Variability and dynamics of the Pacific low-latitude western boundary currents during winters of late 2010 and 2012

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First Institute of Oceanography, Ministry of Natural Resources, Qingdao, China, 266071**Abstract**

Ship-based hydrographic observations and moored current meter data off the east coasts of the Philippines show a large increase in the Kuroshio (~ 10 Sv; 1 Sv= 106 m3 s-1) and a decrease in the Mindanao Current (5 ~ 10 Sv) during the 2010-11 La Niña winter. After the dissipation of the 2010-11 La Niña, these large transport anomalies almost completely disappeared by late 2021. Here, we use a simple dynamic model to show that the observed interannual variability in the Kuroshio and Mindanao Current is largely driven by coastal Kelvin waves propagating around the Philippines archipelago. We further show that the interannual transport anomalies of the North Pacific western boundary current (WBC) system are comparable to the total meridional transport anomalies integrated across the interior North Pacific Ocean, suggesting the importance of the WBCs in the heat content variability of the western Pacific warm pool during ENSO events.

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

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 North Pacific Ocean. This phenomenon has been studied for over half 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 international research program during the Tropical Ocean Global Atmosphere program (TOGA) 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, disclosing 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.

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 pattern. In addition, several studies showed a contrasting result.. 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 transport in the years before and after the event. Besides, 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, 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 severalmooring-based studies reporting a strengthened MC after the onset of the 2002/03 El Niño (Kashino et al. 2005), as well as during the development of the 201-16 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. However, Chen et al. (2015) reported no correlation between the interannual surface velocity off the east Luzon coast and ONI indicating that the interannual variations of MC 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 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 should increase and the MC transport should 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, 2010b). The interannual NEC split variations derived from the altimetry data is similar to those derived from previous numerical simulations. However, the altimeter data, especially the early Topex/Poseidon data, do not adequately resolve the WBCs since they suffer near the coasts. A comprehensive analysis and validation of the altimetry and numerical model based results is required

Existing studies have attributed interannual NEC split variations to the propagation of wind-driven Rossby waves from the interior North Pacific (Qiu and Lukas, 1996; Kim et al., 2004; Qiu and Chen, 2010b; Zhai and Hu, 2013). However, the interactions of the NEC–Kuroshio-MC system with the circulations in the South China Sea and the Indonesian seas have not been taken into consideration. A earler modeling study by Metzger and Hurlburt (1996) has suggested a coupled western Pacific-South China Sea 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). Specifically, during the Rossby wave reflection into equatorial Kelvin waves, sea level gradient forms between the equatorial western Pacific and the South China Sea, which in turn forces coastal Kelvin waves to propagate clockwise around the Philippine islands, generating northward and southward current anomalies off the east Philippine coasts during El Niño and La Niña events, respectively. However, it is still unclear if the Kelvin waves can reach the east coasts to impact the NEC split in the presence of the strong Kuroshio in the Luzon Strait

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 region of the Kuroshio and the MC. The role of WBCs in the 2010 La Niña 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 past 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.

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 (1 dbar≈1 m) 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 m 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. 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 m, 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 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 current meter 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 75-kHz upward-looking ADCP at 700m depth, the north mooring 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 75-kHz 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 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 combined mooring dataset provides an unprecedented opportunity to focus on the synchronous variations of the two WBCs.

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

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 about upper 2000 m at 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**

A new version of 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 using the interannual anomaly of the ADT by referencing it to the monthly climatology data spanning the period of 1993-2021.

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

With a steady state of the quasi-geostrophic hypothesis, the governing equations for the 1.5-layer reduced gravity model are:

(1)

(e.g., Qiu and Lukas, 1996), where *v* is meridional velocity, *f* is the Coriolis parameter, *h* is the upper layer thickness, , is gravitational acceleration, 𝜌 is layer density, and Δ𝜌 is density difference between the upper and abyssal layers. From equation (1) we can get:

where is the meridional transport of the WBC, while denotes the western boundary, and is the width of the WBC. Considering in the reduced gravity model, can be calculated as:

(2)

where is the vertical displacement (positive upward) of the sea surface which can be represented by the ADT anomaly from satellite altimeter. This study focuses on the interannual variations of . The difference of the sea level squared () between the western boundary and its seaward location where the WBC vanishes is analyzed.

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

Sprintall et al. (2000) and Hu et al. (2019) used a Kelvin wave model to predict the sea level variations in the Indonesian seas associated with the propagation of Kelvin wave. The model is based on the analytical linear wave model described by Gill (1982), and forced by winds at various sections along the Kelvin wave pathway. In this study, we employ the same model to investigate the sea level propagation around the Philippine coasts forced by the local winds. The model integrates the zonal 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. The first 10 baroclinic modes decomposed from the ERA5 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). is the acceleration due to gravity. 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. The detailed variation and its dynamics of the WBCs are further analyzed based on satellite data.

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

The two surveys cover nearly the same periods of the two winters of 2010 and 2012, with the subsurface mooring recording the variations of the WBCs 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 (= potential density – 1000 kg m-3) and 25.8σθ, roughly overlapping with the 20 ℃ and 14 ℃ temperature contours, respectively, represent the upper and lower limits of the pycnocline (Meyers, 1979; Kessler and Taft, 1987).

In comparison with the measurements in the winter of late 2012, the width and magnitude of the Kuroshio origin during the 2010-2011 La Niña winter in the 18ºN section are noticeably smaller, suggesting that the strength of the Kuroshio 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 125ºE is 10 Sv (1 Sv=106 m3 s-1) smaller in the winter of late 2010 than in the winter of late 2012. The weakening of the Kuroshio origin transport is also confirmed by the transport calculation above the 24.7σθ surface (figure omitted).

3.1.2. Geostrophic currents in the 8ºN section

In comparison, the speed and width of the southward MC are larger 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.

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 this section during the first visit (Fig. 3a). The existence of the eddy is confirmed by satellite sea level data (figure omitted). The detailed effects of eddy perturbations on the WBCs are beyond the scope of this study.

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

The dynamic heights relative to 1000 db 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. During the two cruises, the net change of the dynamic height along the 130°E is nearly the same, suggesting small variations of the NEC upper-level transport in the winters of late 2010 and 2012. Significant variations occur in 18° N and 8° N sections evidently. Compared to the dynamic height change along the 18ºN and 8ºN sections in the late 2012 winter, the net height changes during the late 2010 winter are smaller in the 18° N section and larger in the 8° N section, suggesting a stronger MC and weaker Kuroshio in the late 2010 La Niña winter than in the late 2012 normal winter.

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 in Kashino et al. (2009), implying a stronger Kuroshio and a weaker MC during El Niño than during La Niña.

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 exhibits a continuous strengthening trend for 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 weakened during the La Niña winter of 2010-2011 compared to the normal winter of late 2012 (Fig 2).

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 Argo profiles averaged from the monthly gridded data 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 m reference level of no motion is essentially closed. The budget suggests that the split latitude of the NEC above the 25.8σθ density surface is in the range of 12.5ºN ± 1.3º 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 (1.1º~1.3º) 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).

The convergence and divergence of the volume transport above and below the 25.8σθ surface in the box east of the Philippines in our study are 4 Sv in 2010 and 10 Sv in 2012, respectively, which are balanced by an average vertical velocity of 0.6~1.5×10-5 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 NEC transports in the upper layer are nearly unchanged during the two winters in our study, in contrast to the doubling of the NEC transport from September 1987 to April 1988 in Toole et al. (1990), which probably includes significant seasonal variations (Kashino et al., 2009).

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

Velocity and transport (Fig. 8) show a weakened Kuroshio and an intensified MC during December 2010 compared to 2012, which is consistent with the geostrophic current (Figs. 2-4) and direct measurement of current meter (Fig. 6). Composite analysis indicates that, in December, the Kuroshio at 18ºN is strengthened during El Niño (red solid in Fig. 8d) compared to other ENSO phases, as well as the climatology mean in that month. The MC at 8ºN during La Niña December is slight smaller than that of climatology average or neutral phase, while during El Niño it is stronger than an 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).

Although composite analysis can reveal the WBCs’ interannual anomalies related to ENSO cycles, there is still significant uncertainty when it comes to an individual event. For instance, when comparing to the multi-year average of the all neutral phases, December 2012 has shown considerably stronger Kuroshio and weaker MC, suggesting that it is not a typical state of the neutral phase (Li et al., 2018). Compared to the composited El Niño phase, the neutral phase, and the climatology mean, December 2010 exhibits relatively weaker Kuroshio and MC, which is nontypical of a La Niña. The dynamics of the WBC variations during the late 2010 winter deserve a separate study. It is worth mentioning that the 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 geostrophic WBCs derived from the altimeter data.

The time series of anomaly in the western boundary at 18ºN and 8ºN illustrate significant interannual variability, along with higher-frequency seasonal and intraseasonal oscillations (Fig. 9b). 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 reveals a weak correlation coefficient at near 0 lag. Lead-lag correlations also demonstrate that the correlation coefficient between the two does not pass the 95% significance test when the NIO index leads the WBCs interannual anomalies, (Fig. 9c-d). This implies that the WBCs east of the Philippine coasts do not vary with the ONI in a significant statistics (Lukas, 1988; Chen et al., 2015; Hu et al., 2016). The dynamics of the interannual WBCs should be investigated from a different perceptive.

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. The differences in the WBC transports between the two winters are evidently sizable compared to the interannual anomalies of the integrated interior meridional geostrophic transports of about 10 Sv southward during the 2010-2011 La Niña (Fig. 10). The comparison above the 20℃ isotherm is essentially the same (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.

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

The interannual anomalies of the WBCs are associated with agitation of sea level 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). Thus, the strong correlations suggest that the sea level around Philippine archipelago can be affected by the signals from the western Pacific Ocean, which is also investigated by Chen et al. (2015b) and Chen et al. (2019). They suggested that oceanic signals from the Pacific Ocean can potentially propagate clockwise along the Philippine coast and enter into the eastern South China Sea (SCS) through the Sibutu Passage and Mindoro Strait as coastally trapped waves (CTW).

Here we extract the altimeter SLA data along the 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 Fig 12b) is consistent with the first baroclinic Rossby wave, which is about 1.21 m s-1, estimated as with deformation radius of 230 km in the western tropical Pacific (Chelton et al., 1998). Upon entering the Sulu Sea, the anomalies enter the SCS via Mindoro Strait rapidly 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).

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 in the east coast of Luzon from the Mindoro Strait, which provids a more quantitative assessment of the Kelvin wave propagation around the Philippines. The first 10 baroclinic modes of Kelvin wave in the model are integrated, following Hu et al. (2019), which effectively reproduces the SLA around Philippine archipelago observed by altimeter (Figs. 13a and b). For example, the positive SLA during 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 negligible (Fig. 13c). Kashino et al. (2009) and Zhuang et al. (2013) also stated 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

As noted above, the dynamics of the WBC changes can be explained by the coastal Kelvin wave propagation around the Philippine archipelago during La Niña (Fig. 14). Strong downwelling equatorial Rossby waves were generated by the westerly wind bursts in the western equatorial Pacific Ocean during the onset of the 2011-2011 La Niño, which propagate westward and hit the western boundary. The energy of the downwelling equatorial Rossby waves is believed to be carried away from the Sulawesi Sea in three ways: to the east by the reflected equatorial Kelvin waves, to the Indian Ocean by the Indonesian Throughflow variations, and into the South China Sea through the Sibutu Channel, the Sulu Sea, and the Mindoro Strait via the coastally trapped Kelvin waves as illustrated in Figure 14. The energy partition between the three route is likely influenced strongly by the WBC variability, as suggested by a series of theoratical and observational nonlinear studies of the WBC hysteresis in the vicinity of a wide gap (Yuan et al. 2019; Li X. et al. 2021).

The propagation of the coastal Kelvin waves is consistent with existing high-resolution modeling (Metzger and Hurlburt, 1996) and the altimeter data analyses (Liu et al., 2011; Zhuang et al., 2013). Significant correlations of the sea level anomalies around the Philippine islands with those in the equatorial western Pacific, as well as the SLA reproduction from a linear Kelvin wave model evidence the propagation of the coastally trapped Kelvin waves through the eastern South China Sea and the southern Luzon Strait to reach the east coasts of the Philippines (Fig. 14).

The present study has suggested a new potential dynamics controlling the WBCs interannual variations beyond the remote wind-forced Rossby waves in the western Pacific Ocean (Qiu and Lukas, 1996; Kim et al., 2004; Zhai and Hu, 2013; Hu et al., 2016; Ren et al., 2020) and the simplistic mass redistribution according to NEC split latitude shift during ENSO events (Qiu and Lukas, 1996; Kim et al., 2004; Qiu and Chen, 2010b). This can partly explain the ongoing debate regarding the interannual variation of the NEC–Kuroshio-MC system associated with ENSO. The interannual variation of the WBCs may be a result of the combined effects of multiple mechanisms. Besides the ENSO-related sea level fluctuations 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 Throughflow (Liu et al., 2011; Wang et al., 2011), the study of which is beyond the scope of this study.

1. Conclusions

In this paper, the interannual variations of the northwestern Pacific western boundary currents (WBCs) are studies based on hydrographic data collected during two research cruises in the winters of late 2010 and 2012. The comparisons of the WBCs at 8ºN and 18ºN in these two winters suggest that the Kuroshio origin decreases significantly and the MC increases significantly during the 2010-2011 La Niña peak. These WBC variations are inconsistent with the existing paradigm of the WBC variability associated with ENSO.

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. It is suggested that during El Niño (La Niña), 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 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.

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Table caption

Table 1. Time windows of the sectional measurements.

Figure caption

**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.

**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. The 24.7σθ and 25.8σθ 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.

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

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

**Figure 5.** Dynamic height along the 18° N, 130°E, and 8°N sections relative to 1000 db in the winter of 2010 (cycles) and 2012 (stars). 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.

**Figure 6.** Vertically averaged daily meridional velocity from the moorings at 18ºN, 122.7ºE (a) and 8ºN, 127ºE (b). The time series has been smoothed by a 3-day running mean filter, with the linear trend plotted in the dash line. The abscissa is the time in year/month. Unit is cm s-1.

**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 the gridded monthly Argo data in November and in December of 2012. 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 are 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.

**Figure 8.** Meridional geostrophic velocity (upper panel) in the western boundary at 8°N and 18°N section. The zonal integration of of two sections are illustrated in the down panel. The dotted pink and cyan are in Decembers of 2010 and 2012. The gray line is the averaged result of the December of 1993-2021. Respectively, the green, blue and red lines are the results of a composite analysis for the following periods: cold phase: December to February of 1995–1996, 1998–1999, 1999–2000, 2007–2008, 2010-2011, 2011–2012, and 2017-2018; warm phase: December to February of 1994–1995, 1997–1998, 2002–2003, 2006–2007, 2009–2010, 2015–2016, and 2018–209; neutral phases: December to February during the left years.

**Figure 9.** Time series of anomaly in the west boundary at 18ºN (green lines in b) and 8ºN (blue lines in b). The thin lines are monthly anomaly. The thick lines has been smoothed by a 13-month butterworth lowpass filter from the thin lines. Unit is m2. The abscissa is the time in year. The 95% significance level in dash line in c) and d) is based on the freedom degree of Bretherton et al. (1999). Positive lags here indicate the lead of ONI over the anomaly. The widths of the Kuroshio and the MC, in equation (2), are respectively selected as 2º and 3º according to their V profiles indicated in Fig 8.

**Figure 10.** Meridional geostrophic transports 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.

**Figure 11** Interannual sea level anomalies of satellite altimeters in the northwestern Pacific Ocean in December of 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 (c) 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.

**Figure 12.** Contour map of the sea level anomalies in December 2010 (a) and Hovmöller diagram of the sea level anomalies (b, c) along the waveguide around Philippines. Sea level anomaly unit is cm. The waveguide 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. 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.

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

**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.