial y} = \int_{x_w}^{x_e} w(x,y,z,t)dx \qquad (2)$$

Because there is no vertical velocity (w) provided in GLBu0.08, the meridional overturning streamfunction in SCS could be calculated as:

$$\psi(y,z,t) = -\int_{-H}^{z} dz \int_{x_w}^{x_e} v(x,y,z,t)dx \quad (3)$$

where x_w and x_e are the western and eastern limits of the basin, respectively, and H is the ocean bottom. Although the meridional overturning streamfunction is calculated only by the meridional velocity (v), it also represents the integrated vertical motions in the basin because of the equation of continuity (Endoh et al., 2007). Shu et al. (2014) have used another product of HYCOM+NCODA global 1/12° Reanalysis (GLBa0.08, Fig. 1a) to depict the structure of the SCSMOC. The only difference between GLBa0.08 and GLBu0.08 is the external forcing field. GLBa0.08 is forced by Navy Operational Global Atmospheric Prediction System (NOGAPS), while GLBu0.08 is driven by Climate Forecast System Reanalysis (CFSR). Figure 1 shows the SCS meridional overturning stream function averaged from 2004 to 2010 based on GLBa0.08 and GLBu0.08. It is found that the two products show roughly a similar SCSMOC, which consists of a semi-enclosed clockwise upper overturning cell, a counterclockwise intermediate overturning cell and a clockwise deep overturning cell as shown in Fig. 1. The main difference is that the intermediate cell in GLBu0.08 is stronger and the deep cell stretches less southward compared with the GLBa0.08. And the upper cell in GLBu0.08 is deeper. More importantly, compared with the daily-output GLBa0.08, GLBu0.08 has a three-hour output, which is better for studying motion with periods of only a couple of days. So the GLBu0.08 product in 2010 is chosen to analyze the characteristics of near-inertial variability of the SCSMOC in this study.

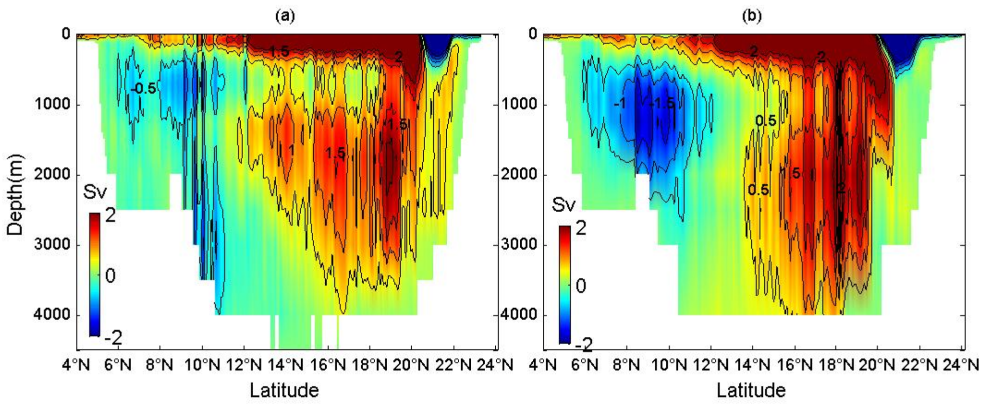

Figure 1. SCSMOC averaged from 2004 to 2010 based on GLBa0.08 (a) and GLBu0.08 (b).

3 Characteristics of the near-inertial variability of the SCSMOC

Figure 2a shows the 120-day time series of the deep SCSMOC (at 1500 m and 14°N) from 1 January, 2010. It is found that the SCSMOC experiences an obvious intra-seasonal variability superimposed with persistent high-frequency undulations (Fig. 2a). The wavelet analysis shows that the high-frequency undulations are corresponding to strong and persistent power on the band of 1-3 days while the intra-seasonal variability has power with periods of about 16-32 days (Fig. 2b). The spectral analysis further confirms that there is an obvious period band of 1–3 days in the deep SCSMOC time series (Fig. 2c). It is also found that the period corresponding to the power peak of SCSMOC is prolonged equatorward from 1 day at 20°N to 3 days at 10°N (Fig. 3a). It is noted that the near-inertial band in the SCS is from 1.46 days at 20°N to 3.59 days at 10°N (Chen et al, 2014). Comparing with the local inertial period in the SCS, the deep SCSMOC is at super-inertial frequencies (the frequency corresponding to the power peak is larger than the local inertial frequency), while the shallow SCSMOC is at inertial frequencies. However, the SCSMOC between 8°N and 10°N is at sub-inertial frequencies (the frequency corresponding to the power peak is less than the local inertial frequency). Our results also show that these near-inertial variations of the SCSMOC exist in other seasons and other years (not shown). The near-inertial variations of the SCSMOC also have a strong seasonality. The analysis of other months or years cannot change our conclusion significantly, so we just use the 2010 data to depict the near-inertial variations of the

SCSMOC.

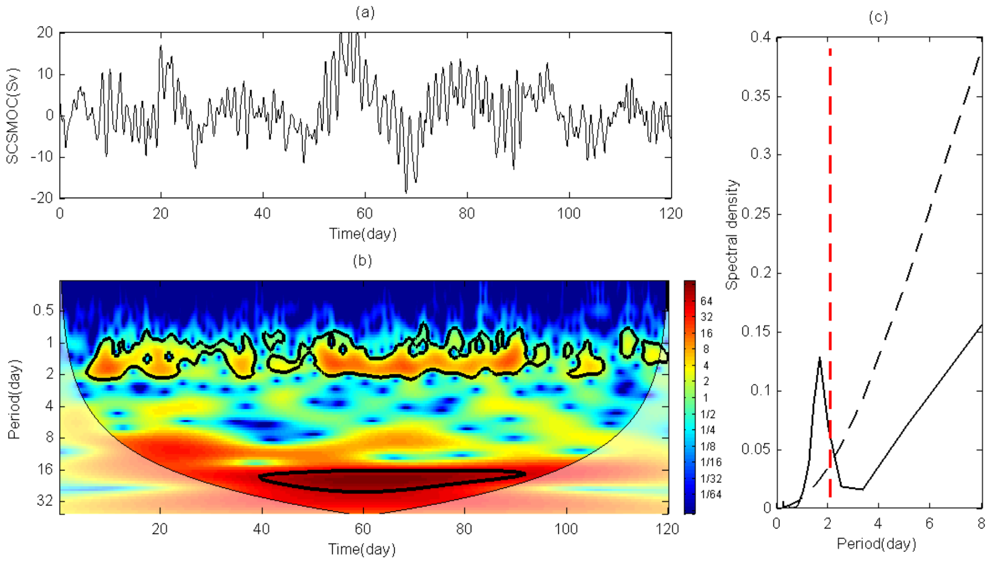

Figure 2 (a) Time series of SCSMOC at 1500m, 14°N; (b) The continuous wavelet power spectrum (black contours representing 95% significance); (c) The power spectrum (the dashed black line and red line show 95% confidence levels and the local inertial period respectively).

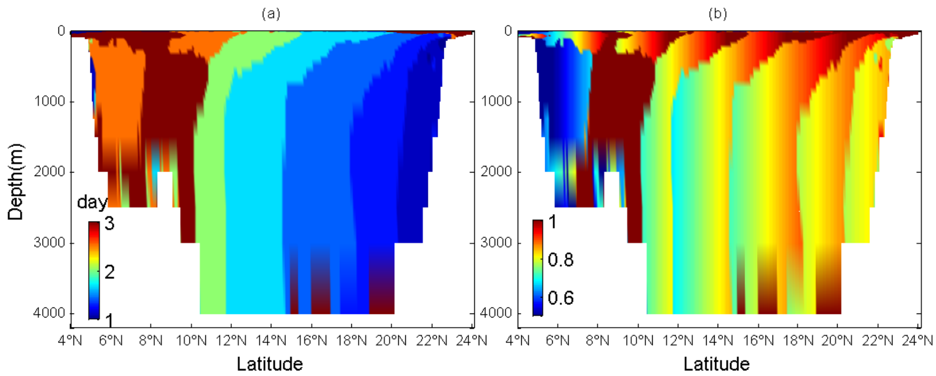

Figure 3 (a) The period corresponding to the power peak of the SCSMOC, which passes 95% significance; (b) The ratio of the peak period of the SCSMOC to the local inertial period.

To extract the near-inertial signal of the SCSMOC, a third-order Butterworth filter is applied to the time series of the SCSMOC at each latitude and depth. Cutoff frequencies are set at [0.33, 1] cpd, which is corresponding to the 1-3day band. The maximum standard deviation (STD) of the filtered SCSMOC signal is nearly 4 Sv (Fig. 4b), nearly half of the maximum STD of total SCSMOC in 2010 (Fig. 4a). The largest amplitude of the near-inertial signal in SCSMOC is found in mid layer (500–2500 m). There are two high STDs at the mid depth (500–2500 m), the northern one is between 16°N and 20°N, and the southern one between 12°N and 14°N (Fig. 4b). Near the Luzon Strait (around 19°N in Fig. 4b) there exists a maximum of the shallow SCSMOC variability in the layer (100–500 m).

Based on the snapshot of the integrated filtered meridional velocity field from the bottom to 1000m at 24:00, January 15, 2010 (Fig. 5a), it is obvious that the integrated velocity field consists of regularly alternating positive and negative bands. Furthermore, Fig. 5b is the snapshot of the filtered SCSMOC signal at the same time as in Fig. 5a. The spatial structure of the near inertial signal is stacked with regularly alternating positive and negative cells. The maximum amplitude of these cells is nearly 5Sv, and most of the cells concentrate in the depth between 1000m to 2500m and within the latitude between 10 °N and 20 °N while the cells are not so evident in the upper layer. These cells are stretched not in the meridional direction but in the vertical direction, which means each cell consists of both the strong upwelling branch and the downwelling branch. The regularly alternating positive and negative bands in the meridional direction imply a characteristic wavelength of ~150-200 km while the vertical coherent structure suggests that these cells are dominated by the first baroclinic mode, which is consistent with the near-inertial variations of AMOC (Blaker et al., 2012; Sévellec et al., 2013). From 4 °N to 10 °N and 20 °N to 22 °N, there are also weak cells. Upwelling and downwelling in the mid depths are also found in the open ocean like the Atlantic and Pacific Oceans based on the high-resolution model simulations where the vertical velocity was used to diagnose the deep ocean near-inertial gravity waves (Komori et al., 2008; von Storch, 2010). The pattern of the near-inertial variability of SCSMOC (Fig. 4b) is very similar to the near-inertial variability of the Atlantic Ocean (Komori et al., 2008; Blaker et al., 2012; Sévellec et al., 2013). The imprint of NIGWs in AMOC is also stacked with regularly alternating positive and negative cells between 10 and 40°N , which are spanning 500m to 4000m (Blaker et al., 2012; Sévellec et al., 2013). The power peak of AMOC is at super-inertial frequencies, which is similar to that of the SCSMOC.

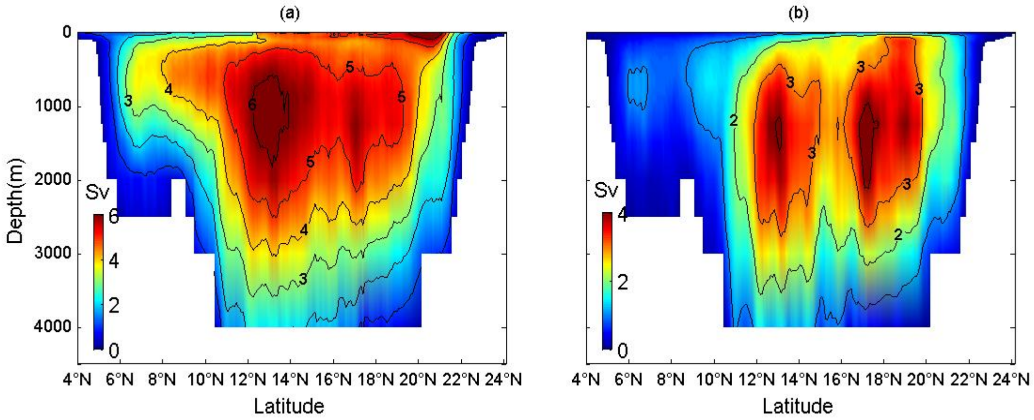

Figure 4 (a) The standard deviations of the SCSMOC in 2010and (b) The filtered 1-3day SCSMOC signal in 2010.

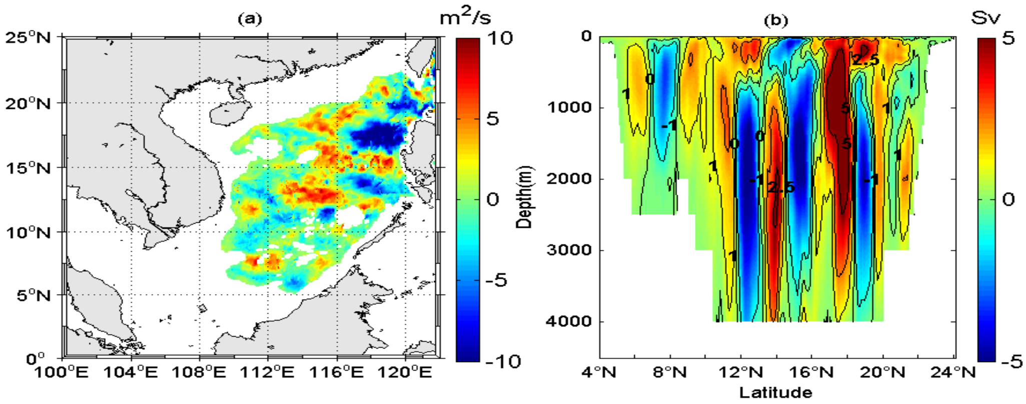

Figure 5 The snapshot of (a) the integrated meridional velocity field from the bottom to 1000m and (b) the filtered SCSMOC signal at 24:00, January, 2010.

To investigate the meridional propagation of near-inertial signals in the SCSMOC in mid-depths (500–2500m), Fig. 6 shows the meridional structure of the filtered near-inertial signal at 1500m in four typical months (January, April, July and October) in 2010. It is found that most of the signal propagates southwards from the region near Luzon Strait (where 18^{o}N is the latitude of the southern tip of the Luzon Strait in Fig. 6) regardless of the different months. The propagating velocity is about 1-3 m/s. It was noted that the NIGWs usually have the dominant frequency of f (Coriolis frequency) and usually propagate equatorward due to beta-dispersion (Anderson and Gill, 1979; Nagasawa et al., 2000; Garrett, 2001). The meridional propagation of the filtered SCSMOC signal and near inertial period (Fig. 3b) indicate that the striped pattern of the filtered 1-3day SCSMOC signal represents ocean NIGWs formed especially near the Luzon Strait and propagating equatorward.

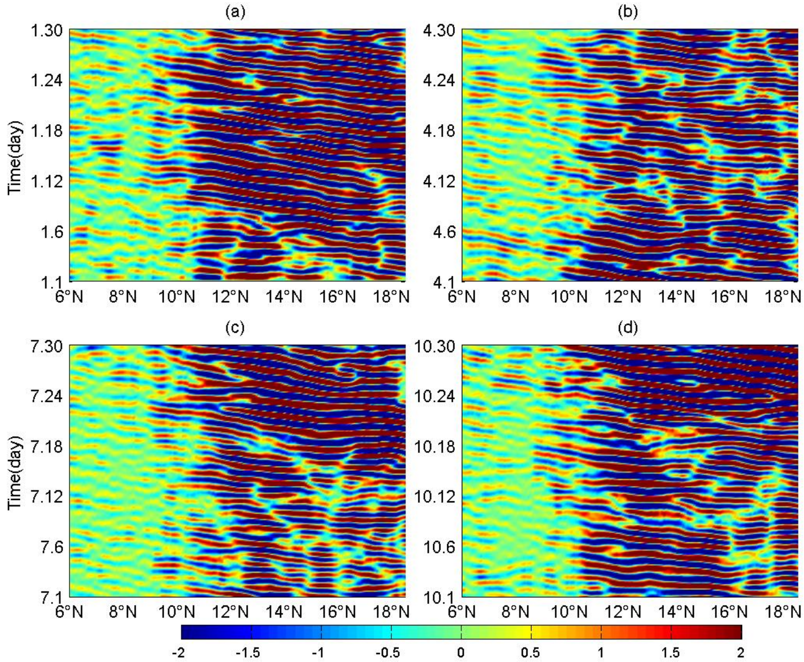

Figure 6 Time-latitude plot of 1-3day band-passed SCSMOC signal at 1500m in (a) January, (b) April, (c) July and (d) October in 2010.

4 Discussion

The East Asian monsoon system prevails over the SCS, which is frequently affected by strong tropical cyclones(TCs) originating from the western Pacific (Zheng et al., 2015). Strong vertical mixing and horizontal pressure gradients caused by typhoon winds can lead to the formation of strong NIGWs in the ocean interior (Garrett, 2001). Previous observations of NIGWs are focused on the upper layer in the SCS (Liang et al., 2005;Xie et al., 2009; Xu et al., 2013; Chen et al., 2013), only Yuan et al. (2002) have found there are strong NIGWs below 1800m in the northeastern SCS using two current-meters. A mooring was located at 114.57 °E, 17.99 °N, where the water depth is about 3500m. An Aanderaa current-meter was positioned at 300 m above the bottom and the valid current-meter data were collected from March 21, 2006 to September 19, 2006 with the sampling interval of 1 h. The 120-day data since April 1, 2006 was used in this study. The power spectrum of zonal velocity and meridional velocity in the mooring data and model output peak near the inertial frequency (Fig. 7).

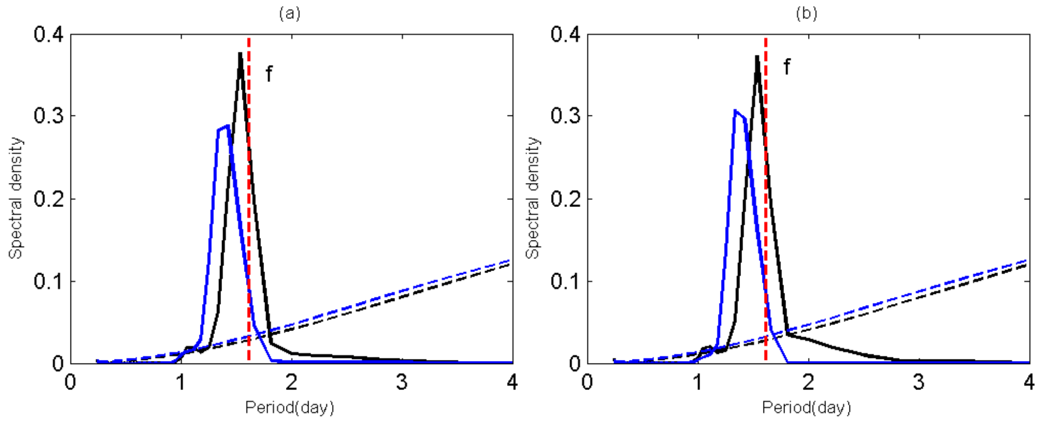

Figure 7 The power spectrum of zonal velocity (a) and meridional velocity (b) derived from the mooring (black line) and GLBu0.08 (blue line). The dashed black and blue line shows 95% confidence levels while the dashed red line represents the local inertial period. The tide effects have been removed in the mooring data.

Near-inertial variability in the ocean is mainly caused by wind variability through a resonant response of ocean currents to wind (Gill, 1984).The imprint of NIGWs on AMOC has been found mostly related to wintertime storm tracks (Blaker et al., 2012; Sévellec et al., 2013; Furuichi et al., 2013; Rimac et al., 2013) while the imprint of NIGWs on SCSMOC might be related to wind variability near Luzon Strait (Li et al., 2015). Figure 8 further shows the monthly mean near-inertial energy input by wind during four representative months (January, April, July and October) in 2010. It is found that wind-induced near-inertial energy input is always strong west of the Luzon Strait. In spring, autumn and winter, these strong high-frequency wind wakes in the Luzon Strait could drive the NIGWs near the Luzon Strait (Fig. 8a–b and d). An average of about 7 TCs pass through the Luzon Strait from the Northwest Pacific Ocean each year (Wang et al., 2007; Zheng et al., 2015), especially there were 2 TCs on July 2010 and 1 TC on October 2010 passing through the region to the west of the Luzon Strait, inducing strong wind-induced near-inertial energy input into the ocean (Fig. 8c), so TCs could also be drivers of the NIGWs near the Luzon Strait. The horizontal distribution of large integrated near-inertial kinetic energy roughly corresponds to that of the strong wind-induced near-inertial energy input (Figs. 8 and 9). In addition, due to beta-dispersion of the NIGWs (Anderson and Gill, 1979;

Garrett, 2001), the region of the integrated near-inertial kinetic energy is stretched equatorward. Furthermore, a strong density front usually exists in the Luzon strait due to the Kuroshio (Wang et al., 2001), inducing positive vorticity west of the Kuroshio and negative vorticity to its east. On the one hand, the disturbance of the front (Kuroshio) can drive NIGWs through geostrophic adjustment (Kunze, 1985; Wang et al., 2009; Whitt et al., 2013). On the other hand, the transfer of near-inertial energy to the deep ocean can be enhanced by the negative vorticity field (Lee et al., 1998; Zhai et al., 2005). As the NIGWs leave the density front, they will propagate equatorward due to beta-dispersion (Anderson and Gill, 1979; Garrett, 2001). Therefore, strong NIGWs near the Luzon Strait can be detected in the deep SCSMOC south of the Luzon Strait as far as 10°N. Although the Kuroshio intrusion is a low-frequency process, it can provide the background vorticity field for the vertical propagation through the chimney effect (Lee et al., 1998; Zhai et al., 2005) because negative vorticity west of the Kuroshio near the Luzon Strait always exists. When the Kuroshio intrusion changes states among the looping path, the leaking path, and the leaping path (Nan et al., 2015), the geostrophic adjustment will also trigger near-inertial waves. This process is well depicted by Nagai et al(2015) in relation to the Kuroshio meander.The question of the relative importance of high-frequency wind and Kuroshio intrusion on the near-inertial variations of SCSMOC needs more observational and modelling work in a future study.

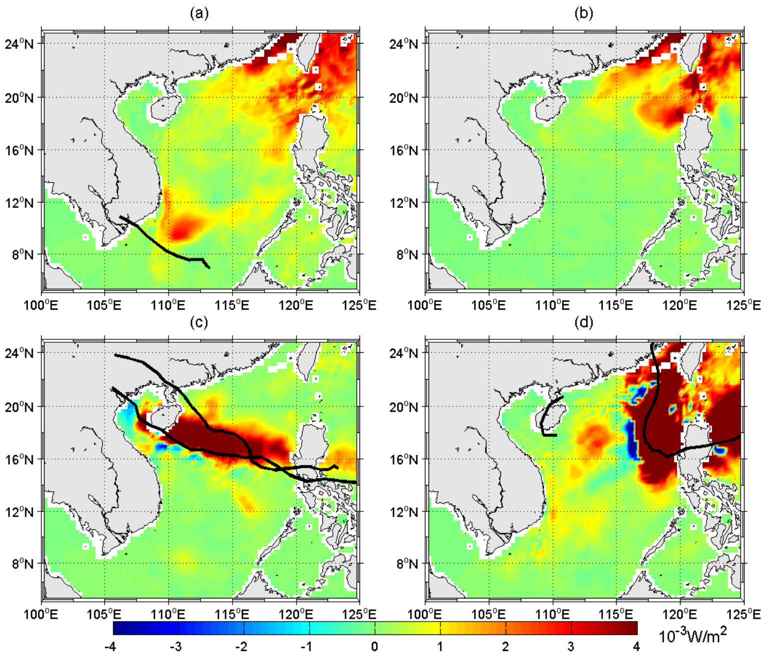

Figure 8 Spatial distribution of the monthly mean near-inertial energy input by wind in (a) January, (b) April, (c) July and (d) October in 2010.The black line is the best track of TC derived from the Joint Typhoon Warning Center (JTWC).

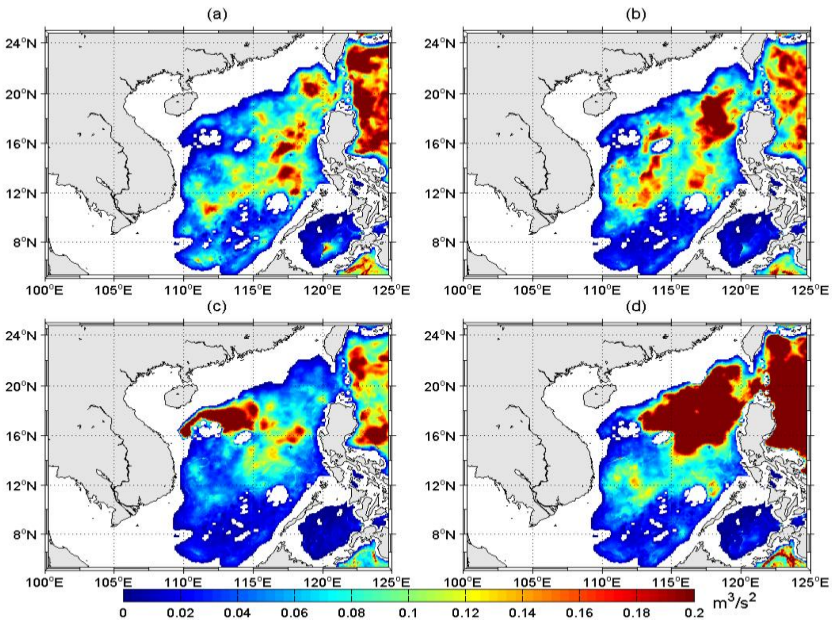

Figure 9 The monthly mean integrated near-inertial kinetic energy from the bottom to 1000m in (a) January, (b) April, (c) July and (d) October in 2010.

5 Conclusion

A high-resolution ocean reanalysis (GLBu0.08) is used to reveal characteristics of the near-inertial variability in the deep SCSMOC. It is shown that there is an obvious high power peak on the near-inertial band in the deep SCSMOC time series. The maximum amplitude of the near-inertial signal in the SCSMOC is nearly 4 Sv, and its largest amplitude appears in the middle layer (500–2500m).The near-inertial signal in the SCSMOC propagates equatorward with the speed of 1-3m/s from the region near the Luzon Strait. The imprint of NIGWs on the SCSMOC highlights the possible importance of NIGWs in the horizontal and vertical redistribution of wind energy throughout the SCS. Although the effect of these NIGWs in depth on turbulent mixing is still unknown, however, it is speculated that the breaking of these deep ocean NIGWs could be a candidate for the enhanced mixing in the SCS.

Acknowledgements

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