**Variability and dynamics of the Kuroshio and Mindanao Current during the 2010-2011 La Niña and in late 2012**

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First Institute of Oceanography, Ministry of Natural Resources, Qingdao, China, 266071**Abstract:** Variability of two Pacific western boundary currents (WBCs)—the Kuroshio and the Mindanao Current, during the recent strong 2010-2011 La Niña event is investigated using ship-based hydrographic observations and moored current meter data collected off the east coasts of the Philippines. The geostrophic currents calculated using the hydrographic observations show that, during the 2010-2011 La Niña winter, the Kuroshio decreased by ~ 10 Sv (1 Sv= 106 m3 s-1) whereas the Mindanao Current increases by ~ 5-10 Sv, relative to the normal winter in late 2012. The interannual variability based on the hydrographic observations is confirmed by moored current measurements and altimeter geostrophic currents. A coastally trapped Kelvin wave model is used to explain the interannual variability of the two WBCs during the different ENSO phases. The good comparison of the simulated sea level anomalies around the Philippines with the altimeter data suggest that the interannual variability of the WBCs is associated with Kelvin wave propagation from the Sulawesi-Sulu seas clockwise around the Philippines archipelago. We identified that the Kelvin waves are excited by downwelling equatorial Rossby waves propagating into the Indonesian seas during the La Niña. The transport anomalies of the WBCs are comparable to the total meridional transport anomalies integrated across the interior North Pacific Ocean, suggesting the importance of the WBCs in the heat charge-discharge processes of the western Pacific warm pool during ENSO events.

**Keywords**: western boundary current, Kuroshio, Mindanao Current, North Equatorial Current, ENSO, coastal Kelvin wave

**Plain language significance**

The two WBCs—the Kuroshio and the Mindanao Current—play the role of closing the subtropical and tropical gyre circulation of the Pacific Ocean. Their variability during ENSO is unknown. Existing studies based on numerical modeling suggest their variability highly correlated with ENSO, with the Kuroshio stronger and Mindanao Current weaker during La Niña and vice versa during El Niño. Here, we use in situ hydrographic observations combined with mooring and satellite altimeter data to show that the Kuroshio transport decreases and the Mindanao Current transport increases during the 2010-2011 La Niña, the dynamics of which are controlled by the Kelvin wave propagation from the Sulawesi-Sulu seas clockwise around the Philippine archipelago. The result is importance for the warm pool dynamics during ENSO.

1. Introduction

The North Pacific Ocean circulation features western intensification, with the western boundary currents (WBCs) along the east Philippine coasts much stronger than the circulation in the interior basin. This phenomenon has been studied for over one half of a century, leading to the births of the modern wind-driven ocean circulation theories (Sverdrup, 1947; Stommel, 1948; Munk, 1950). An early description of the general ocean circulation in the Philippine Sea and in the southeast Asian marginal seas is given by Wyrtki (1961) based on historical data, showing that the North Equatorial Current (NEC) of the Pacific Ocean flows westward against the east Philippine coasts and splits into two WBCs, the Kuroshio and the Mindanao Current (MC). The detailed structure of the WBCs was not disclosed until the late 1960s during the Cooperative Study of the Kuroshio (CSK) (Nitani, 1972). Later, the cooperative research program between the People’s Republic of China and the United States during the Tropical Ocean Global Atmosphere (TOGA) program made measurements of these WBCs along the periphery of a box east of the Philippines (Toole et al., 1990). The Western Equatorial Pacific Ocean Circulation Study (WEPOCS) project from 1985-1988 has conducted three surveys in the far western equatorial Pacific Ocean, and uncovered important structures of the MC and the New Guinea Coastal Current/Undercurrent (NGCC/UC) (Lindstrom et al., 1987; Lukas et al., 1991). Wijffels et al. (1995) summarized all of these cruises in the 1980s and early 1990s, based on which the mean circulation and transport of the MC were estimated. The low-latitude WBCs have been systemically observed during the past decade with the implementation of the Northwestern Pacific Ocean Circulation and Climate Experiment (NPOCE, Hu et al., 2011; Ma et al., 2022).

Earlier measurements of the WBC transports off the east Philippine coasts have mostly been made in boreal summer-fall (Toole et al., 1990; Hu et al., 1991; Lukas et al., 1991; Wijffels et al., 1995). The interannual anomalies of the Kuroshio and the MC at the mature phase of El Niño and Southern Oscillations (ENSO) events have rarely been obtained. Kashino et al. (2009) showed stronger MC and weaker Kuroshio in late 2006 El Niño than in early 2008 La Niña using ship-board Accoustic Doppler Current Profiler (SADCP), but the dynamic height difference along the WBC sections in their hydrographic observations seems to suggest an opposite variational pattern. In addition, some other studies showed contrasting results. For example, Qu et al. (2008) reported a minimum transport of the NEC–Kuroshio-MC system during the mature phase of the 1986-1987 El Niño and maximum transports in the years before and after the event. Hu and Hu (2014) suggested that the interannual variability of the NEC, observed by 16 years of repeated SADCP sections, is tied to the Niño 3.4 index but lags the latter by 6 months. In contrast, several other studies illustrated that the Oceanic Niño Index (ONI) has no significant simultaneous correlation with the upstream Kuroshio transport (Zhai and Hu, 2013; Chen et al. 2015a). For instance, using sea level records from tidal gauges, Lukas (1988) found that the fluctuations of the MC have no apparent relationship with the strength of ENSO.

Indeed, variations of the North Pacific WBCs during the mature phase of major ENSO events are not very well understood partly due to the scarcity of direct observations. Although limited, there are several mooring-based studies reported a strengthened MC after the onset of the 2002-2003 El Niño (Kashino et al. 2005), and during the development of the 2015-2016 El Niño from July to December 2015 (Liu et al., 2023). Using long mooring measurements, Hu et al. (2016) reported the weakest MC in June 2012, in contrast to the maximum peaks in December 2010 and June 2014, with no significant relation found between the MC velocity and the Niño 3.4 index. Chen et al. (2015a) also reported low correlation of 0.05 between the interannual surface velocity off the east Luzon coast and ONI, indicating that the interannual variations of the WBC do not always follow the ENSO cycle (Zhang et al., 2014).

The westward mass transport of the NEC splits into the northward and southward flows along the Philippine coasts. The NEC split latitude is estimated to be between 11ºN and 14.5ºN at the sea surface, and increases northward with depth (Nitani, 1972; Toole et al., 1990; Qu et al., 1998, 1999; Qu and Lukas, 2003). Existing modeling studies have suggested that the interannual variations of the NEC split latitude should be highly correlated with ENSO, moving northward during El Niño and southward during La Niña (Qiu and Lukas, 1996). Therefore, the Kuroshio transport is expected to decrease and the MC transport to increase during El Niño, and vice versa during La Niña (Kim et al., 2004). These modeling studies thus suggest that the WBCs in the North Pacific Ocean counter the recharge and discharge of equatorial Pacific warm water volume by the interior Sverdrup circulation during ENSO events.

With the advent of sea level measurements by satellite altimeters, variations of the NEC split latitude have been investigated using the altimetry-derived surface geostrophic currents (Wang and Hu, 2006; Qiu and Chen, 2010). The interannual NEC split variations derived from the altimeter data is similar to those derived from previous numerical simulations. However, the altimeter data, especially the early Topex/Poseidon data, do not resolve the WBCs well since they suffer from the edge effects near the coasts. A comprehensive validation of the altimeter analysis and the numerical-model-based results is required.

Existing studies have attributed the interannual NEC split variations to the propagation of the wind-driven Rossby waves from the interior North Pacific (Qiu and Lukas, 1996; Kim et al., 2004; Qiu and Chen, 2010; Zhai and Hu, 2013). However, the interactions of the NEC–Kuroshio-MC system with the circulation in the South China Sea and the Indonesian seas have not been taken into consideration. An earlier modeling study by Metzger and Hurlburt (1996) has suggested a coupled western Pacific-South China Sea (SCS) circulation, which was later shown to be associated with the Kelvin wave propagation into the South China Sea along the west Philippine coasts based on the altimeter data (Liu et al., 2011; Zhuang et al., 2013). Recent modeling study has suggested that the Mindoro–Sibutu Pathway is the gateway for the Kelvin waves to propagate clockwise around the Philippines from the western Pacific Ocean into the SCS (Li et al., 2021). However, it is still unclear if the Kelvin waves can reach the east coasts to impact the NEC splitting and the WBCs in the presence of the strong Kuroshio in the Luzon Strait in reality.

Earlier studies of ENSO dynamics have demonstrated that interannual variations of the tropical Pacific Ocean circulation play an important role in sea surface temperature variability and global atmospheric circulation (Clarke, 2008; Sarachik and Cane, 2010; Hu et al., 2015). Existing theory has hypothesized that the anomalous Sverdrup interior circulation discharge or recharge the equatorial warm water volume and heat content during El Niño or La Niña, respectively (Jin, 1997a, b). However, the potential effects of the WBCs on the recharge/discharge of the warm pool and the tropical climate variations have been overlooked so far.

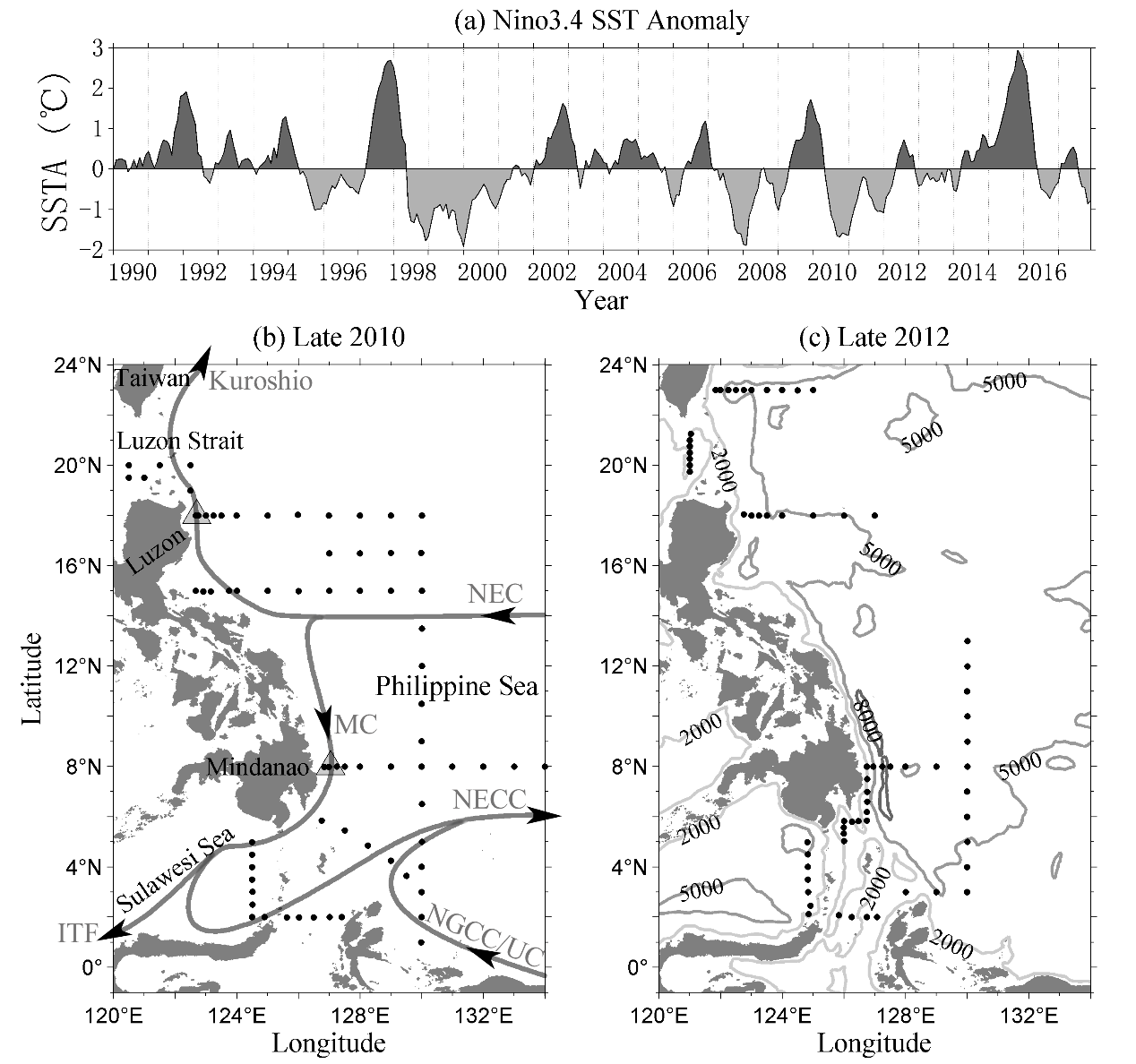
Since 2010, multiple research cruises on an annual basis have been conducted to survey the northwestern Pacific Ocean. Among them, two cruises were carried out during late 2010, the mature phase of a strong La Niña, and late 2012 under a neutral ENSO condition. The surveys made measurements along the 18ºN and 8ºN sections off the east Philippine coasts, which represent the source regions of the Kuroshio and the MC, respectively. The variability of the WBCs in a La Niña winter in comparison with a normal winter is evaluated in this study.

1. Data and Method

The data used in this study include ship-based hydrographic data during the research cruises, density profiles from the international Argo project, satellite altimeter data, and long time series of moored current meter data. The analyses of these data have resulted in consistent WBC transport variations.

* 1. **Hydrography data**

The periods of the two comparative cruises are late November through December of 2010 and 2012, corresponding to the 2010-2011 La Niña winter and a normal late 2012 winter (Table 1). Based on the Niño 3.4 index calculated as the average sea surface temperature anomalies in the area of (170ºW–120ºW, 5ºS–5ºN) of the NOAA OISST.v2 dataset (http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices), the 2010-2011 La Niña is one of the strongest La Niña events in the recent few decades (Fig. 1). The difference of the ocean circulation between the two winters may represent the interannual anomalies during the strong 2010-2011 La Niña peak to a certain extent.



**Figure 1.** a) Niño 3.4 index based on OISST.v2 dataset, showing a La Niña state in the winter of 2010 and a normal state in the winter of 2012. Unit is ℃. b) CTD stations (black dots) during the winter cruises of 2010. Arrows and triangles indicate the general flows pattern and locations of subsurface moorings, respectively. c) Same as (b) but for the winter 2012 cruise. Contours in (c) are water depths in meters.

**Table 1.** Time windows of the sectional surveys

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | 18ºN | 8ºN | 130ºE | 8ºN (second visit, 128ºE west) |
| 2010 | 20th–26th November | 2nd –5th December | 20th –24th December | 17th –18th December |
| 2012 | 25th –27th November | 8th –10th December | 5th –12th December | – |

The research cruises were carried out on board of R/V “Kexue-1” using a SeaBird 911/917 plus conductivity-temperature-depth (CTD) sensor manufactured by the SeaBird Electronics (SBE), Inc. to measure ocean temperature and salinity profiles. CTD sectional casts were made along 18ºN, 8ºN, and 130ºE in the western Pacific Ocean, which represent the states of the Kuroshio origin, the MC, and the NEC in the western Pacific in the two winters (Fig. 1).

The raw CTD downcast data were processed using the manufacturer’s software, averaged into 10 dbar pressure bins in the vertical, and interpolated onto a 0.25º-interval zonal grid in the 8ºN and 18ºN sections and onto a 1º-interval meridional grid in the 130ºE section using the Akima interpolation (Akima, 1970).

* 1. **Geostrophic currents**

The geostrophic currents of the WBCs are calculated in reference to the 2,000 dbar level of no motion. The currents in the upper layer above the pycnocline are not sensitive to the choice of the level of no motion deeper than 1,500 m (Hu et al., 2021). The subsurface geostrophic currents are sensitive to the choice of the reference level, their transports are, therefore, not estimated in this paper. The dynamic height near the sea bottom, where water depth is less than 2,000 dbar, was assumed to be the same as the nearby seaward station, which is equivalent to assuming zero bottom geostrophic velocity.

The CTD sections along 18ºN and 8ºN stop at about 0.25º from the coast. The currents between the coast and the western-most station of the section are linearly interpolated assuming the nonslip condition at the coast. A comparison of the linear interpolation within 0.5º from the coast with the Munk WBC model, assuming a horizontal mixing coefficient of 800 m2 s-1 (Lien et al., 2014), suggests an error of about 13.5% in the transport estimate, which is small.

* 1. **Moored ADCP data**

During the 2010 winter cruise, two moorings were deployed east of the Philippine coast and were later retrieved and redeployed in July 2011 (represented as triangles in Fig. 1b). Following the recovery of the second set of moorings during the 2012 winter cruise, the duration of direct measurements extended to nearly two years. With a 75kHz upward-looking ADCP at a 700m nominal depth, the north mooring was deployed in the Kuroshio at 18°N, 122.7°E on November 20, 2010. The instruments were redeployed on July 11, 2011, and recovered on October 30, 2012, with both upward- and downward-looking ADCPs at about 500 m depth during the second deployment. The south mooring at 8°N, 127°E was equipped with upward- and downward-looking 75kHz ADCPs at 500 m depth for MC observation from December 1, 2010, to December 7, 2012, with one retrieval and redeployment on July 15-16, 2011. ADCPs measured velocity in sixty 8-meter bins every 1 hour or 30 minutes. For more details, see Hu et al. (2013), Zhang et al. (2014), and Chen et al. (2015a).

Daily averages were calculated from the original velocity measurements of these moorings for further analysis. The data shallower than 50 m were discarded due to contamination from reflection at the surface. This double-mooring dataset provides an unprecedented opportunity to investigate the synchronous variations of the two WBCs.

* 1. **Argo profiles and absolute geostrophic currents**

The Argo profile data of the upper 2 000 dbar were downloaded from China Argo Real-time Data Center (ftp://ftp.argo.org.cn/ pub/ARGO/global/). We used those profiles concurrent to the cruise period from November through December of 2012 to supplement the missing CTD casts in the vicinity of 18°N, 130°E (Fig. 1b). The Argo profiles within 45 km of the CTD stations were used to fill the missing data (128º-130ºE along 18ºN and 14º-18 ºN along 130 ºE with a 1º interval). Weighted averages of the Argo profiles according to their inverse distance squared within 45 km from each CTD station are used to calculate the geostrophic currents. The system errors between the Argo and the CTD profiles can be neglected since both kinds of the instruments are equipped with the sensors of the same SBE company, e.g. SBE 911 or 917.

A set of gridded Argo data were downloaded from the website https://sio-argo.ucsd.edu/RG\_Climatology.html, which includes salinity and temperature profiles of upper 2000 m at a 1º longitude by 1º latitude resolution (Roemmich and Gilson, 2009) and were used to estimate the geostrophic meridional transport of the interior Pacific Ocean gyre. Absolute geostrophic currents (AGCs) were calculated from the gridded data using the P-vector method (Chu, 1995), showing good agreement with the altimeter geostrophic currents at the sea surface and with moored current measurements at a few locations in the tropical North Pacific Ocean (Yuan et al., 2014).

* 1. **Satellite altimeter data**

The satellite altimeter sea level L4 product was distributed by the Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu) in November 2022. The products are processed with the CNES/CLS DUACS (Data Unification and Altimeter Combination System) system. The delayed-time, merged, global ocean gridded absolute dynamic topography (ADT, sea surface height above geoid) and the absolute surface geostrophic velocity of the dataset are adopted in this study. The data have a 1/4°×1/4° Mercator spatial resolution and a 1-day temporal resolution. The daily data were monthly averaged for further analyses. The sea level anomaly (SLA) was then calculated by referencing the ADT to the monthly climatology data spanning the period of 1993-2021.

* 1. **Transport of the WBCs derived from ADT**

In the tropical Pacific, the ocean circulation can be approximated by a 1.5-layer reduced gravity model, given the existence of a strong pycnocline that separates the upper layer from the abyssal ocean. Near the western boundary, the velocity of the WBC, including all of the locally and remotely forced currents, is governed by the geostrophic balance:

(1)

where *v* is the meridional velocity, *f* the Coriolis parameter, *h* the upper layer thickness, , the gravitational acceleration, 𝜌 the sea water density, and Δ𝜌 the density difference between the upper and abyssal layers. From equation (1) we can calculate the meridional transport of the WBC as:

where is the coordinate of the western boundary and is the width of the WBC. Considering in the reduced gravity model, is calculated as:

(2)

where is the vertical displacement (positive upward) of the sea surface which can be represented by the ADT anomalies. The difference of the sea level squared () across the WBC is thus used to represent the WBC transport, the interannual anomalies of which are analyzed in our paper.

* 1. **The Linear Coastally Trapped Kelvin Wave Model**

The Kelvin wave model is based on the analytical linear wave model described by Gill (1982), and forced by winds stress along the Kelvin wave pathway. Sprintall et al. (2000) and Hu et al. (2019) used the model to predict the sea level variations in the Indonesian seas associated with the propagation of Kelvin wave. In this study, we employ the same model to investigate the sea level propagation around the Philippine coasts forced by the Kelvin waves and the local winds. The model integrates the momentum equation in the alongshore direction as follows:

(3)

Here, represents the sea level anomaly (SLA) along the Kelvin wave characteristics line. denotes the alongshore wind stress projected onto each baroclinic mode, and is the acceleration due to gravity. The first 10 baroclinic modes decomposed from the ERA5 ocean dataset are used in this study. The wave speed of the first baroclinic mode, , is 3.0 m s-1 near the Philippines (Chelton et al., 1998). We replace with , allowing the integration of (3) along the Kelvin wave characteristics to yield the solution of at any location along a Kelvin wave pathway at any given time.

1. Results

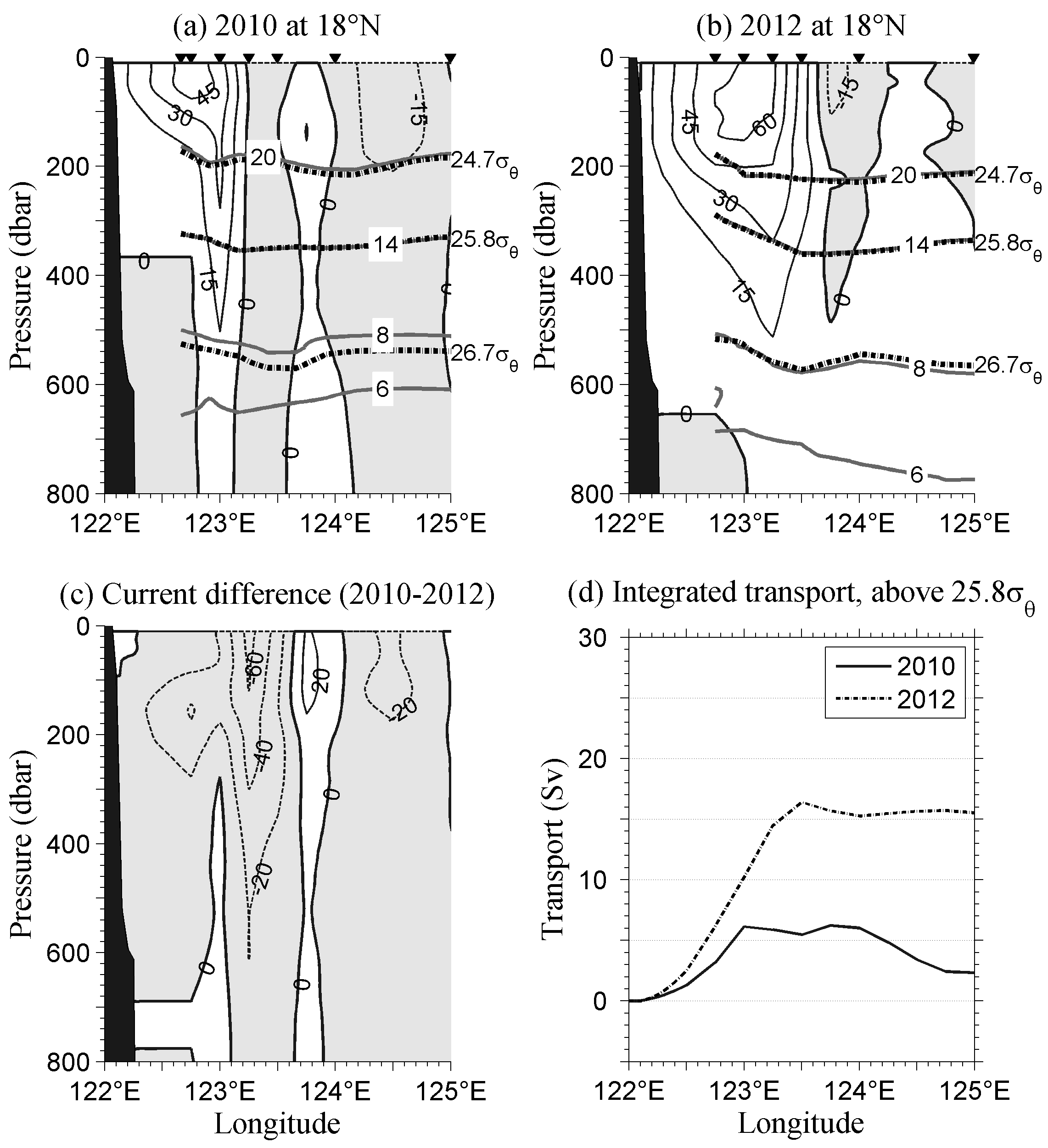
In this section, the NEC-Kuroshio-MC system and its variations are analyzed based on the geostrophic currents and the moored current meter data, combining with satellite data.

* 1. **The NEC-Kuroshio-MC system in the in-situ observation**

The two surveys were conducted in nearly the same calendar days of the two winters of 2010 and 2012, between which the subsurface moorings equipped with ADCPs measured the WBCs’ velocities at a single point. These data provide an unprecedented opportunity to examine the interannual variations of the NEC-Kuroshio-MC system.

3.1.1. Geostrophic currents in the 18ºN section

The distributions of temperature, salinity, and geostrophic currents in reference to the 2000 m level of no motion in the 18ºN section in these two winters are shown in Figure 2. Two density levels of 24.7σθ (i.e., potential density minus 1000 kg m-3) and 25.8σθ, roughly overlapping with the 20 ℃ and 14 ℃ isotherms, respectively, represent the upper and lower limits of the pycnocline (Meyers, 1979; Kessler and Taft, 1987).

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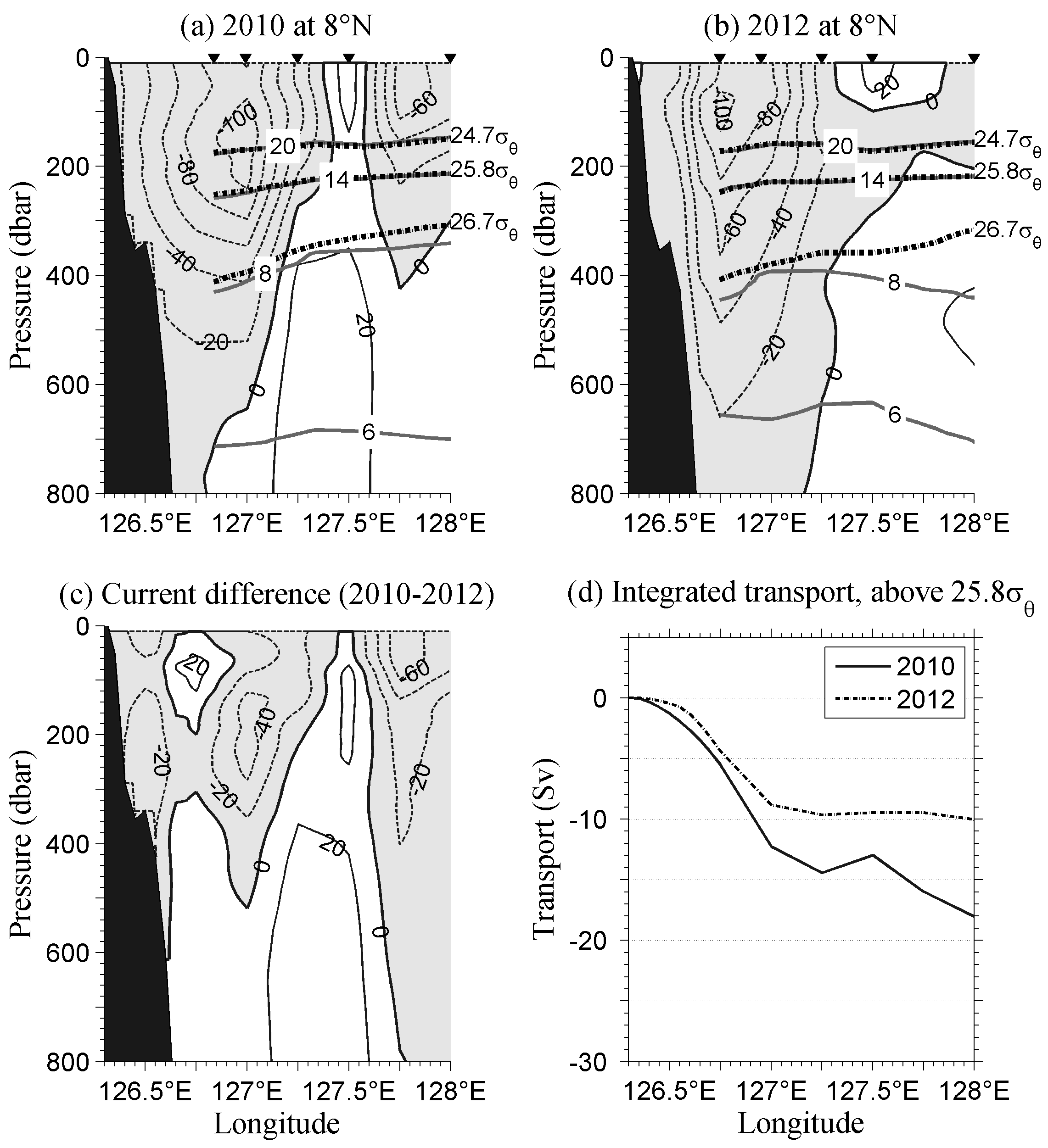
**Figure 2.** Distribution of potential temperature (thick contour), and meridional geostrophic currents (thin contour) in the 18ºN section in the winters of 2010 (a) and 2012 (b). The geostrophic currents are in reference to the 2,000 m level of no motion. c) The difference of the meridional geostrophic currents of the two winters. Solid (dash) contours indicate northward (southward) currents. Solid-gray curves mark the potential temperature. The 24.7σθ, 25.8σθ and 26.7σθ density surfaces are plotted in dot-dash curves in (a) and (b). d) The integrated transports above the 25.8σθ density surface from the western boundary. Current unit is cm s-1 , temperature in ℃, and the integrated transport in Sv. Shading in (a-c) indicates southward flow.

The width and magnitude of the Kuroshio origin during the 2010-2011 La Niña winter in the 18ºN section are noticeably smaller than those in the winter of late 2012, suggesting that the strength of the Kuroshio in the origin decreases during the La Niña event (Figs. 2a,b). The differences of the meridional geostrophic currents in the 18ºN section between the two winters (Fig. 2c), representing the WBC anomalies during the La Niña winter, are predominantly negative, suggesting that the Kuroshio origin is weakened significantly during the 2010 La Niña mature phase.

The geostrophic transports are integrated from the Philippine coast offshore, which bring the transports back to its mainstream value after crossing the eddies. The integrated meridional transports above the 25.8σθ density surface from the western boundary clearly show that the transport of the WBC west of 124ºE is about 6 Sv (1 Sv=106 m3 s-1) in the winter of late 2010, 10 Sv smaller than in the winter of late 2012. The 25.8σθ density surface is chose because of its proximity to the ocean thermocline, above which is the wind driven circulation important for ENSO dynamics. The weakening of the Kuroshio origin transport is also confirmed by the transport calculation above the 24.7σθ and 26.7σθ surfaces (figure omitted).

3.1.2. Geostrophic currents in the 8ºN section

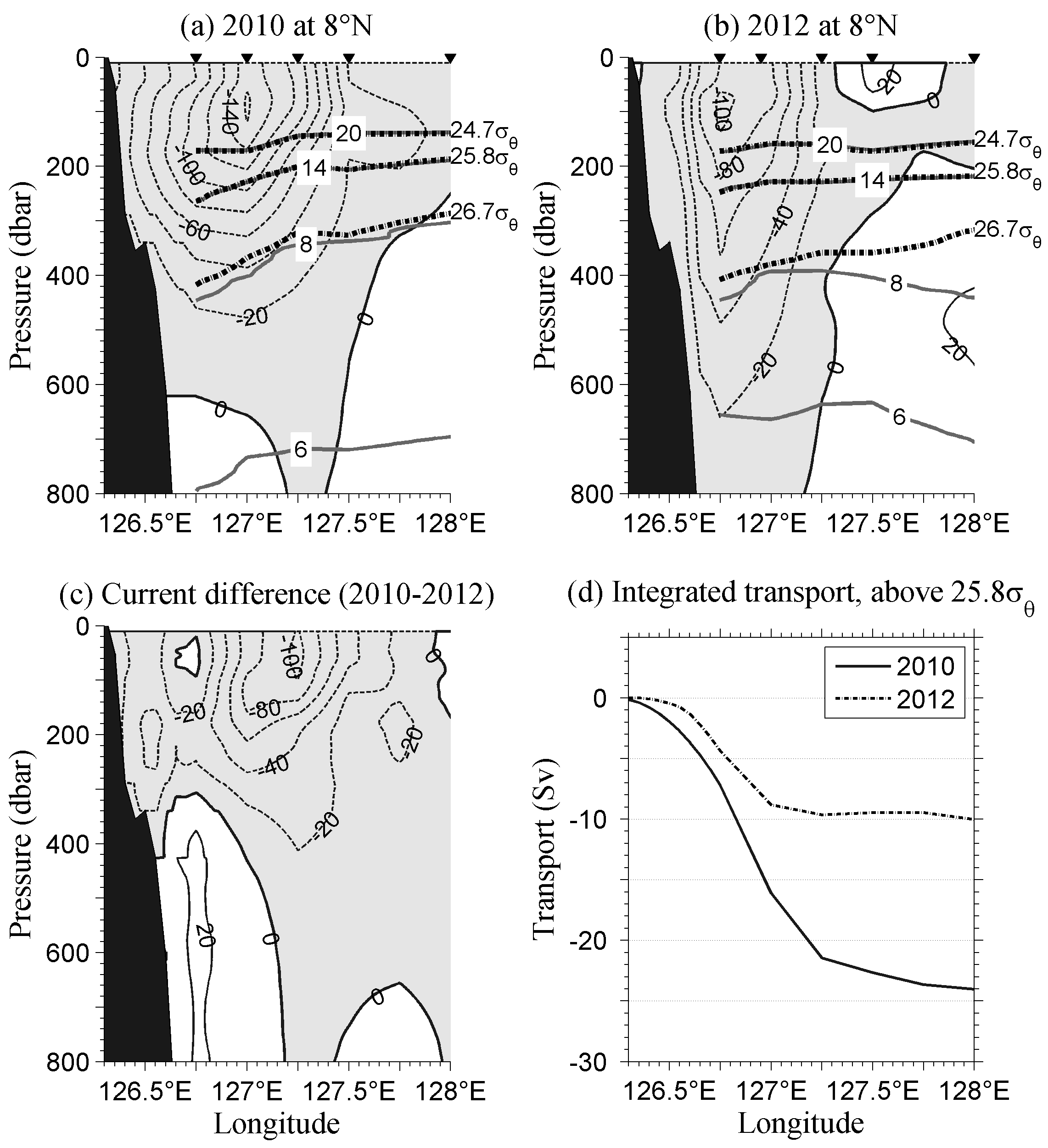
In comparison, the speed and width of the southward MC are elarger in the winter of late 2010 than in the winter of late 2012 in the 8ºN section (Fig. 3). The difference of the meridional geostrophic currents in the 8ºN section shows predominantly southward anomalies in the upper layer, suggesting a strengthened MC in the 2010-2011 La Niña winter. The integrated meridional transports above the 25.8σθ density surface from the western boundary show that the transport of the MC west of 128ºE is about 5 Sv larger in the winter of late 2010 than in the winter of late 2012.



**Figure 3.** Similar to Fig. 2 but for 8ºN section

In the subsurface, the geostrophic currents show a northward current offshore in the late 2010 winter, which could be the Mindanao Undercurrent (Hu et al., 1991) or a part of an anticyclonic eddy (Kashino et al., 2015). This current essentially disappeared in the winter of late 2012, suggesting significant variability of this subsurface flow.

During the late 2010 winter survey, the western-most four stations of the 8ºN section were visited for the second time about two weeks after the first visit. The geostrophic currents of the second visit also show a stronger MC southward in the surface layer and anomalous northward currents in the subsurface than in the winter of late 2012 (Fig. 4). The southward transport of the MC west of 128ºE and above the 25.8σθ density surface has exceeded 20 Sv, showing an increase of more than 10 Sv from the winter of 2012. The upper layer of the MC is stronger in the second visit than in the first, because an eddy was present in the area during the first visit, reducing the southward speed somewhat at that time (Fig. 3a). The existence of the eddy is confirmed by satellite sea level data. It was centered at 128.4ºE, 7.5ºN from 4th to 10th of December, and disappeared on 12th of that month (figure omitted). Whether influenced by the eddy or not, the MC in the two observations in 2010 remain consistently stronger than that in 2012. The detailed effects of eddy perturbations on the WBCs are beyond the scope of this study.

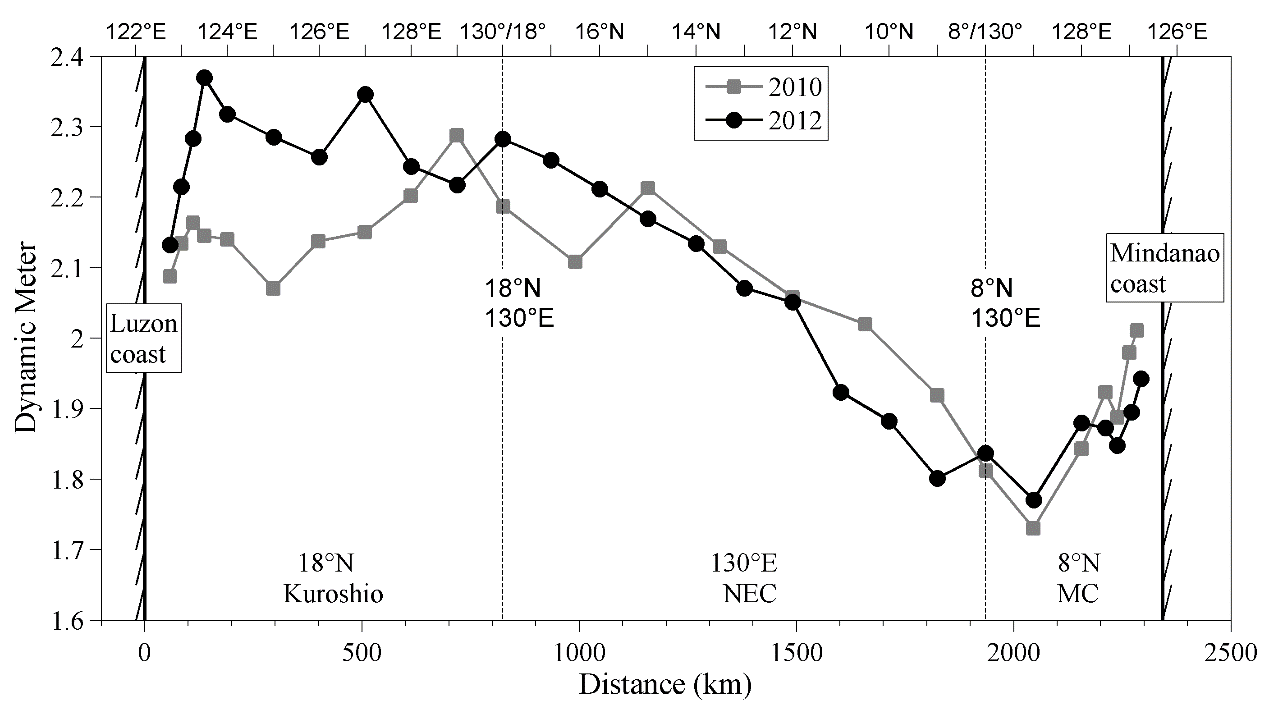


**Figure 4.** Similar to Fig. 3, but for the 2nd visit of 8ºN section of late 2010 winter.

3.1.3. Dynamic heights of the NEC-Kuroshio-MC system

The dynamic heights relative to 1000 dbar along the 18° N, 130°E, and 8°N sections are shown in Figure 5. This figure can be compared with Figure 3 in Toole et al. (1990) and with Figure 4 in Kashino et al. (2009). The gradients of the dynamic heights indicate the magnitude of shallow geostrophic currents across each section. The dynamic height variations along 18° N and 8° N sections over the two cruises are quite pronounced, especially near the boundary. The net height changes during the late 2010 winter are smaller in the 18° N section and larger in the 8° N section than in the late 2012 winter, suggesting a stronger MC and weaker Kuroshio in the late 2010 La Niña winter than in the late 2012 normal winter.

A stronger MC and weaker Kuroshio off the east Philippine coasts during late 2010 than those during late 2012 can be also respectively inferred from the zonal ADT gradient along 8 ºN and 18 ºN averaged from November to January (Li et al., 2018). The results show that a robust interannual variation of the WBCs is still present at low frequencies, consistent with the diagnosed results based on in-situ CTD data.

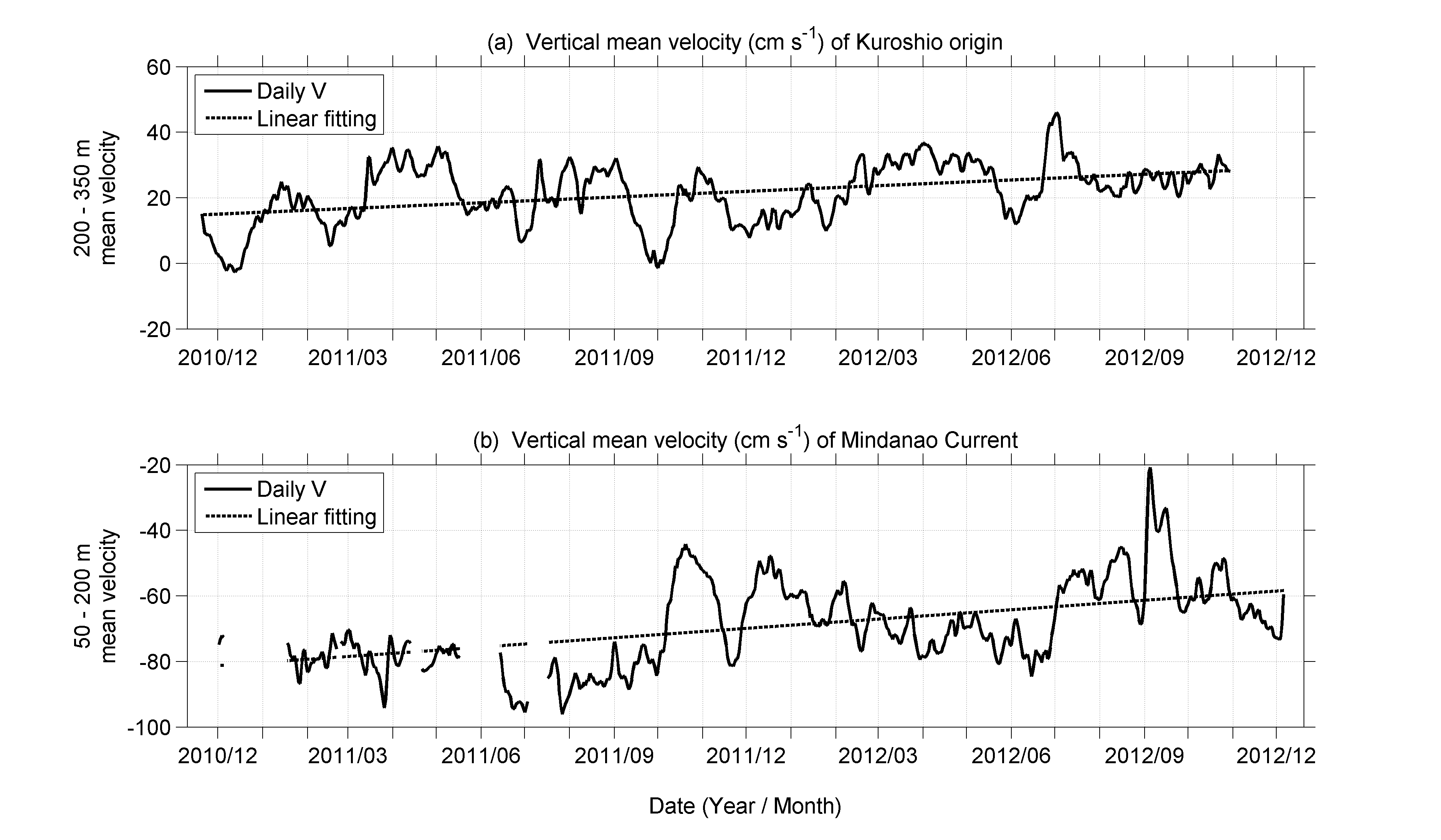
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**Figure 5.** Dynamic height along the 18° N, 130°E, and 8°N sections relative to 1000 dbar in the winter of 2010 (square) and 2012 (dot). The bottom x-axis indicates the distance from the east Luzon coast at 18ºN along the boundary of the box surrounded by 18ºN, 130ºE and 8ºN sections, with the longitudes/latitudes marked in the top x-axis. The two feathered vertical lines at the ends mark the east coasts of the Philippines at 18ºN and 8ºN, respectively. The two dotted vertical lines in the middle indicate the corners of the box.

The interannual variability of the sectional WBC transports in this study is different from that of Toole et al. (1990) showing stronger transports of the NEC, the Kuroshio, and the MC in the spring of 1988 during a cold phased of ENSO than in the fall of 1987 after the 1986-1987 El Niño. Kashino et al. (2009) suggested that the differences of the three currents shown by Toole et al. (1990) were mostly associated with the seasonal variability in this region and due to a cyclonic eddy located at the northernmost part of the 130°E section. Our analysis is consistent with the dynamic height calculation by Kashino et al. (2009), implying a stronger Kuroshio and a weaker MC during El Niño events than during La Niña events.

3.1.4. Mooring measurements of the WBCs

In the northern mooring’s first deployment at 18ºN, 122.7ºE east of Luzon, the upward-looking ADCP's shallowest measurement reached only 200 m. Thus, this study analyzes Kuroshio observation data below this depth. The vertically averaged current data between 200-350 m exhibit a continuous strengthening trend of the Kuroshio origin from the November 2010 to the October 2012 (Fig 6a), which is also confirmed by Chen et al. (2015a). The current meter observation is consistent with the conclusions based on the 18ºN geostrophic flow that the Kuroshio was weakened during the La Niña winter of 2010-2011 compared to the normal winter of late 2012 (Fig 2).

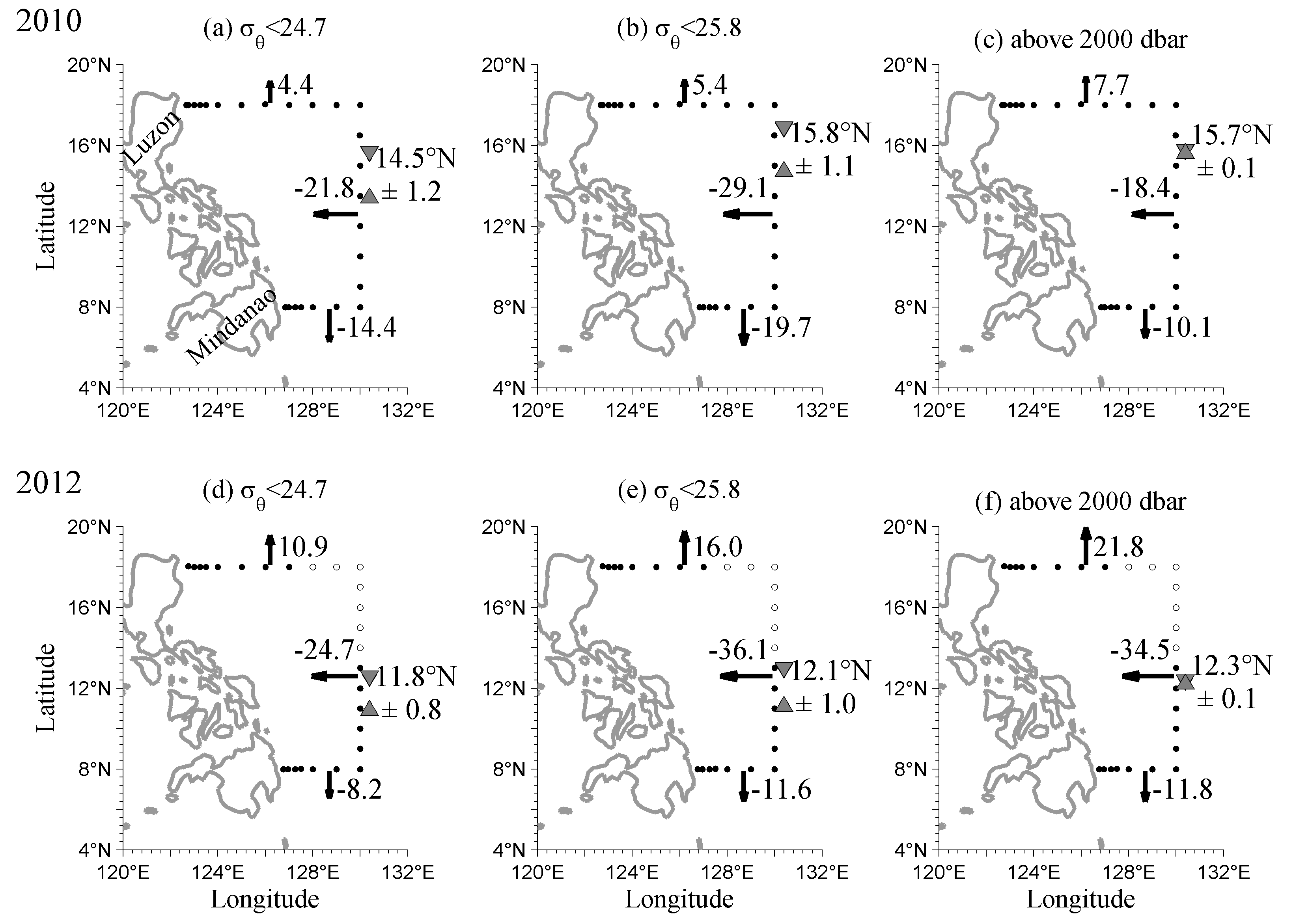


**Figure 6.** Vertically averaged daily meridional velocity between 200m-350m from the 18ºN, 122.7ºE mooring (a) and between 50m-200m from the 8ºN, 127ºE mooring (b). The time series has been smoothed by a 3-day running mean filter, with the linear trend plotted in the dash line. The trends both exceed 95% significance level according to the Mann-Kendall test (Hamed and Rao, 1998). The abscissa is the time in year/month. Unit of velocity is cm s-1.

The mooring for the MC observation was deployed east of Mindanao Island at 8ºN, 127ºE. As seen in Fig 6b, the vertically averaged velocity series above 200 meters and its linear trend indicate clearly that the MC is stronger in the winter of 2010-2011 La Niña than in the winter of late 2012, which is consistent with the geostrophic calculations in the 8ºN section (Figs 3-4). This mooring was maintained to cover the period until August 2014.  With the measurements, Hu et al. (2016) further reported the weakest MC observed in June 2012, in contrast to the maximum peaks in December 2010 and June 2014.

3.1.5. Change of the NEC split latitude

The movement of the NEC split latitude is estimated based on a volume budget of a box surrounded by the Philippine coast, and the 8ºN, 18ºN, and 130ºE sections (Fig. 7). The CTD profiles north of 13ºN in the 130ºE section and east of 127ºE in the 18ºN section in 2012 are complemented with nearby Argo profiles in November and December 2012. The top-up and top-down triangles in the 130ºE longitude mark the points of zero transport integrated from the Philippine coast along the southern (8ºN and 130ºE) and northern (18ºN and 130ºE) peripheries of the box, respectively. The volume budget above the 2000 dbar reference level of no motion is essentially closed. The budget suggests that the split latitude of the NEC above the 25.8σθ isopycnic surface is in the range of 12.1ºN ± 1.0º along the 130ºE section in the winter of late 2012, and has moved northward to 15.8ºN±1.1º during the La Niña winter of late 2010. This movement is larger than the uncertainty of the NEC split latitude estimates (1.0º~1.1º) based on the budget surplus of the box and is believed to be robust. Similar northward movement of the split latitude is also obtained based on the volume budget of the box above the 24.7σθ surface. This northward movement of the split latitude during a La Niña is contrary to the existing paradigm of the WBC interannual variability in the published literature (Kim et al., 2004; Qiu and Chen, 2010; Zhai and Hu, 2013).

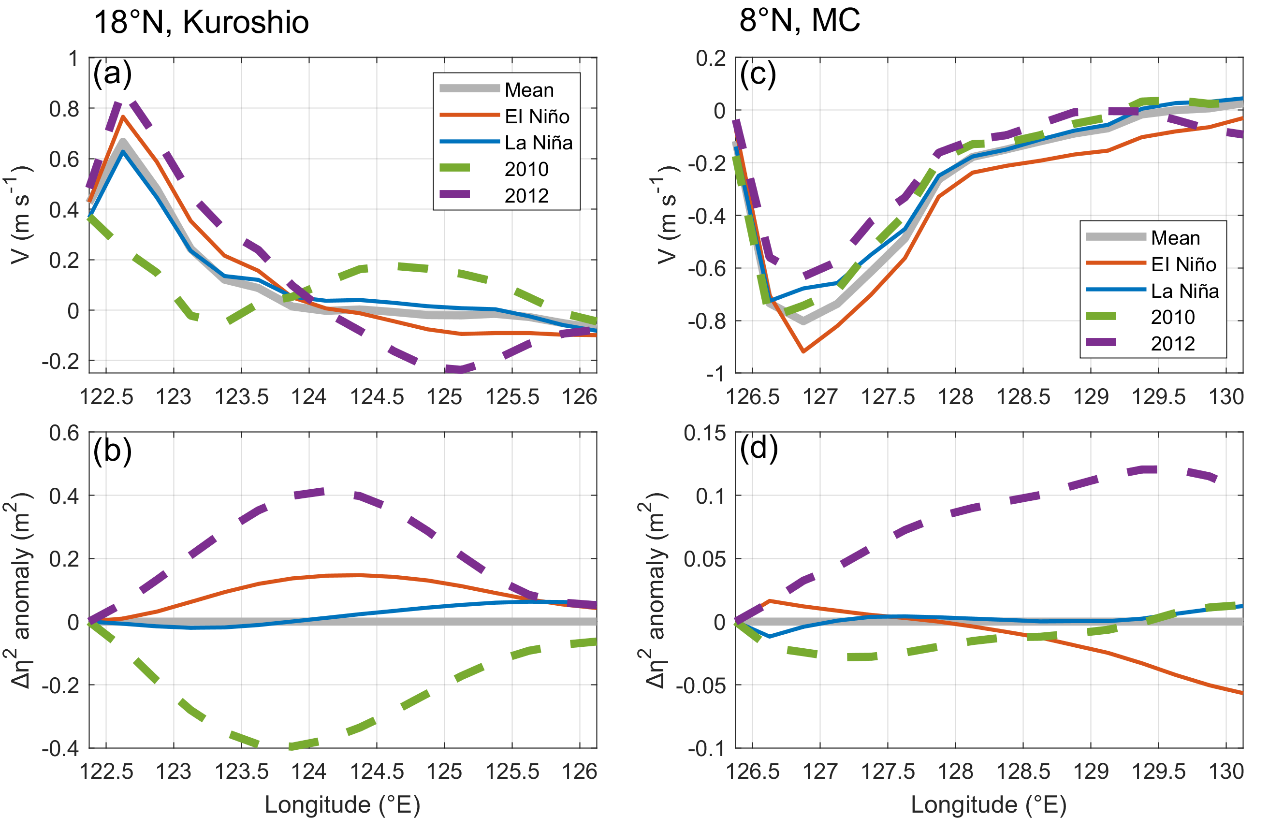


**Figure 7.** Comparison of the geostrophic transport budgets above different isopycnic surfaces within a box east of the Philippines in the winters of 2010 (a-c) and 2012 (d-f). Dots mark the hydrographic stations of the survey. Data at the circles in the northeastern corner of the box in 2012 are averaged from nearby Argo profiles within 45 km during November through December of that year. The numbers and arrows at the boundaries indicate the magnitude and direction of the volume transports across the sections. Unit is 106 m s-1. The top-up and top-down triangles in 130ºE mark the positions of zero value transports integrated from the Philippine coast along the southern (8ºN and 130ºE) and northern (18ºN and 130ºE) peripheries of the box, respectively. The middle of the triangles in the 130ºE section is taken as the mean NEC split latitude. The distance between them is the uncertainty of the NEC split latitude estimate, resulting from surplus of the volume transport of the upper ocean NEC through the eastern boundary of the box.

The convergence and divergence of the volume transports above and below the 25.8σθ isopycnic surface in the box east of the Philippines in our study are 4.0 Sv in 2010 and 8.5 Sv in 2012, respectively, which are balanced by an average vertical velocity of 0.6~1.2×10-5 m s-1, consistent with the vertical velocity estimate of 9.1×10-6 m s-1 during the 1988 cruise in Toole et al. (1990). The variation of NEC transports above 24.7σθ are small during the two winters in our study (Figs. 7a, d). In 2012, the integrated transport across 130ºE section above 2000 dbar was nearly twice that of late 2010 La Niña (Figs. 7c, f). In contrast, Toole et al. (1990) revealed the doubling of the NEC transport from September 1987 after a warm phase to April 1988 during cold phase, which probably includes significant seasonal variations (Kashino et al., 2009).

* 1. **Comparison with satellite altimeter data**

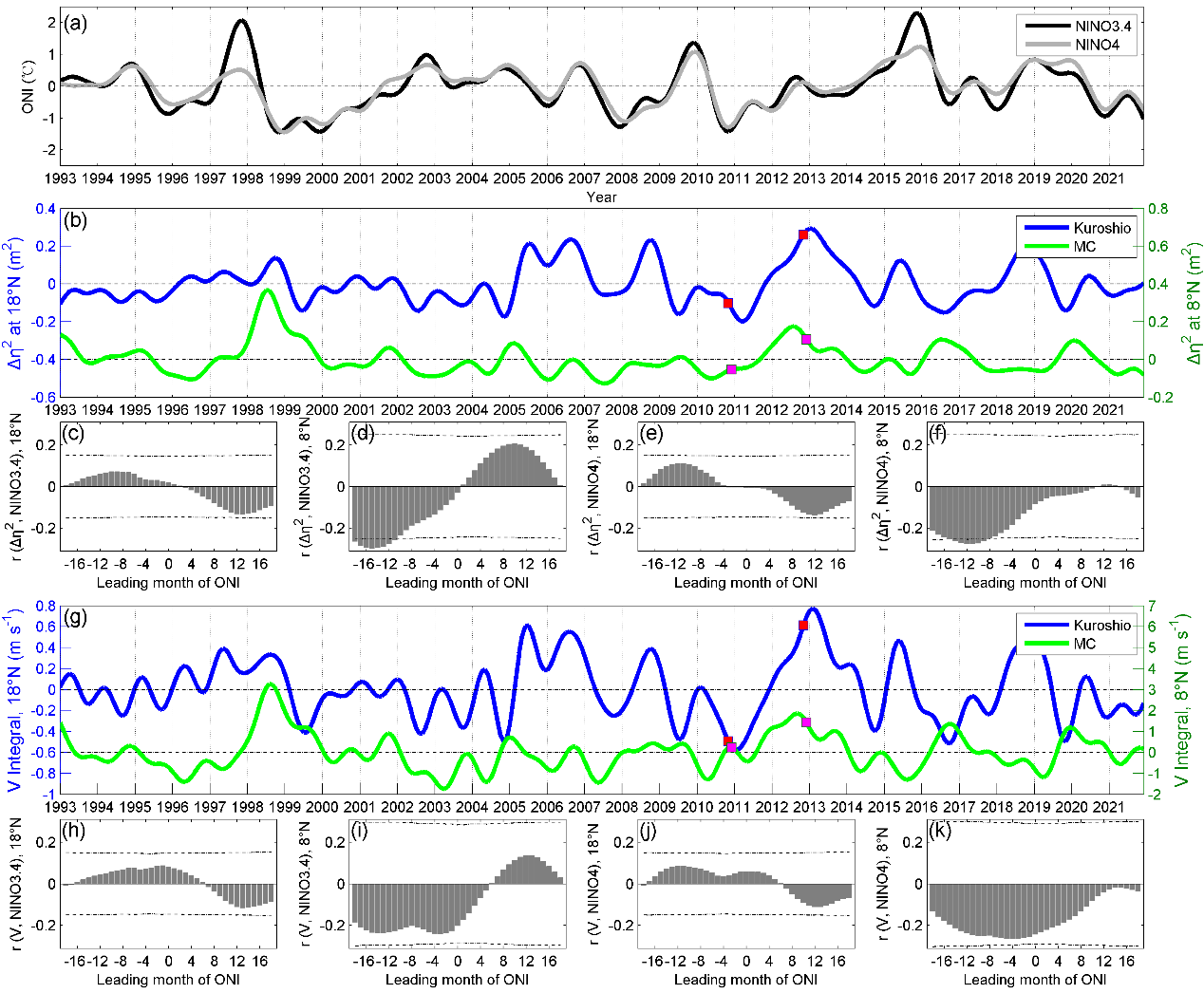
The surface geostrophic current and its estimated transport from satellite altimeter data (Fig. 8) show a weakened Kuroshio and an intensified MC during December 2010 compared to 2012, which are consistent with the geostrophic currents based on hydrographic data (Figs. 2-4) and direct measurements of the current meters (Fig. 6). Composite analysis indicates that, in December, the Kuroshio at 18ºN and the MC at 8ºN are strengthened during El Niño (orange lines in Fig. 8). The Kuroshio and the MC during La Niña December (blue lines) is closer to the climatological average. Composite analysis based on five modeling datasets covering ten warm events during 1980-2015 also suggested a strengthen MC in a developing El Niño (Ren et al., 2020).



**Figure 8.** Meridional surface geostrophic velocity (upper panel) and anomaly integrated from the western boundary (lower panel) at 18°N (a-b) and 8°N (c-d) section. anomaly in b) and d) is based on the climatology of 1993-2021. In each subplot, the thick gray is the December average from 1993-2021, and the dashed green and purple lines are Decembers of 2010 and 2012. Respectively, the orange, and blue lines are the results of a composite analysis for the following ENSO periods: warm phase: December of 1994, 1997, 2002, 2006, 2009, 2015, and 2018; cold phase: December of 1995, 1998, 1999, 2007, 2010, 2011, and 2017.

Although composite analysis can reveal the WBCs’ interannual anomalies related to ENSO phases, there is still significant uncertainty when it comes to an individual event. For instance, when comparing to the multi-year average, December 2012 has shown considerably stronger Kuroshio and weaker MC (Fig. 8), suggesting that it is not a typical neutral WBC state (Li et al., 2018). Compared to the composited La Niña phase, December 2010 exhibits a significantly weaker Kuroshio and a relatively stronger MC. The dynamics of the WBC variations during the late 2010 winter deserve a separate study. It is worth mentioning that the along-track altimeter sea level can be used to calculate the geostrophic WBCs only if the satellite tracks are perpendicular to the western boundary. The various angles between the altimeter satellite tracks and the Philippine coasts in reality suggest large uncertainties of the along-track geostrophic WBCs derived from the altimeter data.

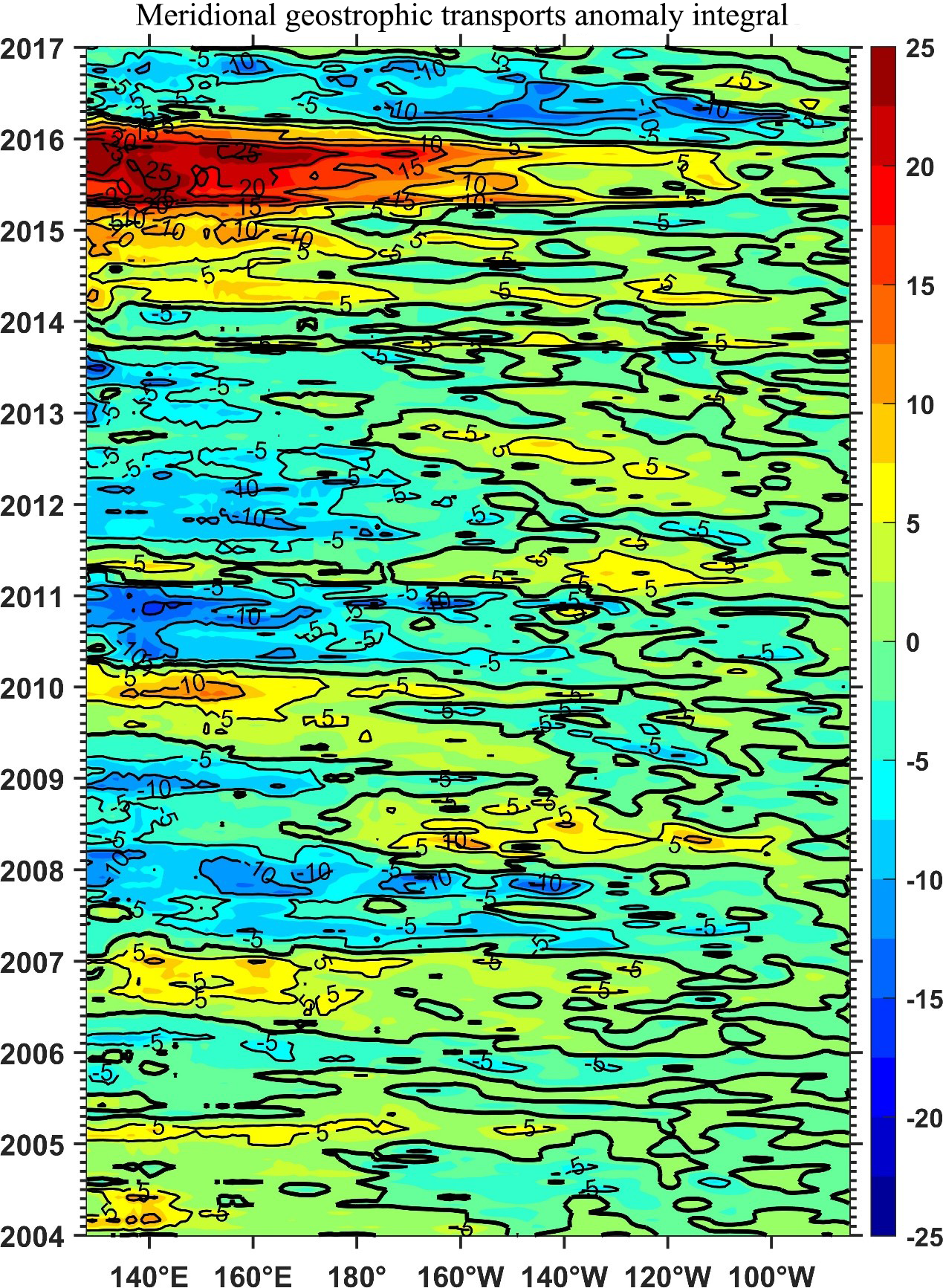
The time series of anomaly in the western boundary at 18ºN and 8ºN illustrate significant interannual variability not in close association with the ONI (Figs. 9a-b). The 13-month lowpass filtered data indicate a strengthening Kuroshio and weakening MC from late 2010 to late 2012, consistent with the mooring observations in Figure 6. The correlation analysis between WBC transport and ONI (both Niño3.4 and Niño4 index) reveals a weak correlation coefficient near 0 lag (Figs.9c-f). Lead-lag correlations also demonstrate that the correlation coefficient between the two does not pass the 95% significance level when the ONI leads the WBCs interannual anomalies. Similar results are presented by lead-lag correlation analyses between integrated surface meridional velocity integral and the ONI (Figs. 9g-k). This implies that the WBCs east of the Philippine coasts do not vary with the ONI above statistical significance.



**Figure 9.** Time series of ONI (a), anomaly (b), and meridional velocity integral (g) in the west boundary at 18ºN (blue line in b and g) and 8ºN (green line in b and g). The time series in b) and g) have been smoothed by a 13-month Butterworth lowpass filter from the monthly anomaly. Time nodes of the sectional observation during the two cruises are marked with squares. Bar charts in c-f represent the lead-lag correlation coefficient (r) between anomaly and ONI (Niño3.4 in c-d, Niño4 in e-f), and the 95% significance level in dash lines is based on the freedom degree of Bretherton et al. (1999). Positive lags here indicate the lead of ONI over the anomaly. Same correlation analysis between integrated meridional velocity and ONI are illustrated in h-k. The widths of the Kuroshio and the MC, in equation (2), are selected as 2º and 3º respectively according to their V profiles in Fig 8a, c.

1. Discussions
   1. **Importance of the WBCs on ENSO**

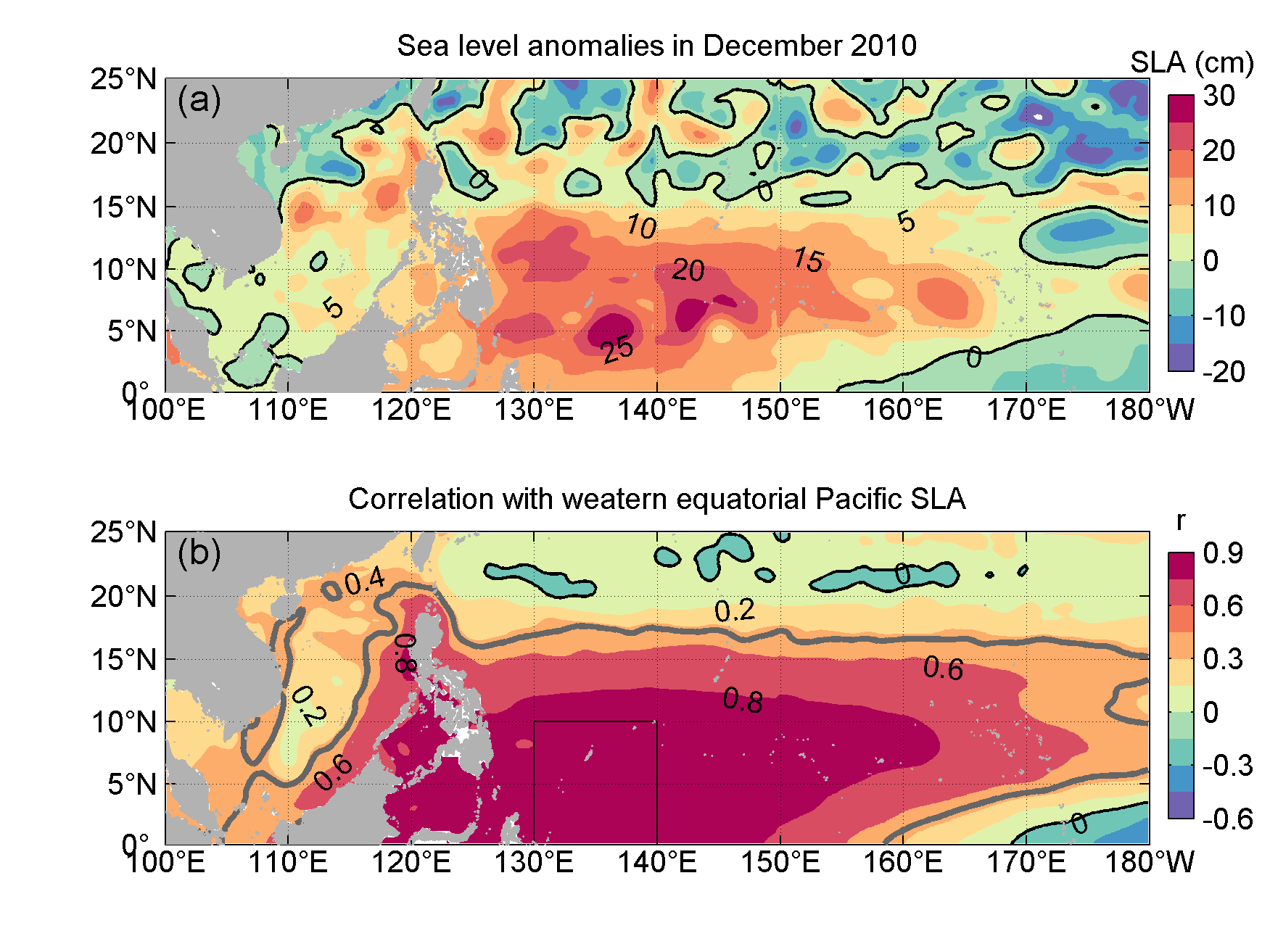
The interannual WBC transports at 8ºN have been compared with the meridional geostrophic transport anomalies integrated across the North Pacific Ocean based on Argo absolute geostrophic currents (AGCs). In the layer above 400 m, the interior meridional geostrophic transports are found to recharge the equatorial Pacific heat content during 2010-2011 La Niña (Fig. 10). The differences in the WBC transport anomalies between the two winters are evidently sizable southward and have enhanced the recharging process by the interannual interior meridional geostrophic transports above 10 Sv southward significantly during the 2010-2011 La Niña. The comparison above the 20℃ isotherm is essentially the same (figure omitted), suggesting that the WBC changes, which have been overlooked in the existing ENSO theories, are important for tropical-extratropical exchange of the Pacific Ocean at the interannual time scales.



**Figure 10.** Meridional geostrophic transports anomaly integrated from the eastern boundary along 8ºN. The transports are based on the Argo absolute geostrophic currents above the 400 m depth. The transport anomalies are based on the Argo climatology of 2004-2016. Unit is Sv. Thick contour is the zero value.

* 1. **Dynamics of the interannual WBC variations**

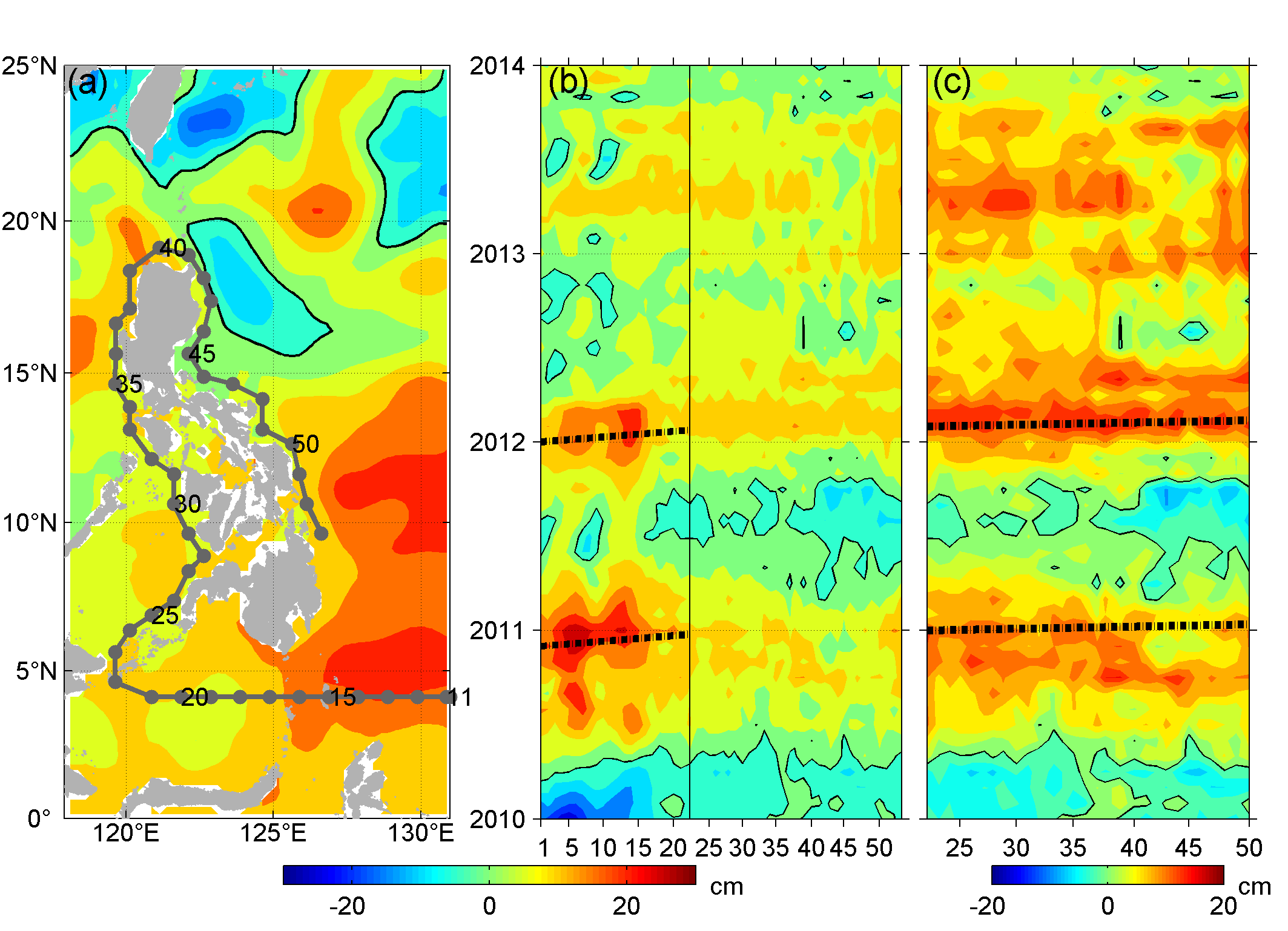
The interannual anomalies of the WBCs are associated with sea level anomalies along the Philippine coasts during the La Niña, as evidenced by the satellite altimeter data in December 2010 (Fig. 11a). The sea level anomalies around the Philippines are in positive correlations, above the 95% significance level, with those in the equatorial western Pacific (Fig. 11b). The strong correlations suggest that the sea level around the Philippine archipelago should be affected by the signals from the tropical western Pacific Ocean (Chen et al., 2015b; Chen et al., 2019). Existing studies have suggested that oceanic signals from the Pacific Ocean can propagate into the eastern SCS through the Sibutu Passage and Mindoro Strait as coastally trapped waves (Liu et al., 2011; Zhuang et al., 2013; Li et al., 2021).



**Figure 11.** Interannual sea level anomalies of satellite altimeters in the northwestern Pacific Ocean in December 2010 (a), based on the climatology of 1993-2021. b) Correlation coefficients between the interannual sea level anomalies in the northwestern Pacific and those averaged in the western Pacific rectangle (0º- 10ºN, 130º- 140ºE). Sea level anomaly unit is cm. The Grey contour in b) marks correlations at 95% significance level for 16 degrees of freedom, which correspond to the SLA freedom degree in the western Pacific rectangle. The freedom degree in the area is based on Bretherton et al. (1999) approach.

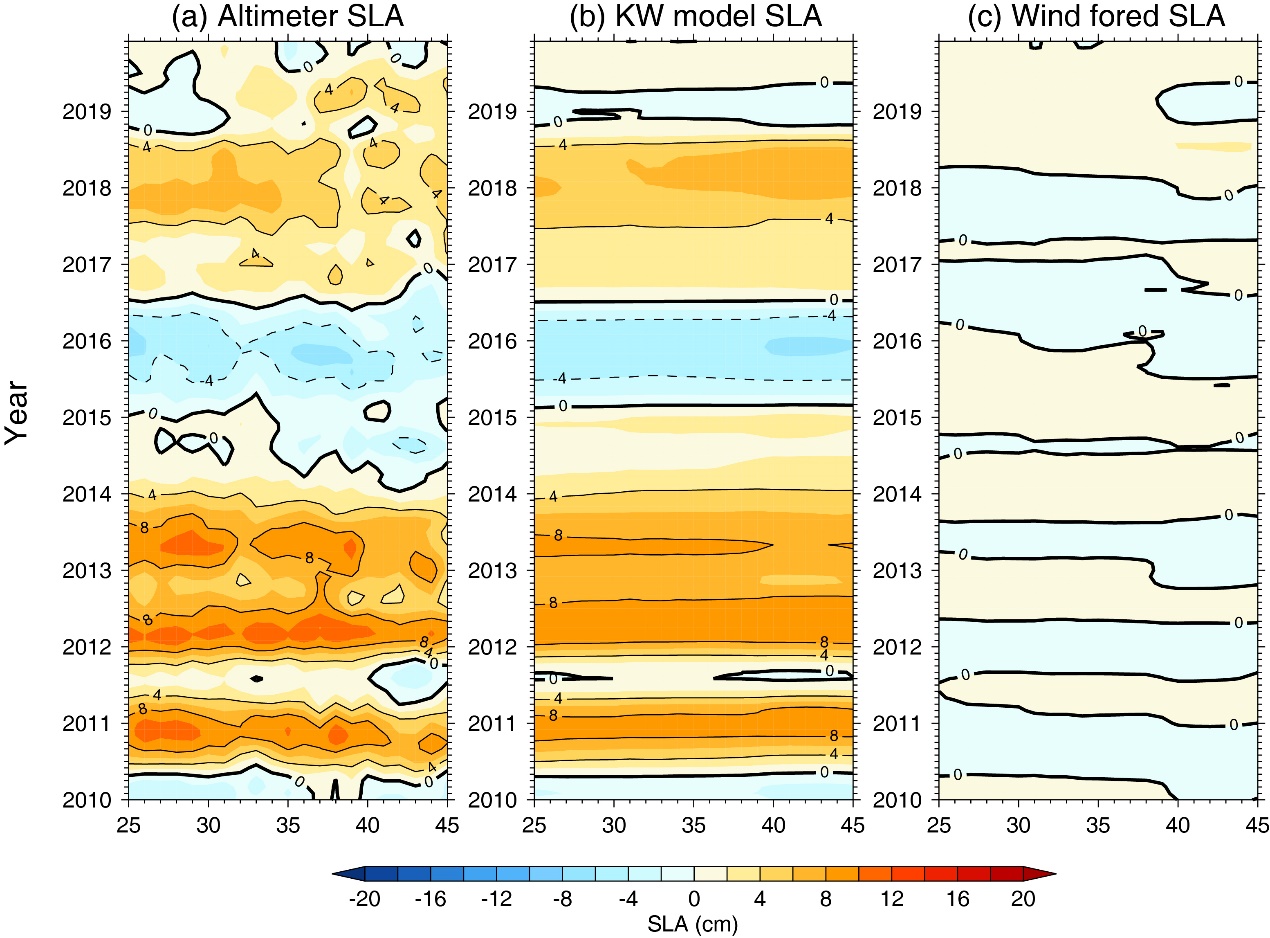
Here we extract the altimeter SLA data along the Rossby-Kelvin waveguide in the equatorial western Pacific around the Philippine archipelago (Fig. 12). Before entering the Sulu Sea through the Sibutu and Balabac Passages, the SLA anomalies propagates westward from the equatorial Pacific. The speed of the propagation (before Sta. 22 in Figs. 12a-b) is about 1.21 m s-1 , consistent with the first baroclinic Rossby wave estimated as , with the deformation radius of 230 km in the western tropical Pacific (Chelton et al., 1998). The Rossby wave propagation is blocked or interfered by the WBCs, so their propagation near the boundary is meant to be different from the propagation in the open ocean. The SLA enter the SCS via the Mindoro Strait and then return to the western Pacific via the Luzon Strait, completing the circum-island propagation around the Philippines (from Sta. 22 to Sta. 45 in Fig 12c), with the propagation speed in agreement with the phase speed of the first gravity wave of 3.0 m s-1 around 8º-18ºN (Chelton et al., 1998). The Kelvin waves propagate very fast, the effects of which are revealed as nearly synchronous positive or negative belts in the Hövmuller plot.

The altimeter data suggest that the dissipation of the Kelvin wave energy occurs mainly in the Sulawesi Sea and the Sulu Sea as passing through the Sibutu passage (Sta. 18-25 in Fig. 12b). After entering into the SCS, the reduction of the Kelvin wave amplitudes is actually very small around the Philippines (Sta. 25-45). The Kelvin waves have evidently arrived at the east Philippine coasts through the Luzon Strai to influence the WBC transports, as suggested by the interannual variability of ―the differences of the squared sea level across the WBCs. The Rossby waves arriving at the Philippine coast may also excites Kelvin waves propagating clockwise into the Sulawesi Seas(Qu et al., 1998). As a matter of fact, changes of the WBCs are induced by such wave propagation dynamics, which shall induce current variations strongly nonlinear in nature at the entrance of the Indonesian seas and could affect the nonlinear reflections of the equatorial Rossby waves. It is the interactions of the WBCs and the incoming equatorial Rossby waves that determine the Kelvin wave generation in the Sulawesi Sea. We emphasize that the main energy of the Kelvin waves may come primarily from the equatorial area, because the amplitudes of the sea level anomalies at the equator are much larger than those in the off-equatorial areas during ENSO events. The altimeter data indeed have shown that such Rossby wave influence is negligibly small to the sea level anomalies along the east Philippine coast than that of the Kelvin waves north of about 12ºN (Sta. 50 in Fig. 12b).



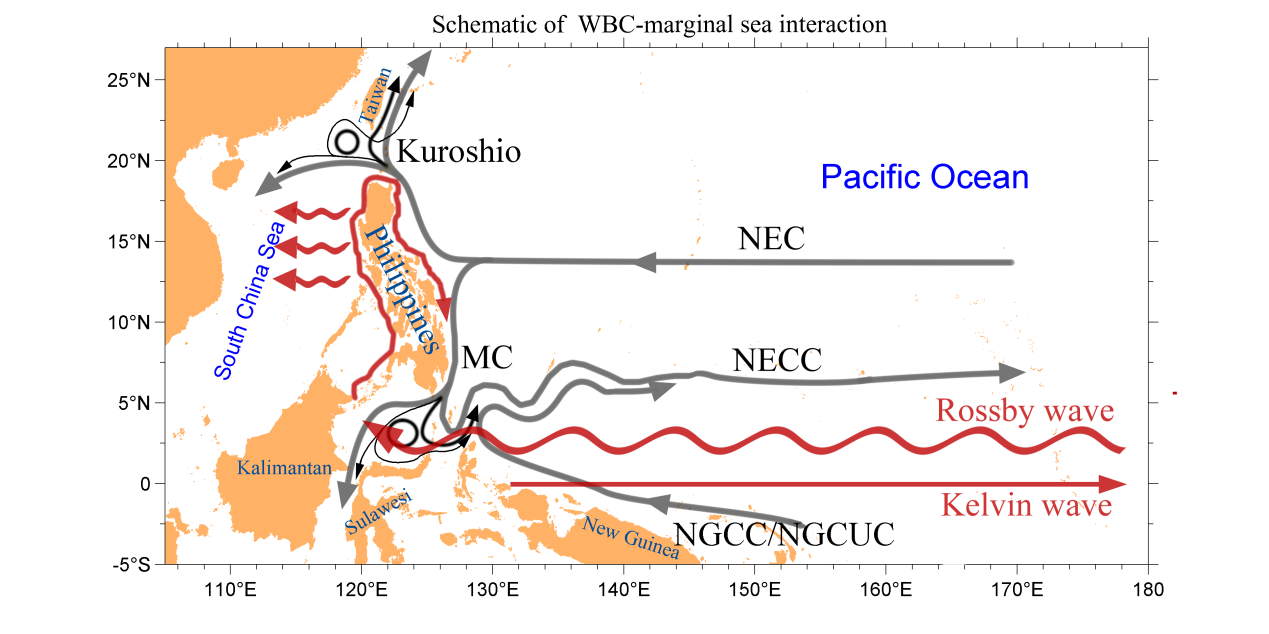
**Figure 12.** Contour map of the sea level anomalies in December 2010 (a) and Hovmöller diagram of the sea level anomalies (b, c) around Philippines. The waveguide around Philippines is noted by thick dotted line in a). Sta. 1-10 from 140.875ºE to 131.875ºE with interval of 1º along 4.125ºN have been omitted. Vertical line in b) indicated in Sta. 22 is the position of Sibiu Channel. The dash lines in b) and in c) correspond to the phase speed of the first-mode baroclinic Rossby wave in the western tropical Pacific (~1.2 m s-1) and the phase speed of the first-mode gravity wave around 8º- 18ºN (~3.0 m s-1), respectively.

As a gravity wave, the Kelvin waves are not easily blocked by the Kuroshio in the Luzon Strait. A theoretical coastal Kelvin wave model (Gill, 1982) is employed to predict the SLA along the east coast of Luzon from the Mindoro Strait, which provides a quantitative assessment of the Kelvin wave propagation around the Philippines. The first 10 baroclinic modes of Kelvin waves in the model are integrated, following Hu et al. (2019), which have effectively reproduced the SLA around the Philippine archipelago observed by the satellite altimeter (Figs. 13a and b). For example, the positive SLA during late 2010 and 2012 to 2013, and the negative SLA during 2015/2016 super El Niño are reproduced successfully by the Kelvin wave model. In comparison, the sea level anomalies forced by the alongshore winds are small enough to be neglected (Fig. 13c). For instance, at the 18ºN off the eastern Philippines coast (Sta. 42 in Figure 13), the standard deviation of wind forced SLA is 0.77 cm while that of kelvin wave forced SLA is 5.65 cm. Kashino et al. (2009) and Zhuang et al. (2013) have also mentioned that local wind variability in this region did not appear to contribute significantly to changes in the current system. The Kelvin wave propagation around the Philippine archipelago is evidently the primary dynamics on the seal level variations at the western boundary, which would impact on the WBCs via the geostrophic balance.



**Figure 13.** Hovmöller diagram of the sea level anomalies from altimeter observation (a), simulated by coastally trapped Kelvin wave model (b), and forced by the alongshore wind forcing (c) around Philippines. The waveguide from Sta. 25 to 45 is indicates in Fig. 12a.

The dynamics of the WBC changes are explained as the following (Fig. 14). Strong downwelling equatorial Rossby waves in the western Pacific were forced by the easterly winds during the onset of the 2010-2011 La Niña, which propagated westward and hit the western boundary. Sea level gradient between the equatorial western Pacific and the South China Sea was established, and the interactions between the MC and the Rossby waves generated nonlinear reflections of the Rossby waves with leakage into the Sulawesi Sea. The Rossby wave leakage forced ITF anomalies and downwelling coastal Kelvin waves to propagate clockwise around the Philippine islands. As the Kelvin waves arrived at the east Philippine coasts, southward current anomalies were generated in the WBCs. The situation is the opposite during El Niño events. It is worth mentioning that the energy of the Kelvin waves is likely influenced strongly by the nonlinearity of the WBC-Rossby wave interactions, as suggested by a series of theoretical and observational studies of the WBC hysteresis in the vicinity of a wide gap (Yuan et al. 2019; Li X. et al. 2021).



**Figure 14.** Schematic of the interactions between the WBCs and the Indonesian sea, South China Sea circulation. Grey arrows stand for mean circulation. Thick and thin black arrows stand for eddy shedding and penetrating states of the WBCs, respectively. Red arrows indicate wave propagation. The equatorial Rossby waves are reflected into equatorial Kelvin waves at the western boundary. Some Rossby wave energy propagates into the South China Sea and around the Philippines as coastal Kelvin waves, while radiating Rossby waves into the northern South China Sea.

Besides the ENSO-related sea level anomalies driving the observed WBC variability, readers are reminded of other mechanisms, such as off-equatorial eddy activity (Lien et al., 2014), local Ekman pumping (Kim et al., 2004; Ren et al., 2020), Pacific Decadal Oscillation phase shifts (Chen et al. 2015a), and interannual SCS circulation (Liu et al., 2011; Wang et al., 2011; Wang et al., 2020), the study of which is beyond the scope of this study.

1. Conclusions

In this paper, the interannual variations of the Pacific low-latitude western boundary currents (WBCs) are investigated using hydrographic data collected during two research cruises in the winters of late 2010 and 2012, combining with satellite data and numerical experiments. Observations suggest that the Kuroshio at its origin decreased significantly and the MC increased significantly during the 2010-2011 La Niña peak.

The interannual WBC variations are likely generated by the propagation of coastal Kelvin waves around the Philippines during strong ENSO events, as suggested by the agreement of the Kelvin wave model simulation with the altimeter data. We suggest that, during El Niño (La Niña) events, upwelling (downwelling) Rossby waves arrive at the western equatorial Pacific to depress (elevate) the sea level in the Sulawesi Sea, which then excite upwelling (downwelling) coastal Kelvin waves to propagate into the South China Sea. These Kelvin waves propagate clockwise and depress (raise) the sea level along the east Philippine coasts to generate the northward (southward) anomalies of the WBCs by changing the offshore sea level gradient.

The interannual anomalies of the WBC transports are found comparable to the total geostrophic meridional transport anomalies integrated over the interior North Pacific Ocean, suggesting that the WBCs play an important role in the discharge and recharge of warm water volume of the equatorial Pacific Ocean during ENSO events.

Acknowledgments.

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Data Availability statement.

The Niño 3.4 index data are based on the NOAA OISST.v2 dataset, which can be downloaded from website: http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices. The ADCP data of the subsurface mooring were from NPOCE website: http://npoce.org.cn/dateAcc.aspx. The Argo profiles were from China Argo Real-time Data Center: ftp://ftp.argo.org.cn/ pub/ARGO/global/. The gridded Argo data based on Roemmich-Gilson Argo Climatology were downloaded from the website: https://sio-argo.ucsd.edu/RG\_Climatology.html. The absolute dynamic topography (ADT) and derived variables of the satellite product distributed by the CMEMS can be downloaded from the website: https://data.marine.copernicus.eu/product/SEALEVEL\_GLO\_PHY\_L4\_MY\_008\_047/download?dataset=cmems\_obs-sl\_glo\_phy-ssh\_my\_allsat-l4-duacs-0.25deg\_P1D. Monthly wind reanalysis data provided by ERA5 ocean dataset can be downloaded from the following website: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form. The hydrographic CTD data are available on the website: http://itf.adio.ac.cn/xzlxz/CTD2010.mat, CTD2012.mat.

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