



Interannual modulation of the Pacific Decadal Oscillation (PDO) on the low-latitude western North Pacific

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ABSTRACT

To investigate the interannual variability in the northwestern Pacific, an empirical mode decomposition (EMD) was applied to 17-year Absolute Dynamic Topography (ADT) data west of Luzon Island, the Philippines. The mean sea surface height in this area is an appropriate index for the Kuroshio intrusion into the South China Sea (SCS). Significant interannual fluctuations were extracted by the EMD. The interannual variability was strongly correlated with the Pacific Decadal Oscillation (PDO) index, but not the El Niño–Southern Oscillation (ENSO). This indicated the potential impact of the PDO on the circulation in the area. In the warm phase of the PDO (positive index), a southerly anomalous wind off the Philippines causes a northward shift of the North Equatorial Current Bifurcation Latitude (NECBL). This leads to a weakened Kuroshio off Luzon, favoring Kuroshio intrusion into the SCS. The northward migration of the NECBL also results in a weakened Kuroshio off southeast Taiwan and a larger Kuroshio transport off northeast Taiwan. The abundant westward propagating eddies impinging on the Kuroshio in the Subtropical Countercurrent region increases this transport. Although the ENSO has little effect on monsoonal winds during the warm PDO phase, it has a strong impact on the monsoon and meridional migration of the NECBL during the cold phase of the PDO. Therefore, NECBL variations only show a close correspondence with the ENSO during the cold PDO phase. Because the influence of the ENSO is not stationary, the impact of the PDO should be taken into account when examining interannual variability in the low-latitude western North Pacific.

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1. Introduction

The Kuroshio exchanges waters between the Pacific Ocean and the South China Sea through the Luzon Strait, playing an important role in mass, heat, salinity, and nutrient balances in the western Pacific marginal seas. Recent studies demonstrated that the South China Sea throughflow plays an essential role in the climate variability of the Indo-Pacific Ocean (e.g., Qu et al., 2006). Both observations and simulations revealed that variations in the Kuroshio intrusion are closely related to the Kuroshio intensity off Luzon Island in the Philippines (e.g., Qu and Lukas, 2003; Sheu et al., 2010). For example, a numerical simulation by Sheu et al. (2010) demonstrated that when the Kuroshio transport at 18°N decreases (increases), the Kuroshio intrusion into the South China Sea is enhanced (reduced). Tracing back upstream, the strength of the Kuroshio is associated with the North Equatorial Current (NEC) bifurcation latitude off the Philippines (Toole et al., 1990; Qiu and Chen, 2010a). Toole et al. (1990) observed that the transport values of the NEC and the Kuroshio in spring 1988 were twice

those in fall 1987. Accompanying the transport increase was a visually southward shift of the NEC bifurcation latitude in 1988.

The NEC bifurcation latitude also varies on an interannual time-scale (Qiu and Lukas, 1996). Until recently, almost all studies attributed the interannual variability of the NEC bifurcation latitude to the El Niño–Southern Oscillation (ENSO), which made a northward shift during El Niño and a southward shift during La Niña (e.g., Qu and Lukas, 2003). Among dynamical phenomena, the ENSO is known to have the largest impact on the interannual variability of the global climate. In East Asia, the mature phase of El Niño events is usually accompanied by a weakened East Asian winter monsoon (Wang et al., 2000). In the tropical Pacific, the variability in surface currents is mainly induced by the time-varying wind forcing. Wind fluctuations would trigger a meridional shift in the NEC bifurcation latitude. However, the ENSO may not be solely responsible for the atmospheric variability over the northwestern Pacific. In a pioneering study, Qiu and Chen (2010a) analyzed a long-term time series of the NEC bifurcation latitude. They noted that the Niño-3.4 index explains only ~25% of the NEC bifurcation latitude variance. This implies that climate phenomena other than the ENSO may play a role in modulating the meridional migration of the NEC bifurcation latitude.

Mantua et al. (1997) noted that the interannual relationship between the ENSO and the global climate is not stationary and can be

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modulated by the Pacific Decadal Oscillation (PDO). Wu and Wang (2002) found that the ENSO and East Asian summer monsoon relationship during 1978–1993 differed significantly from that during 1962–1977, corresponding to a phase change in the PDO.

Here I examine whether the NEC bifurcation latitude varies with the PDO phase change. Section 2 briefly describes the PDO index, data, and methodology used in this study. Section 3 shows the main results. An index for the Kuroshio intrusion is defined. The index is then decomposed into a finite number of components for further interpretation. Interannual variability and its causes are also examined. Section 4 discusses the relationship between the PDO phase change and the ENSO impact. Section 5 summarizes the results.

2. Data and methodology

The PDO is a climate index (<http://jisao.washington.edu/pdo/PDO.latest>) based on North Pacific sea surface temperature (SST) variations (Mantua et al., 1997). Warm (positive index) and cold (negative index) phases can persist for decades (Fig. 1a). For example, a cool phase lasted from 1947 to 1976, switching to a warm phase between 1977 and 1998. Recently, these decadal cycles have broken down. In late 1998, the PDO entered a cold phase that lasted only 4 years followed by a 3-year warm phase, with another cold phase starting after 2008 (Fig. 1a). Fig. 1b displays the ENSO index (monthly Niño-3.4 index) for reference (<http://www.cpc.ncep.noaa.gov/data/indices/ssstoi.indices>).

Surface wind data are provided by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis project. Monthly averages on global grids ($2.5^\circ \times 2.5^\circ$) are available at the Physical Sciences Division of the National Oceanic and Atmospheric Administration's (NOAA; <http://www.cdc.noaa.gov/>) Earth System Research Laboratory. Maps of Absolute Dynamic Topography (MADT) and absolute geostrophic velocity are distributed by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data; <http://www.aviso.oceanobs.com>), which are merged from multi-satellite altimeter data of the TOPEX/Poseidon, European Remote Sensing satellites 1 and 2 (ERS-1 and 2), Jason-1 and 2, Envisat, and Geosat Follow On (GFO). The dynamic topography is calculated as the sum of the sea level anomaly and mean dynamic topography. The product is gridded on a Mercator grid of $1/3^\circ \times 1/3^\circ$ and a time interval of 7 days and is available from October 1992 onward.

The sea level anomaly difference between two tidal stations was used to calculate the Kuroshio transport off northeastern Taiwan. Hourly data at Ishigaki, Japan, were obtained from the Joint Archive for Sea Level (JASL, <http://uhslc.soest.hawaii.edu/uhslc/jasl.html>). Those at Keelung, Taiwan, were provided by the Central Weather Bureau of Taiwan (<http://www.cwb.gov.tw/eng/index.htm>).

The Hilbert–Huang transform (HHT), which is designed to work well for nonstationary and nonlinear time series data, includes an empirical mode decomposition (EMD) (Huang et al., 1998). The HHT uses the EMD method to decompose a complicated dataset into a finite number of components, the so-called intrinsic mode functions (IMFs). The EMD is adaptive, with each IMF giving an individual (orthogonal) frequency and amplitude. Usually the EMD components are physically meaningful because the characteristic scales are defined by the physical data. The Hilbert transform is then performed on each IMF to obtain the instantaneous frequency.

3. Results

3.1. Kuroshio intrusion index

Beyond the seasonal variation, the year-to-year variation is also prominent in the NEC and Kuroshio, occasionally overwhelming the seasonal signal. Fig. 2 compares the gridded altimeter-based MADT and geostrophic velocity in November 1997 and 1998. Compared to the observational mean NEC bifurcation latitude ($\sim 12.5^\circ\text{N}$) east of the Philippines (Centurioni et al., 2004), the NEC shifted northward and bifurcated at $\sim 15^\circ\text{N}$ in November 1997 (Fig. 2a). In November 1998, however, the NEC shifted southward with bifurcation latitude $\sim 11^\circ\text{N}$ (Fig. 2b). This interannual variation in the NEC bifurcation latitude agrees closely with previous findings (e.g., Qu and Lukas, 2003). Qu and Lukas (2003) further attributed the interannual variability of the NEC bifurcation latitude to the ENSO. Until recently, almost all existing studies suggested that the ENSO is chiefly responsible for this interannual variability. The ENSO is well known to have significant impacts on the interannual variability of the global climate, and has been reported to most strongly influence the low-latitude western North Pacific. For example, in East Asia, Wang et al. (2000) found that the mature phase of El Niño events was usually accompanied by a weakened East Asian winter monsoon. In the tropical Pacific, the variability

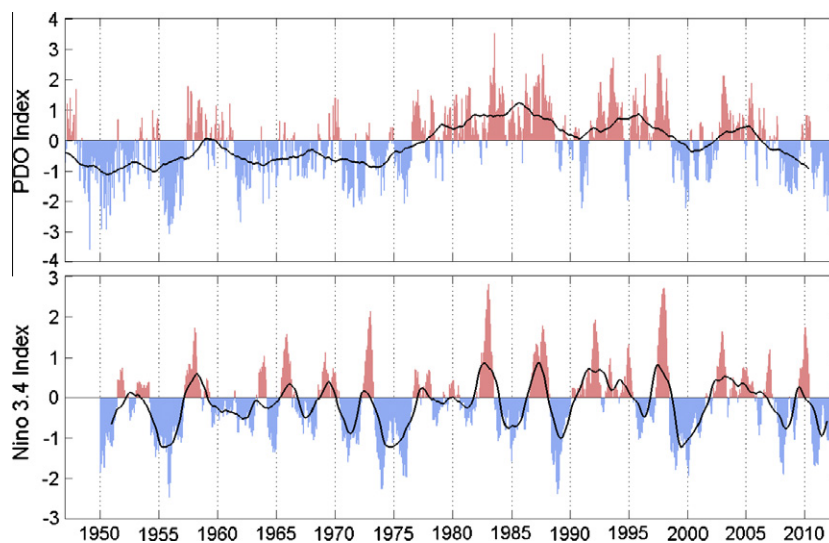


Fig. 1. Low-pass filtered (a) PDO index and (b) Niño-3.4 index.

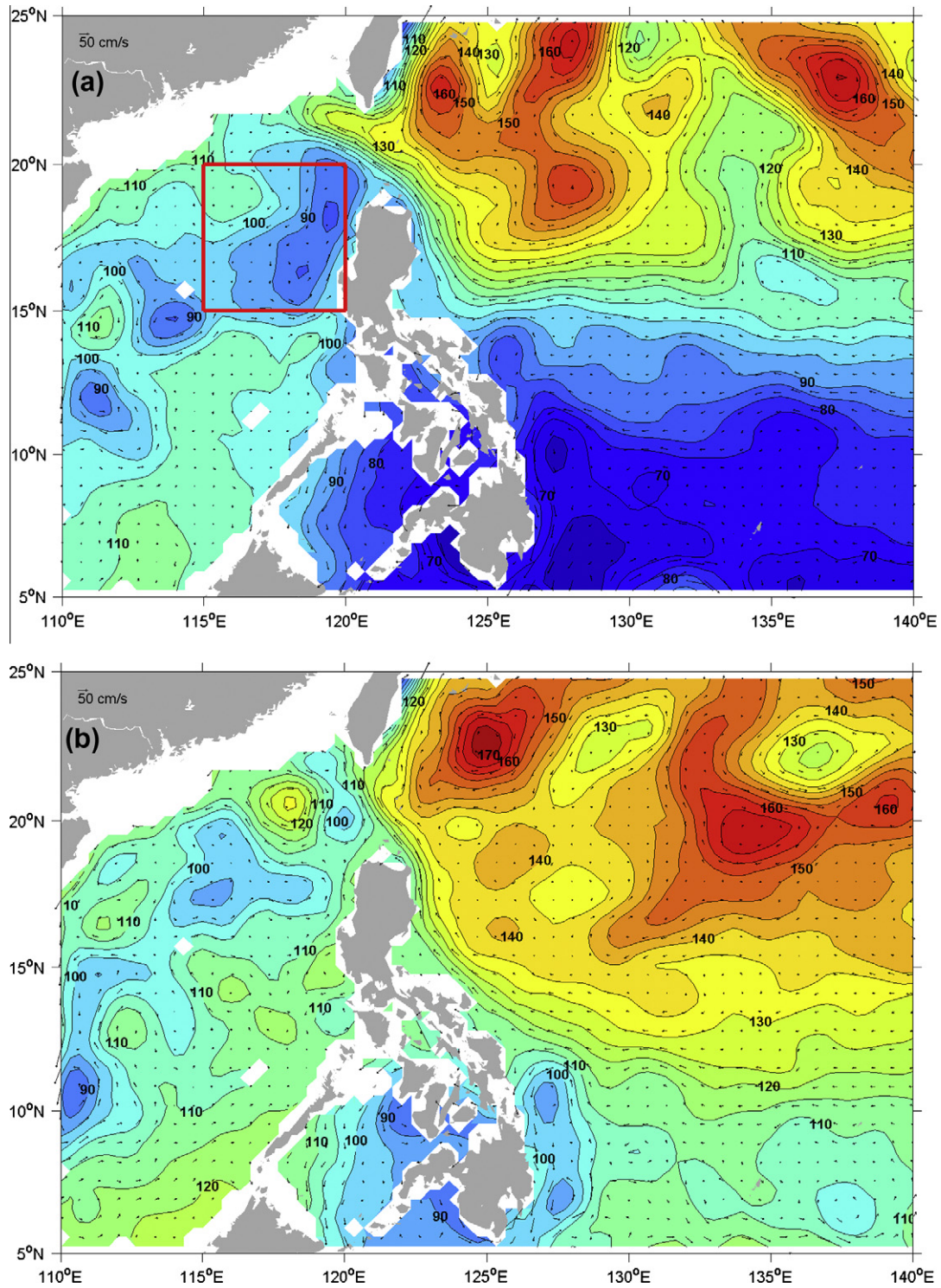


Fig. 2. Maps of Absolute Dynamic Topography (MADT) and absolute geostrophic velocities in (a) November 1997 and (b) November 1998. Contour interval is 5 cm. Red frame in panel (a) is the domain served as a sea level index for the Kuroshio intrusion into the South China Sea. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in the surface current was particularly induced by time-varying wind forcing. The wind fluctuation modulated by ENSO would therefore trigger the meridional shift of the NEC bifurcation latitude. Nevertheless, the present results indicate that ENSO may not be solely responsible for the atmospheric variability over the northwestern Pacific. Later I discuss a climate condition other than ENSO that plays a key role in modulating the meridional migration of the NEC bifurcation latitude.

The NEC bifurcation location aside, the MADT was generally less than 100 cm south of the NEC (~15°N) in November 1997, whereas it was about 120 cm at ~11°N in November 1998 (Fig. 2). The larger MADT gradient in Fig. 2a indicates that both the NEC and the Kuroshio intensified in November 1997, associated with the northward migration of the NEC bifurcation latitude. Furthermore, following the Kuroshio downstream, a distinct flow pattern was observed in the vicinity of the Luzon Strait. The Kuroshio made a

larger meander and the intrusion was not confined within the Luzon Strait but also extended into the South China Sea, reaching west of 118°E along the continental slope in November 1997 (Fig. 2a). However, in November 1998 the Kuroshio followed a relatively straight path and the intrusion was confined within the Luzon Strait east of 120°E. Most of the Kuroshio waters returned to the east and continued to flow northward along the east coast of Taiwan (Fig. 2b). To a certain extent, the Kuroshio intrusion behavior in Fig. 2b is not like a typical winter pattern, but is instead somewhat similar to a summer regime (Fig. 8 of Wu and Chiang, 2007). Seasonal Kuroshio intrusions were previously observed and closely documented (Centurioni et al., 2004; Wu and Chiang, 2007; Hsin et al., 2012; Tsui and Wu, 2012). In general, in summer, the Kuroshio tends to bypass the Luzon Strait without making a significant westward encroachment. Intrusive Pacific water during wintertime can be found west of 117°E inside the South China Sea (Shaw, 1989, 1991; Wu and Hsin, 2012).

Seasonal variations aside, less is known about the interannual variability of the Kuroshio intrusion into the South China Sea because of limited available observations. The comparison in Fig. 2 sheds some light on the year-to-year variation. The altimeter-based MADT map and velocity field reveal significant difference between the winters of 1997 and 1998. The Kuroshio tends to intrude into the South China Sea as the NEC bifurcation latitude shifts northward (Fig. 2a). The larger Kuroshio intrusion is associated with a larger meridional pressure gradient across the Luzon Strait, which corresponds with the findings of Qu (2000). The pressure gradient generated by the meridional sea level difference, which is lower to the south, may trigger the Kuroshio intrusion into the South China Sea. Because the Kuroshio intrusion correlates closely with the low sea surface height west of Luzon Island, an appropriate sea level index for the latter could serve as a good indicator of the interannual variability of the Kuroshio intrusion.

The 17-year MADT data west of Luzon Island, averaged over the domain 115–120°E and 15–20°N (the red rectangle in Fig. 2a), during the period from October 1992 to March 2010 were used to investigate the interannual variability of the Kuroshio intrusion into the South China Sea. The MADT data in the frame excluded depths shallower than 500 m, where the satellite altimetric sea surface height could be subject to large uncertainties. A correlation map was used to examine the relationship between the Kuroshio Intrusion (KI) index (red frame) and the nearby region of the western North Pacific (Fig. 3). Surprisingly, the KI index was not relevant to the zonal band east of the Luzon Strait. Several studies demonstrated that westward-propagating eddies from the interior Pacific may penetrate into the South China Sea through the Luzon Strait and modulate the regional circulation (e.g., Sheu et al., 2010). However, this map indicates that the direct penetration of eddies through the Luzon Strait from the east may not be significant. Instead, Fig. 3 shows that the KI index is highly correlated with the zonal band between 8°N and 12°N, with the correlation coefficient larger than 0.6. In that band, it is associated with the velocity core of the westward-flowing NEC. The higher correlation values (>0.6) follow the northward-flowing Kuroshio along the east coast of the Philippines, connecting the KI index region through the Luzon Strait. The correlation map confirms that the KI index is an appropriate sea level indicator for the interannual variability of the Kuroshio intrusion into the South China Sea. The intrusion fluctuations could be tracked back to the variation in the upstream Kuroshio off the Philippines, as well as the NEC variability in the equatorial Pacific.

3.2. Interannual variability and its cause

The spatial structure of the annual cycle is of interest; however, the large annual signal could hinder identification of the interannual timescale fluctuation. Here, my focus is on interannual

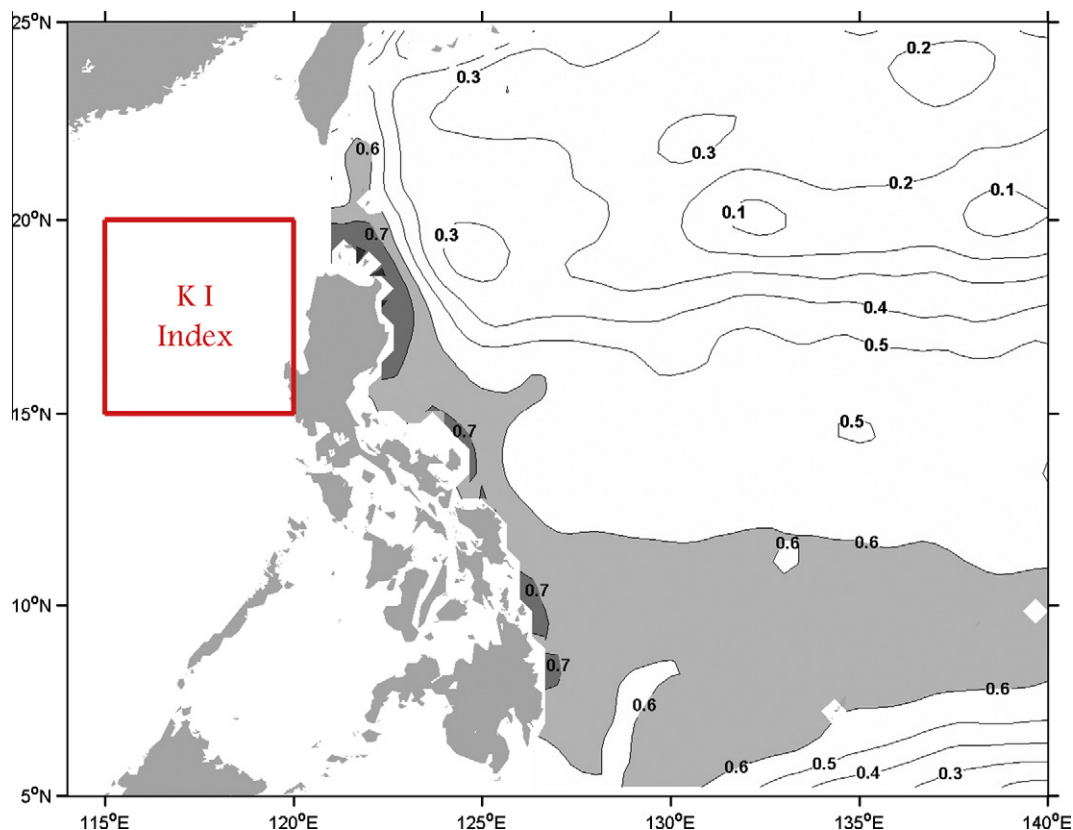


Fig. 3. Correlations between the Kuroshio Intrusion index and 17-year MADT data in the nearby region of the western North Pacific, during the period from October 1992 to March 2010. Areas where the correlation coefficient exceeds 0.6 are shaded.

variability. Thus, an EMD (Huang et al., 1998) is performed to extract various IMFs. A cubic spline is applied for extrapolation of the data at the end points. When applied to 17-year MADT data in the KI index area (115–120°E, 15–20°N), the EMD yielded nine IMFs (Fig. 4). The 1st and 2nd IMFs are short-period fluctuations below the seasonal timescale. The 6–8th IMFs are the ‘residue’ with small amplitudes, and the 9th IMF is the tendency. In between, the IMFs have various amplitudes and frequencies. The 3rd IMF contains a strong annual signal that is negative in winter but positive in summer. The seasonal variation is always prominent because the South China Sea circulation is largely influenced by the seasonal reversal of monsoonal winds. The cyclonic circulation in winter leads to the negative MADT, whereas the positive MADT in summer results from an anticyclonic circulation. The 4th IMF shows quasi-biennial oscillations. The East Asian monsoon also contains quasi-biennial oscillations, but is not a target subject of this study. The 5th IMF shows significant year-to-year variation

beyond the earlier explanation for the interannual variability in the area. This new feature requires a detailed examination.

Fig. 5 is a close-up view of the 5th IMF. The positive MADT peaks in 1995, 2000, and 2008, whereas minimum values occur in 1993, 1997, and 2003. It is curious that the variability of this IMF is not relevant to the ENSO, even though a wealth of studies have demonstrated that the interannual variability of the South China Sea circulation is closely related to the ENSO (e.g., Chao et al., 1996; Wu and Chang, 2005). Rather than the ENSO indices, the 5th IMF variation is highly correlated to the PDO index. The PDO indices are superimposed in Fig. 5 with positive (negative) value in the red (blue) colored bars. A 12-month running mean was applied to the PDO indices, making the interannual variability easily discernible (red dashed line). Positive and large PDO indices (larger than one standard deviation) are found in 1993, 1997, and 2003, while large negative indices are evident in 1995, 2000, and 2008. The peak-to-peak comparison between the 5th IMF

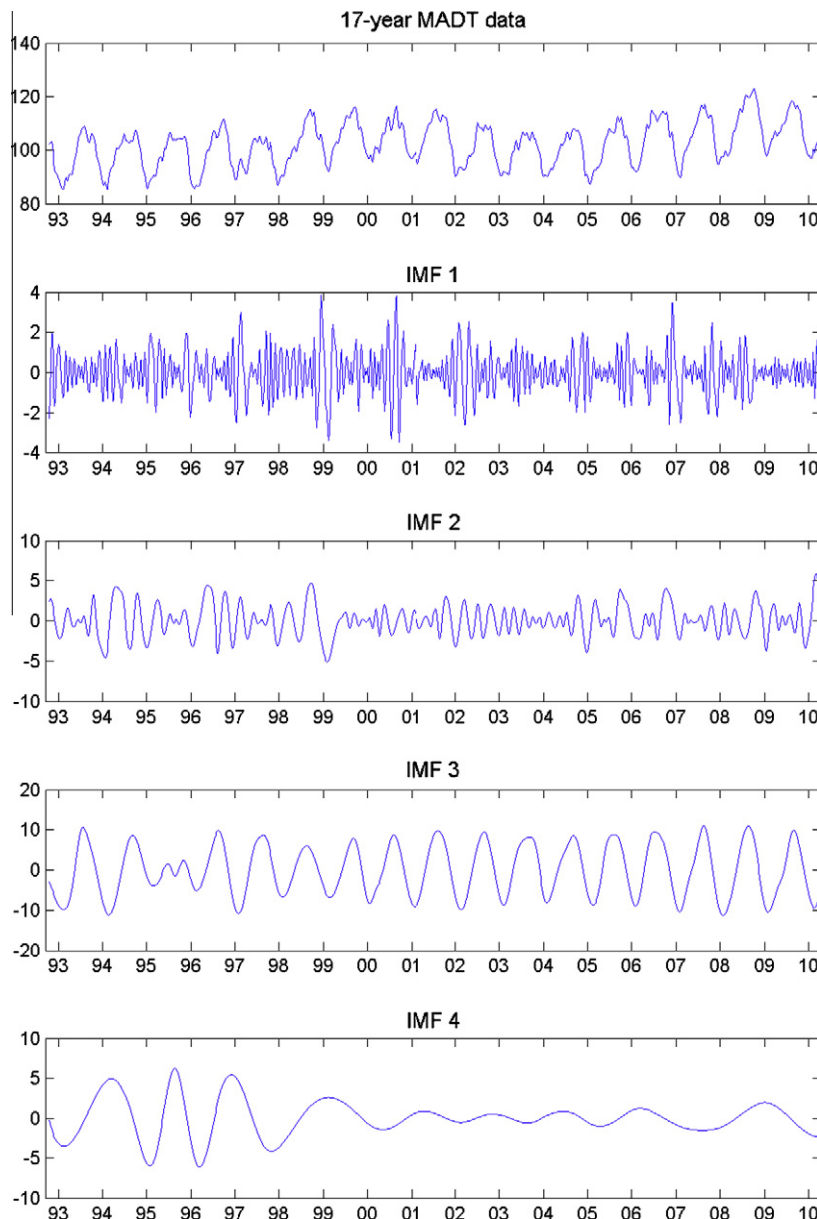


Fig. 4. Time series of 17-year MADT data, averaged over domain of 115–120°E and 15–20°N (defined as the Kuroshio intrusion index), and its EMD components (nine intrinsic mode functions).

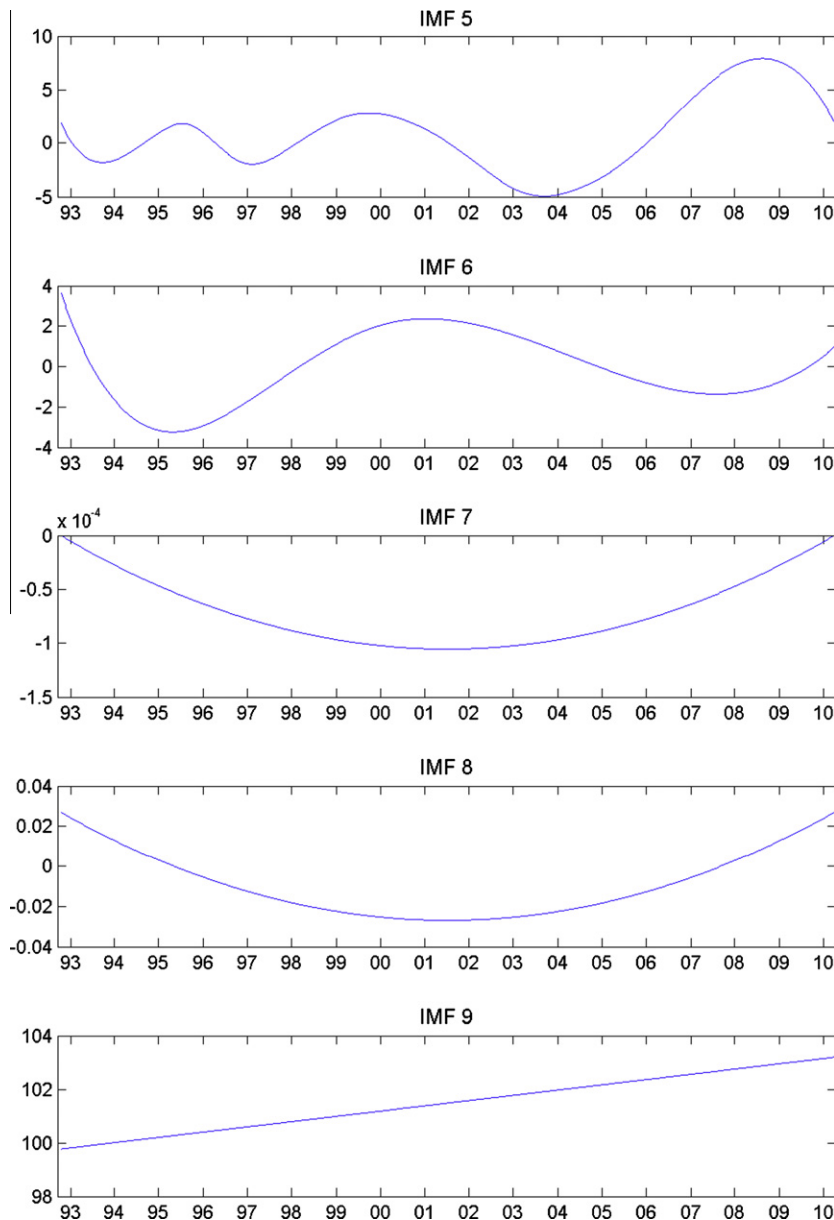


Fig. 4. (continued)

and the PDO index shows close agreement. The correlation between the IMF and the monthly PDO index is significant at $\gamma = -0.53$ (the 99% significance level is 0.30). Nevertheless, the impact of the PDO on the Kuroshio intrusion and the South China Sea circulation deserves further clarification.

As mentioned in the Introduction, the northward shift of the NEC bifurcation latitude results in weakened Kuroshio transport off Luzon, leading to a larger Kuroshio intrusion into the South China Sea. On interannual and longer timescales, most previous studies suggested that the NEC bifurcation latitude is generally related to the ENSO (e.g., Qiu and Lukas, 1996). However, a recent study by Qiu and Chen (2010a) noted that the exact location of the NEC bifurcation latitude is determined by wind forcing in the 12–14°N band, whose variability is not fully represented by the Niño-3.4 index. Their result seems to be on the right track, but the source mechanism needs to be further specified.

The climate conditions in the northwestern Pacific basin were examined. The wind anomaly field and its curl composite for the warm PDO phase are shown in Fig. 6. The composite was

performed over the episodes when the positive PDO index was larger than one standard deviation. An apparent anticyclone was observed over the Philippine Sea. A similar anticyclonic circulation has also been observed by Hung et al. (2004) using wind products from the European Centre for Medium-Range Weather Forecast Re-Analysis 40 (ERA40). They found during the warm PDO phase, the SST in the extra-tropical North Pacific was lower than normal, while the SST over the tropical central-eastern Pacific was higher. These SST variations induced an anomalous anticyclonic wind field over the Philippine Sea. Thus, the southerly anomalous wind off the Philippines can cause a northward shift of the NEC bifurcation latitude. In contrast, in the cold PDO phase a northerly anomalous wind off the Philippines (figure not shown) tends to induce a southward shift from the NEC bifurcation latitude.

3.3. Updated examination of the transport variability

Connected with the PDO, several historical observations have become much more significant when considering interannual

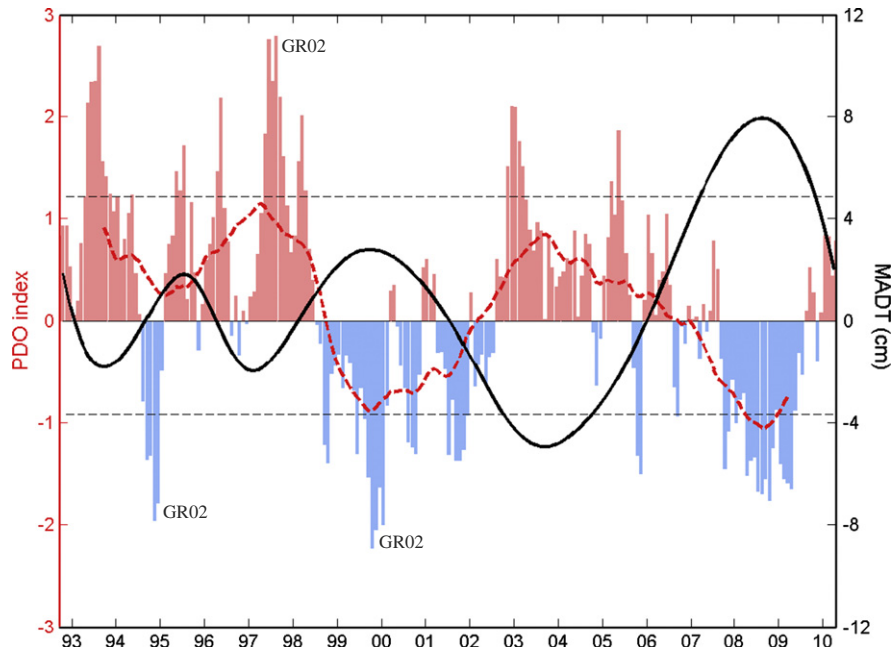


Fig. 5. Time series of the 5th Intrinsic Mode Function (IMF) (bold black line). Monthly PDO index with positive (negative) value is shown in the red (blue) colored bars. Red dashed line is the low-pass filtered PDO index. “GR02” indicates the year when the Kuroshio extreme takes place. Black dashed line shows one standard deviation of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

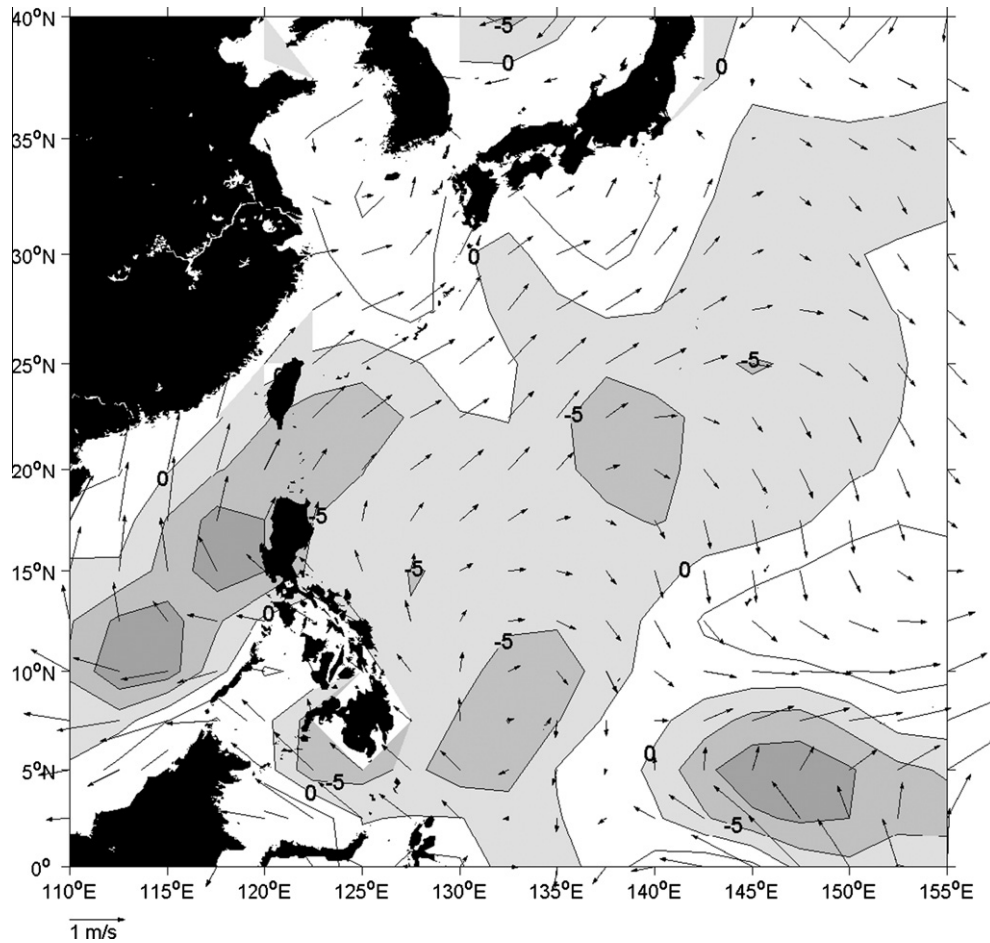


Fig. 6. Wind anomaly field and its curl composite for the positive PDO phase. The composite is performed over the episodes when the positive PDO index is larger than one standard deviation. Contour interval is $5 \times 10^{-7} \text{ Nm}^{-3}$, and negative contours are shaded.

variability. For example, [Gilson and Roemmich \(2002\)](#) examined zonal hydrographic transects south of Taiwan for the period between 1993 and 2001. They found that the Kuroshio transport east of the Luzon Strait exhibited interannual variability, with maxima in 1995 and 2000 and a minimum in 1997–1998. The three extremes did not correlate well with ENSO events. However, in [Fig. 5](#) of the PDO index, there are negative peaks in the end of 1994 and in 1999 and a positive peak in the middle of 1997. Graphically, the PDO peaks lead the three Kuroshio extremes by a few months. The impact of the PDO on these Kuroshio transports is obvious. Applying the climate condition above, the anomalous anticyclone accompanied by a southerly anomalous wind off the Philippines causes the northward migration of the NEC bifurcation latitude during the warm phase of PDO. It then reduces the Kuroshio transport east of the Luzon Strait (or south of Taiwan), as [Gilson and Roemmich \(2002\)](#) observed in 1997–1998. The situation tends to be reversed during negative PDO peaks.

On interannual and longer timescales, the strength of the downstream Kuroshio has the opposite tendency to that south of Taiwan. [Hwang and Kao \(2002\)](#) first noted this unusual feature of the Kuroshio variability between the northeast and southeast of Taiwan. Using TOPEX/POSEIDON altimeter data and a gravimetric geoid, [Hwang and Kao \(2002\)](#) derived 7-year time series of the Kuroshio transport northeast and southeast of Taiwan, and identified that the transport variabilities between the two locations are out of phase. They further related the volume transports to the ENSO index and found that the Kuroshio transport variation northeast of Taiwan lags the ENSO index by 1 month with a correlation coefficient of 0.6, whereas the variation southeast of Taiwan leads the ENSO index by 9–10 months with a negative coefficient of -0.6 . The distance between the northeast and southeast of Taiwan is less than 400 km. The distinct variability between the two locations implies that there should be a dynamic modulation around $22\text{--}24^\circ\text{N}$. Mesoscale eddy activities at these latitudes are dominantly responsible for the variability differences. I will again demonstrate that the interannual transport variability in this area is more closely related to the PDO phase than to ENSO as proposed by [Hwang and Kao \(2002\)](#).

The sea level anomaly difference between two tidal gauge stations, Ishigaki and Keelung, was adopted to estimate the Kuroshio

transport off northeast Taiwan. By validation with data from the Acoustic Doppler Current Profiler (ADCP) mooring array of northeast Taiwan, [Yang et al. \(2001\)](#) demonstrated that the Kuroshio transport calculated by these two tidal stations is accurate. [Fig. 7](#) shows the tidal-gauge-based Kuroshio transport off northeast Taiwan ($\sim 24.5^\circ\text{N}$) alongside PDO indices during 1980–2008. The low-pass filtered PDO and Kuroshio transport are also superimposed in the figure. The two time series are virtually in phase with each other, and Kuroshio transports are generally larger in association with larger positive PDO indices. The Kuroshio transport was also larger in 1997 than in 1995 and 2000. This transport variability is the opposite of that in the upstream area calculated by [Gilson and Roemmich \(2002\)](#). They found that the Kuroshio transport east of the Luzon Strait was larger in 1995 and 2000 but weaker in 1997. The opposite tendency between the two locations was consistent with the findings of [Hwang and Kao \(2002\)](#). Nevertheless, although the Kuroshio transport variation at $\sim 24.5^\circ\text{N}$ was the opposite of that southeast of Taiwan, the source were the same, which is also related to the meridional shift of the NEC bifurcation latitude. The opposite tendencies in the northeast and southeast of Taiwan can be attributed to the interplay between the Kuroshio and mesoscale eddies. In the Subtropical Countercurrent (STCC, $20\text{--}23^\circ\text{N}$) region, the westward-propagating eddies originating in the interior Pacific frequently approach the eastern coast of Taiwan (e.g., [Hwang et al., 2004](#)). These mesoscale eddies collide with the Kuroshio and influence the flow pattern and volume transport in the downstream region off northeast Taiwan. For example, using altimeter-based sea surface height anomaly data, [Hsin et al. \(2011\)](#) found that the Kuroshio transport variability corresponds closely with the arrival of cyclonic eddies. The cyclonic eddies decelerate the Kuroshio velocity, and hence the Kuroshio shifts shoreward off northeast Taiwan.

How does the meridional migration of the NEC bifurcation latitude affect the Kuroshio transports northeast and southeast of Taiwan? [Qiu and Chen \(2010b\)](#) demonstrated that eddy activity in the STCC causes interannual variability. A recent study by [Chang and Oey \(2012\)](#) further related the eddy activity in the STCC to the NEC bifurcation. As mentioned above, a positive PDO is always associated with the northward shift of the NEC bifurcation latitude and a weakened Kuroshio transport off southeast Taiwan (e.g., a

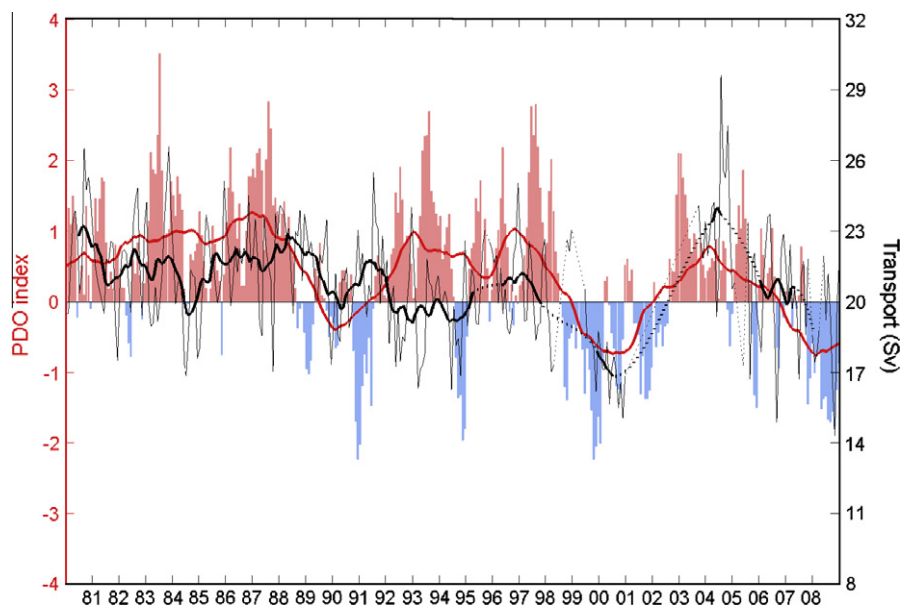


Fig. 7. Time series of the tidal-gauge-based Kuroshio transport off northeast Taiwan ($\sim 24.5^\circ\text{N}$) (thin black line), together with monthly PDO index during 1980–2008 (colored bars). Thick black and red lines are the low-pass filtered Kuroshio transport and PDO index, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

minimum in 1997 reported by Gilson and Roemmich, 2002). According to Chang and Oey (2012), the northward shift of the NEC will increase eddy activity in the STCC by changes in the vertical shear of the STCC–NEC system. More abundant westward-propagating eddies strike the Kuroshio off east Taiwan in the STCC region (20–23°N), increasing its downstream transport. Therefore, the Kuroshio transport off northeast Taiwan becomes larger during the eddy-rich period. Positive PDO indices are therefore always associated with a larger Kuroshio transport off northeast Taiwan, as revealed in the phase between the two (Fig. 7).

Furthermore, there is a contradiction in the NEC transport variability associated with El Niño in historical observations. According to Qiu and Joyce (1992), the NEC is generally larger than normal during El Niño events. In contrast, using repeated hydrographic sections (1986–1991) near the Philippine coast, Qu et al. (1998) found that minimum transport of the NEC at 130°E (and the Kuroshio at 18°N) was concurrent with the mature phase of 1986/1987 El Niño. This confusion indicates again that the ENSO alone cannot be fully responsible for the interannual variability of the current system in the low-latitude western North Pacific. However, the contradiction among these historical observations can be resolved simply by including the impact of the PDO. The positive PDO index in 1987 is quite large (see Fig. 7). The aforementioned mechanism for the positive PDO is applicable. A large positive PDO induces a southerly anomalous wind off the Philippines, causing northward shift of the NEC bifurcation latitude and reducing the Kuroshio transport at 18°N, as Qu et al. (1998) observed. Hydrographic surveys off the Philippine coast lend further support to this phenomenon. Toole et al. (1990) observed significantly reduced transport of the NEC and Kuroshio in fall 1987 as compared to spring 1988. The NEC bifurcation latitude in 1987 was 14.1°N and shifted south to 12.6°N in 1988. Again this interannual variability is more related to the PDO phase than to the ENSO phase. Positive PDO indices in 1987 but negative PDO indices in 1988 can be seen in Fig. 7.

4. Discussion

One outstanding question is why earlier studies found close correlations between the ENSO and the interannual variability of the NEC bifurcation latitude (e.g., Qiu and Lukas, 1996; Qu and Lukas, 2003). Does this imply that the ENSO exerted a stronger impact earlier, but has had less effect recently? I believe that this is the case. Qiu and Chen (2010a) extended the time series of the NEC bifurcation latitude variability back to 1962 using a dynamic model and proxy sea level anomalies. They found that the interannual variability in the NEC bifurcation latitude was roughly correlated to the Niño-3.4 index (their Fig. 7d). However, closer inspection indicates that this consistency has broken down in recent years, especially after 1995. The change in the PDO phase is most responsible for this variance.

Warm and cold PDO phases can usually persist for decades. However, the warm/cold phase has alternated more often in recent decades (see also Fig. 1a). Wang et al. (2008) found that two atmospheric teleconnections (low-latitude Pacific–East Asian and mid-latitude geopotential height response to the ENSO) over the northwestern Pacific were weak during the warm phase of the PDO. This indicates that during the positive PDO, the winter monsoon would not be significantly influenced by the ENSO. In other words, the interannual relationship between the ENSO and the monsoonal wind is weak and insignificant in the warm phase of the PDO. This explains why the interannual variability in the NEC bifurcation latitude was not closely correlated to the Niño-3.4 index recently: it was because of the significantly weakened impact of the ENSO on the winter monsoon during the warm PDO phase.

The time-varying NEC bifurcation latitude is in agreement with the PDO indices, not those of the ENSO. The NEC bifurcation latitude variability inferred from monthly satellite altimeter sea level measurements lends support to this connection. Qiu and Chen (2010a) found that the NEC bifurcation latitude was at a northerly latitude in late 1992, 1997–1998, and 2003–2004 and at a southerly latitude in 1999–2000 and 2007–2009 (their Fig. 2a). To a lesser degree, those episodes coincided respectively with positive and negative peaks of the low-frequency PDO time series (red dashed line in Fig. 5). On the other hand, during the cold regime of PDO, the ENSO exerted a strong impact on the monsoonal winds, as did the NEC bifurcation latitude. Consequently the interannual variability in the NEC bifurcation latitude could show closer correlation with that of the Niño-3.4 index, as noted in earlier studies (e.g., Qiu and Lukas, 1996). This indicates that the ENSO's impact on the monsoonal winds is not stationary. The impact of the PDO phase change should be included when studying interannual variation in this area.

5. Summary

This study found that the interannual variability in the low-latitude western Pacific has been much more closely related to the PDO than to the ENSO in recent years. Especially during the warm phase of the PDO, an anomalous anticyclonic wind field appeared over the Philippine Sea. The southerly anomalous wind off the Philippines caused a northward shift of the NEC bifurcation latitude, reducing the Kuroshio transport off Luzon and increasing the Kuroshio intrusion into the South China Sea. The sequential process suggests that an appropriate sea level index in the South China Sea could serve as a good indicator of the NEC bifurcation latitude variation, the interannual variation of the Kuroshio off the Philippines, and the Kuroshio intrusion variability. The northward shift of the NEC bifurcation latitude also results in a weakened Kuroshio east of the Luzon Strait, but larger Kuroshio transport off northeast Taiwan owing to abundant westward-propagating eddies arriving at the Kuroshio in the STCC and increasing its downstream transport.

The impact of the ENSO on the northwestern Pacific is not stationary, and it depends on the phase of the PDO. The interannual relationship between the ENSO and the winter monsoon is weak and insignificant in the warm phase of the PDO. The time-varying NEC bifurcation latitude is also in agreement with the concurrent PDO indices. However, ENSO exerts a strong impact on the winter monsoon in the cold phase of the PDO, at a time when the NEC bifurcation latitude variability can be better represented by the Niño-3.4 index. The significant impact of PDO phase change should be considered when examining interannual variability in the low-latitude western North Pacific.

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References

- Centurioni, L.R., Niiler, P.P., Lee, D.K., 2004. Observation of inflow of Philippine sea surface water into the South China sea through the Luzon Strait. *Journal of Physical Oceanography* 34, 113–121.
- Chang, Y.-L., Oey, L.-Y., 2012. The Philippines–Taiwan oscillation: monsoonlike interannual oscillation of the subtropical–tropical western North Pacific wind system and its impact on the ocean. *Journal of Climate* 25, 1597–1618.

- Chao, S.-Y., Shaw, P.-T., Wu, S.-Y., 1996. El Niño modulation of the South China sea circulation. *Progress in Oceanography* 38, 51–93.
- Gilson, J., Roemmich, D., 2002. Mean and temporal variability in Kuroshio geostrophic transport south of Taiwan (1993–2001). *Journal of Oceanography* 58, 183–195.
- Hsin, Y.-C., Chiang, T.-L., Wu, C.-R., 2011. Fluctuations of the thermal fronts off northeastern Taiwan. *Journal of Geophysical Research* 116, C10005. <http://dx.doi.org/10.1029/2011JC007066>.
- Hsin, Y.-C., Wu, C.-R., Chao, S.-Y., 2012. An updated examination of the Luzon Strait transport. *Journal of Geophysical Research* 117, C03022. <http://dx.doi.org/10.1029/2011JC007714>.
- Huang, N.E., Shen, Z., Long, S.R., et al., 1998. The empirical mode decomposition and the Hilbert spectrum for nonlinear and nonstationary time series analysis. *Proceedings: Mathematical, Physical, and Engineering Sciences* 454 (1971), 903–995.
- Hung, C.-W., Hsu, H.-H., Lu, M.-M., 2004. Decadal oscillation of spring rain in northern Taiwan. *Geophysical Research Letters* 31, L22206. <http://dx.doi.org/10.1029/2004GL021344>.
- Hwang, C., Kao, R., 2002. TOPEX/POSEIDON-derived space–time variations of the Kuroshio current: applications of a gravimetric geoid and wavelet analysis. *Geophysical Journal International* 151, 835–847.
- Hwang, C., Wu, C.-R., Kao, R., 2004. TOPEX/Poseidon observations of mesoscale eddies over the subtropical countercurrent: kinematic characteristics of an anticyclonic eddy and a cyclonic eddy. *Journal of Geophysical Research* 109, C08013. <http://dx.doi.org/10.1029/2003JC002026>.
- Mantua, N.J., Hare, S.R., Zhang, Y., et al., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78 (6), 1069–1079.
- Qiu, B., Joyce, T.M., 1992. Interannual variability in the mid- and low-latitude western North Pacific. *Journal of Physical Oceanography* 22, 1062–1079.
- Qiu, B., Lukas, R., 1996. Seasonal and interannual variability of the north equatorial current, the Mindanao current and the Kuroshio along the Pacific western boundary. *Journal of Geophysical Research* 101, 12315–12330.
- Qiu, B., Chen, S., 2010a. Interannual-to-decadal variability in the bifurcation of the north equatorial current off the Philippines. *Journal of Physical Oceanography* 40, 2525–2538. <http://dx.doi.org/10.1175/2010JPO4462.1>.
- Qiu, B., Chen, S., 2010b. Interannual variability of the North Pacific STCC and its associated mesoscale eddy field. *Journal of Physical Oceanography* 40, 213–225.
- Qu, T., Mitsudera, H., Yamagata, T., 1998. On the western boundary currents in the Philippine sea. *Journal of Geophysical Research* 103, 7537–7548.
- Qu, T., 2000. Upper-layer circulation in the South China sea. *Journal of Physical Oceanography* 30, 1450–1460.
- Qu, T., Lukas, R., 2003. The bifurcation of the north equatorial current in the Pacific. *Journal of Physical Oceanography* 33, 5–18.
- Qu, T., Du, Y., Sasaki, H., 2006. South China sea throughflow: a heat and freshwater conveyor. *Geophysical Research Letters* 33, L23617. <http://dx.doi.org/10.1029/2006GL028350>.
- Shaw, P.-T., 1989. The intrusion of water masses into the sea southwest of Taiwan. *Journal of Geophysical Research* 94, 18213–18226.
- Shaw, P.-T., 1991. The seasonal variation of the intrusion of the Philippine sea water into the South China sea. *Journal of Geophysical Research* 96, 821–827.
- Sheu, W.-J., Wu, C.-R., Oey, L.-Y., 2010. Blocking and westward passage of eddies in the Luzon Strait. *Deep-Sea Research II* 57, 1783–1791.
- Toole, J., Millard, R., Wang, Z., Pu, S., 1990. Observations of the Pacific north equatorial current bifurcation at the Philippine coast. *Journal of Physical Oceanography* 20, 307–318.
- Tsui, I.-F., Wu, C.-R., 2012. Variability analysis of Kuroshio intrusion through Luzon Strait using growing hierarchical self-organizing map. *Ocean Dynamics* 62, 1187–1194. <http://dx.doi.org/10.1007/s10236-012-0558-0>.
- Wang, B., Wu, R., Fu, X., 2000. Pacific–east Asian teleconnection: how does ENSO affect east Asian climate? *Journal of Climate* 13 (9), 1517–1536.
- Wang, L., Chen, W., Huang, R., 2008. Interdecadal modulation of PDO on the impact of ENSO on the east Asian winter monsoon. *Geophysical Research Letters* 35, L20702. <http://dx.doi.org/10.1029/2008GL035287>.
- Wu, C.-R., Chang, C.-W.J., 2005. Interannual variability of the South China sea in a data assimilation model. *Geophysical Research Letters* 32, L17611. <http://dx.doi.org/10.1029/2005GL023798>.
- Wu, C.-R., Chiang, T.-L., 2007. Mesoscale eddies in the northern South China sea. *Deep Sea Research II* 54, 1575–1588. <http://dx.doi.org/10.1016/j.dsr2.2007.05.008>.
- Wu, C.-R., Hsin, Y.-C., 2012. The forcing mechanism leading to the Kuroshio intrusion into the South China sea. *Journal of Geophysical Research* 117, C07015. <http://dx.doi.org/10.1029/2012JC007968>.
- Wu, R., Wang, B., 2002. A contrast of the east Asian summer monsoon–ENSO relationship between 1962–77 and 1978–93. *Journal of Climate* 15 (22), 3266–3279.
- Yang, Y., Liu, C.-T., Lee, T.N., Johns, W., Li, H.-W., Koga, M., 2001. Sea surface slope as an estimator the Kuroshio volume transport east of Taiwan. *Geophysical Research Letters* 28 (12), 2461–2464. <http://dx.doi.org/10.1029/2000GL011709>.