Decadal Variability of the Anticyclone in the Western North Pacific

MINGMEI XIE

State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, and University of Chinese Academy of Sciences, Beijing, China

CHUNZAI WANG

State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, and Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), and Innovation Academy of South China Sea Ecology and Environmental Engineering, Chinese Academy of Sciences, Guangzhou, China

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ABSTRACT: The western North Pacific anomalous anticyclone (WNPAC) significantly affects East Asian climate. Previous studies have elucidated interannual variability of the WNPAC associated with El Niño, but decadal variability of the WNPAC remains unknown. The present paper investigates the dominant modes of decadal variability of the WNPAC by using observational data. The first decadal mode, characterized by an anomalous anticyclone centered over the western North Pacific, is associated with the Pacific decadal oscillation (PDO). The relationship between the first mode and the PDO shifted from in phase to out of phase around 1966. From 1900 to 1966 when the PDO and the first mode are in phase, the anticyclone is maintained by the effects of both the strengthened Aleutian low through meridional atmospheric forcing and Indian Ocean warming through enhanced zonal Walker circulation. From 1967 to 2012, the anticyclone is induced by cold SST anomalies over the central equatorial Pacific when the PDO and the first mode are out of phase. The second decadal mode is characterized by an anomalous anticyclone extending from southeastern China to the Philippine Sea and is associated with the Maritime Continent (MC). This anticyclone resides in the sinking branch of the local Hadley circulation, triggered by enhanced convection associated with the MC warming from 1900 to 2012. The finding of the decadal WNPAC in this paper may provide a new way to explain East Asian climate on a decadal time scale.

KEYWORDS: Air-sea interaction; Atmosphere-ocean interaction; Climate change; Climate variability; Decadal variability; Pacific decadal oscillation

1. Introduction

El Niño–Southern Oscillation (ENSO) is the dominant interannual variability in the tropical climate system that can remotely affect climate in East Asia through the western North Pacific anomalous anticyclone (WNPAC) (Chou et al. 2009; Li et al. 2018; Wu et al. 2017). The WNPAC, which is the most pronounced low-level circulation pattern over the tropical Pacific, is a prime system affecting the East Asian monsoon (Chang et al. 2000; Chen et al. 2013; Feng et al. 2014; Song and Zhou 2015; Zhang et al. 1996) and tropical cyclone activity in the western North Pacific (WNP) (Du et al. 2011; Wang et al. 2013; Wang and Wang 2013; Wu et al. 2005). Since the anomalous anticyclone over the WNP has important implications for regional and global climates (Weisberg and Wang 1997; Wang et al. 1999, 2000; Zhang et al. 2017), a better understanding of its variability is important and necessary.

It is well known that on an interannual time scale, the life cycle of the WNPAC is tightly linked with the phase of ENSO (Chou 2004; Wu et al. 2003). The seasonal evolution of the WNPAC, as characterized by the eigenvalues of the first season-reliant empirical orthogonal function (S-EOF) modes in the 850-hPa wind, is shown in Fig. 1a. We use years 0 and 1 to denote the El Niño developing and decaying years, respectively. As documented by previous studies (Wang et al. 2008; Wu et al. 2009b; Yuan et al. 2012), in June–August of the El Niño developing year [JJA(0)] the tropical WNP is dominated by anomalous cyclonic circulation. During September–November [SON(0)], the cyclonic anomalies transform into an anomalous anticyclone, which becomes fully developed in December–February [D(0)JF(1)]. Then, the WNPAC maintains its strength throughout the spring (March–May) of the El Niño decaying year [MAM(1)] and weakens in summer [JJA(1)]. The principal component (PC) time series of the first S-EOF mode of the seasonal 850-hPa wind anomalies and the D(0) JF(1) Niño-3.4 index are shown in Fig. 1b. The correlation coefficient between PC1 and the D(0)JF(1) Niño-3.4 sea surface temperature (SST) anomalies is 0.84, indicating that the seasonal evolution of the first mode coincides with the transition of ENSO events.

The anomalous anticyclone in the WNP may be regarded as a Rossby wave response to suppressed convection over the WNP (Zhang et al. 1996). The maintenance of the WNPAC from the winter of the El Niño mature phase to the early summer of the decaying year is attributed to cold SST anomalies over the WNP (Wang et al. 2000; Wang and Weisberg 2000; Wang et al. 1999). During the El Niño winter, as explained by Wang et al. (2000), the El Niño–induced anomalous heating over the central equatorial Pacific (CEP) can excite
cyclonic anomalies to the west. The northeasterly anomalies of the cyclone coincide with the mean trade winds, resulting in cold SST anomalies through excessive surface evaporation. As a result, the WNPAC forms as a Rossby wave response to the negative heating anomalies induced by the cold SST anomalies over the WNP. During the summer of the El Niño decaying year, although the warm SST anomalies over the equatorial eastern Pacific have faded, the anomalous anticyclone still exists because of the effect of basinwide warming in the Indian Ocean (Wu et al. 2009a; Xie et al. 2009, 2016).

FIG. 1. Interannual variability of the anticyclone in the WNP. (a) Seasonal evolution of the 850-hPa wind anomalies associated with the El Niño transition from the summer of the developing year, JJA(0), to the summer of the decaying year, JJA(1), as calculated based on an S-EOF analysis. (b) Normalized PC time series of the first S-EOF mode (blue line) and the D(0)JF(1) Niño-3.4 index (red line). Interannual variability is obtained by subtracting the 7-yr running mean from the detrended time series.
response to this basinwide Indian Ocean warming, anomalous easterlies associated with the Kelvin wave response appear over the WNP, with their maximum at the equator and decreasing with latitude. The easterly wind shear generates anticyclonic vorticity and leads to surface divergence over the WNP, which suppresses convection and further induces the anomalous anticyclone.

The processes and mechanisms discussed above occur mainly in the mature and decaying phases of El Niño. Wang et al. (2013) further proposed that during the El Niño to La Niña transition phase, the central Pacific (CP) SST anomalies act as a forcing mechanism to explain the maintenance of the WNPAC. The anomalous WNPAC, associated with suppressed convection extending from the Philippine Sea southward to the equatorial western Pacific, is forced by CP cooling. This suppressed convection can directly strengthen the WNPAC through the emanation of descending Rossby waves (Gill 1980). This mechanism was confirmed by numerical experiments with an atmospheric general circulation model under forcing by CP SST cooling. Chen et al. (2016) also suggested that the cooling over the central to eastern Pacific plays an important role in maintaining the WNPAC during the developing years of La Niña.

Previous studies of the WNPAC have mainly focused on its interannual variability; however, decadal variability of the WNPAC has not been documented and investigated. Recent studies suggested that the western Pacific subtropical high (WPSH), which is linked with the WNPAC, has experienced decadal changes (Gong and Ho 2002). Zhou et al. (2009a,b) further examined the role of decadal tropical Indian Ocean warming in modulating the decadal change of the WPSH. Other studies mentioned the important role of the Pacific decadal oscillation (PDO) in the WPSH, which affects the East Asian monsoon (Jiang and Zhou 2019; Li et al. 2010; Qian and Zhou 2014; Si and Ding 2016; Xiao et al. 2019; Yang et al. 2017). Nevertheless, the WNPAC on a decadal time scale remains unknown. The present paper investigates whether the WNPAC exists on the decadal time scale. Furthermore, if decadal variability of the WNPAC exists as hypothesized, what are the physical mechanisms responsible for the anticyclone on decadal time scale? In the present paper, based on the Twentieth Century Reanalysis (20CR) dataset and other datasets, we explicitly separate the dominant modes of decadal variability of the WNPAC. In contrast to its counterpart on interannual time scale (El Niño is the leading forcing of the interannual WNPAC), the WNPAC on decadal time scale exhibits two modes with different central positions. Our study has investigated the roles of the PDO and the Maritime Continent (MC), Indian Ocean, and CP SSTs in decadal variability of the WNPAC, thus providing a new atmospheric bridge that links the SST variations with East Asian climate on decadal time scale. The results obtained based on the 20CR dataset are further verified by using other independent datasets.

The paper is organized as follows. In section 2, the datasets and methodology used in this study are introduced. In section 3, the two leading modes of decadal variability of the WNPAC are extracted. Sections 4 and 5 investigate the physical processes associated with the first and second modes, respectively. Conclusions and discussions are presented in section 6.

2. Datasets and methods

a. Datasets

The data used in the present study consist of the atmospheric circulation fields from the Twentieth Century Reanalysis (20CR) dataset, which covers the period from 1871 to 2012 (Compo et al. 2011). In this paper, we focus on the years from 1900 to 2012. The variables used in this study are monthly atmospheric wind and vertical velocities at levels of 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, and 100 hPa. For better presentation, we multiply the vertical velocities by −1 so that positive values indicate upward movement of air parcels. The SST data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature version 5 dataset (Huang et al. 2017). The results derived from the 20CR are verified through comparison with the ERA-20C dataset, the Japanese 55-year Reanalysis (JRA-55) dataset, and the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) dataset. The ERA-20C dataset is an atmospheric re-analysis of the twentieth century produced by the ECMWF, covering the period of 1900–2010 (Polli et al. 2016). The JRA-55 dataset is from 1958 to 2012, and the ERA-40 dataset is from 1958 to 2002.

b. Methods

1) Extraction of the decadal modes of the WNPAC

In this study, we first removed the long-term trends from the datasets. Then, decadal variability was obtained by performing a 7-yr running-mean calculation on the detrended datasets. Interannual variability was calculated by subtracting decadal variability from the detrended datasets. Thus, the variations on interannual and decadal time scales were separated.

S-EOF analysis has previously been developed to extract interannual modes over the Indo-Pacific region (Wang 2005). Here, we used the same analysis approach but applied it to the WNP region (0°–35° N, 100°–160° E). The S-EOF analysis was applied to five seasons, spanning from June–August of year 0 [JJA(0)] to June–August of the following year [JJA(1)]. We identify the years 0 and 1 in a manner consistent with that of Wang et al. (2008); year 0 represents the developing year of El Niño, while year 1 represents the decaying year. Thus, the evolution of the WNPAC on interannual time scale is characterized by the S-EOF modes in the 850-hPa winds. In the present study, we identify decadal variability of the WNPAC through a direct and consistent way similar to that on interannual time scale, but filter out seasonal and interannual signals. To depict decadal variability of the WNPAC, we first performed a 7-yr running-mean calculation on the detrended datasets to remove interannual signals. Because we mainly focus on the low frequency of the WNPAC, the seasonal variations are ignored. The EOF analysis was applied to the annual mean (from January to December) 850-hPa wind vectors.
over the WNP region. Then, the following analysis steps were performed. First, the anomaly series for the zonal and meridional wind components were separately normalized. Second, the combined matrix of the zonal and meridional wind series was decomposed following the conventional EOF analysis approach. Finally, the empirical functions thus obtained were converted into spatial patterns of the zonal and meridional wind components (Wu et al. 2016). Using the same region (0°–35°N, 100°–160°E) for interannual variability, we decompose the decadal-filtered wind anomalies and obtain the first two dominant modes, which represent decadal variations of the WNPAC. By regressing decadal-filtered fields onto the corresponding standardized PC time series, the atmospheric circulation and SST anomalies patterns associated with these two modes were obtained.

2) SIGNIFICANCE TEST

The statistical significance of the linear regression coefficient between two time series can be calculated via a two-tailed Student’s t test using the effective number of degrees of freedom. The effective number of degrees of freedom is given by the following approximation (Pyper and Peterman 1998):

\[
\frac{1}{N_{\text{eff}}} = \frac{1}{N} + \frac{2}{N} \sum_{j=1}^{N} \rho_{XX}(j)\rho_{YY}(j),
\]

where \(N\) is the sample size and \(\rho_{XX}(j)\) and \(\rho_{YY}(j)\) are the autocorrelations of two sampled time series \(X\) and \(Y\) at time lag \(j\).

3) CLIMATIC MODE INDEX

Two climatic mode indexes were utilized. The Niño-3.4 index is defined as a time series of spatially averaged SST anomalies during winter over the central to eastern tropical Pacific (5°S–5°N, 170°–120°W). The PDO index is defined as the leading EOF PC time series of the annual mean detrended SST anomalies for the Pacific Ocean to the north of 20°N (Zhang et al. 1997), available at http://research.jisao.washington.edu/pdo/PDO.latest.

3. Decadal variability of the WNPAC

To identify the leading modes of decadal variability of the WNPAC, we applied the EOF analysis to the annual mean 850-hPa wind anomalies over the WNP, in which the variability shorter than 7 years was removed. The first two decadal modes of the annual mean 850-hPa wind vectors over the WNP region during 1900–2012 are shown in Figs. 2a and 2b. They explain

![Fig. 2. Decadal variability of the anticyclone in the WNP from the 20CR dataset. The dominant (a) EOF1 and (b) EOF2 modes of the annual mean 850-hPa wind vectors over the WNP region (0°–35°N, 100°–160°E) for the period of 1900–2012. Decadal variability is obtained by performing a 7-yr running-mean calculation on the detrended dataset. (c) Normalized PC time series of the two decadal modes.](image-url)
41% and 30% of the total variance, respectively. Interestingly, these two modes are each dominated by a large anomalous anticyclone, but these anomalies have different central positions. The first mode (EOF1) is characterized by an anomalous anticyclone that forms over the WNP, while the second mode (EOF2) is characterized by an anomalous anticyclone extending from southeastern China to the Philippine Sea. Meanwhile, the standardized PCs represent decadal variations (Fig. 2c).

We also performed the S-EOF analysis on 850-hPa wind anomalies over the WNP based on the 7-yr running-mean wind data. The seasonal variations of the decadal WNPAC show that the anticyclone exists all year round. In this paper, we are only interested in showing decadal variability of the WNPAC based on the annual mean from January to December. Next, we investigate the relationships of the WNPAC decadal modes with SST variations.

4. Mechanisms of the EOF1 mode

a. Relationship between the PDO and PC1

To investigate the mechanisms responsible for the EOF1 mode, a regression map of the SST and 850-hPa wind anomalies onto PC1 is shown in Fig. 3a. The SST anomalies in the Pacific show a PDO-like pattern, with significant cold SST anomalies over the western and central midlatitude Pacific and warm SST anomalies along the rim of the Pacific basin, particularly in the tropical eastern Pacific and on the coast of North America (Dai 2013). To further explore the relationship between the PDO and EOF1 mode, we calculated the correlation between the PDO and PC1 time series (Fig. 3b). Notably, the fluctuations of PC1 are in phase with those of the PDO from 1900 to 1966 ($r = 0.58$) but are out of phase with the PDO from 1967 to 2012 ($r = -0.43$). These findings indicate that the relationship between the PDO and PC1 is different during these two periods. To elaborate the relationship between the PDO and PC1, we perform separate regression analyses on these two periods.

For the earlier decades, from 1900 to 1966, the regression pattern onto PC1 shows positive SST anomalies along the rim of the Pacific basin and negative SST anomalies in the midlatitude western Pacific. Meanwhile, the tropical Indian Ocean is covered by warm SST anomalies. These SST anomalies can be clearly seen in the PDO-related SST anomaly pattern (Fig. 4b). Furthermore, the regression map of the 850-hPa wind anomalies onto the PDO from 1900 to 1966 shows that an anomalous anticyclone was located over the western tropical Pacific. Thus, PC1 had an in-phase relationship with the PDO from 1900 to 1966. By contrast, for the later decades from 1967 to 2012, the regression pattern onto PC1 exhibits the negative phase pattern of the PDO, with significant cold SST anomalies located over the central to eastern Pacific and warm SST anomalies over the central northern and southern midlatitude Pacific (Fig. 4c). Thus, the relationship between PC1 and the PDO was shifted from in phase to out of phase after 1966.

Although the SST anomaly pattern corresponds to the negative phase of the PDO (Fig. 4c), as we will discuss below, the most noticeable features related to the formation of the anticyclone are the cold SST anomalies in the tropical CP. The distinct effects of the PDO on the decadal WNPAC during these two periods suggest that the associated physical mechanisms are different. Thus, we wish to determine physical processes that gave rise to the distinct relationships between the anticyclone and the PDO during these two periods.

b. Physical mechanisms responsible for the EOF1 mode

Interestingly, a comparison of these two periods with respect to the PDO (Figs. 4b,d) reveals that in the positive phase of the PDO, these two periods still have some differences in their SST anomaly patterns. From 1900 to 1966, the PDO is related to cold SST anomalies over the western and central midlatitude Pacific with a strengthened Aleutian low. However, the cold SST anomalies are shifted eastward toward the central midlatitude Pacific region from 1967 to 2012. This eastward shifting of the cold SST anomalies over the western midlatitude Pacific has also been observed in previous studies (Dong and Dai 2015; Si and Ding 2016). In addition to those in the midlatitude Pacific, the anomalous SST patterns of the PDO in the tropical Indian Ocean are also quite different. For the former period, the tropical Indian Ocean is dominated by a basinwide warming with its maximum located over the southern Indian Ocean, while for the latter period, the warm SST anomalies in the southern Indian Ocean have faded and the southern Indian Ocean is covered by weak warm SST anomalies.
Han et al. (2014a) have noted that on decadal time scale, a basinwide warming pattern known as the decadal Indian Ocean basin mode (IOBM) dominates the Indian Ocean. The relationship between the PDO and the decadal IOBM is unstable. According to the study by Han et al. (2014a), the PDO was positively correlated with the decadal IOBM before the 1980s. Dong et al. (2016) has further confirmed that the decadal variations in Indian Ocean SSTs are closely linked to the interdecadal Pacific oscillation (IPO)/PDO-induced variations in the tropical eastern Pacific by using a coupled climate model. However, during the last 40 years the warming in the Indian Ocean has been stronger than that in the Pacific and Atlantic.

**Fig. 4.** Comparisons of the first decadal mode (PC1) and PDO patterns during two periods. (a) Annual mean SST (shading; °C) and 850-hPa wind anomalies (m s⁻¹) regressed onto the PC1 time series from 1900 to 1966. (b)–(d) As in (a), but for the PDO time series from 1900 to 1966, the PC1 time series from 1967 to 2012, and the PDO time series from 1967 to 2012, respectively. SST anomalies exceeding the 10% significance level are indicated by white dots, and thick vectors represent wind whose zonal and meridional components exceed the 10% significance level.

**Fig. 5.** Regional (130°–160°E) meridional overturning circulation during the two periods. Regression maps of meridional–vertical circulation computed from the meridional divergent wind (m s⁻¹) and vertical pressure velocity (Pa s⁻¹) with respect to the PDO index are shown for the periods of (a) 1900–66 and (b) 1967–2012. The vectors represent the circulation obtained after multiplying the vertical velocity by 10.
implying that the SST anomalies in the tropical Indian Ocean have been less modulated by PDO-related forcing (Dong and McPhaden 2017; Wu et al. 2016). Thus, fading of the Indian Ocean warming from 1967 to 2012 is observed in Fig. 4d.

The different SST anomalies during these two periods give rise to distinct atmospheric responses (Figs. 5a,b). During the positive phase of the PDO from 1900 to 1966, with the negative SST anomalies and the dominance of the strengthened Aleutian low in the western midlatitude Pacific, the anomalous anticyclone was centered in the western tropical Pacific. The strengthened Aleutian low in the western midlatitude region could induce an anomalous upward flow that diverged at the upper layer, flowed equatorward, and then sank to the north of 10°N, thus contributing to the divergence at low levels in the subtropical western Pacific. With the deepening of the Aleutian low, the anticyclone was developed over the western tropical Pacific. For the latter period from 1967 to 2012, however, as the Aleutian low was shifted eastward, the anticyclone over the western tropical Pacific disappeared.

In addition, Fig. 6 is presented to further elucidate the influences of the PDO during these two periods on the large-scale atmospheric circulation over the tropical region. Following the positive phase of the PDO from 1900 to 1966 (Figs. 6a,c), the positive SST anomalies over the Indian Ocean led to an anomalous Walker circulation over the equatorial Pacific; anomalous negative and positive divergences were located over the Indian Ocean and the western tropical Pacific, respectively. The enhanced convective heating induced by the strong Indian Ocean warming generated upward air motion in the Indian Ocean, with compensating descending air motion occurring over the Philippine Sea. Thus, the Indian Ocean warming also remotely contributed to the development of the western Pacific anticyclone by enhancing a direct and thermally driven divergent circulation. However, from 1967 to 2012, with the eastward shifting of the Aleutian low and the damping of the IOBM, the anticyclone had disappeared (Figs. 6b,d).

The results presented thus far indicate that the EOF1 mode of the decadal WNPAC is related to the PDO, with the relationship between them shifting from in phase to out of phase after 1966. However, although the SST anomaly pattern regressed onto the PC1 time series from 1967 to 2012 corresponds to the negative phase of the PDO, the most significant features related to the formation of the anticyclone are the cold SST anomalies over the tropical CP region (Fig. 4c). The anticyclonic anomalies over the WNP may develop as a Gill-type Rossby response to cold SST anomalies in the tropical CP region. Meanwhile, the precipitation anomalies associated with PC1 from 1967 to 2012 show that suppressed convection anomalies were located southeast of the anomalous anticyclone to the tropical CP region (Fig. 7a). The features noted above are similar to those found by Wang et al. (2013) on an interannual time scale, suggesting that the decadal anticyclone is a Rossby wave response to negative heating anomalies induced by the cold SST anomalies over the tropical CP region. To examine this possibility, we regressed the 850-hPa streamfunction, from which the variability on time scales shorter than 7 years had been removed, onto a reversed CP SST anomaly.
According to the theory of Gill (1980), suppressed convection over the equator should excite an equatorial symmetric Rossby wave response to the west of the heating sink and result in the formation of twin low-level anticyclones residing on either side of the equator (Gill 1980). The results show that similar anticyclone anomalies are found in the regressions onto the reversed (i.e., cold) tropical CP index, in which negative condensation heating is induced by the cold SST anomalies. This similarity suggests that cold SST anomalies located in the tropical CP region did indeed contribute to the development of the anticyclone anomalies of the EOF1 mode during the period of 1967 to 2012.

5. Mechanisms of the EOF2 mode

a. Relationship between the Maritime Continent and PC2

To investigate the mechanisms responsible for the maintenance of the EOF2 mode of the decadal WNPAC, the SST and precipitation anomalies associated with PC2 are shown in Figs. 8a and 8b. In the Pacific, the most significant regression coefficients appear in the tropical eastern Pacific and the midlatitude North Pacific, exhibiting a PDO-like pattern. Meanwhile, the southern Indian Ocean and the MC (MC SST index: 20°S–0°, 110°–140°E) are covered by noticeable warm SST anomalies (Fig. 8a). On the decadal time scale, interestingly, the suppressed convection over the Philippine Sea corresponds to underlying warm SST anomalies. The opposite relationship between the SST and precipitation anomalies suggests that the anticyclone is caused not by local forcing of the underlying SST anomalies but rather by remote forcing (Wu et al. 2016). Additionally, the warm SST anomalies over the southern Indian Ocean have no significant enhanced convection in the southern Indian Ocean (Fig. 8b). Thus, the suppressed convection over the Philippine Sea is possible to be caused by the MC variation.

To further explore the relationships of the EOF2 mode with the PDO and the MC, we calculated the correlations of the PC2 time series with the PDO index and the decadal MC index. Here, the decadal MC index is defined as the area average of the annual mean SST anomalies in the MC region (20°–0°S, 110°–140°E), from which variability shorter than 7 years has been removed. These correlations are 0.37 and 0.62, respectively, suggesting that the EOF2 mode is tightly associated with the warm SST anomalies in the MC region.

b. Physical mechanisms responsible for PC2

As for the EOF2 mode, our analyses suggest that the anticyclone is likely to originate from SST anomalies in the MC region, which involves the regional Hadley circulation (Sui et al. 2007; Wu and Zhou 2008). The anomalous WNPAC

FIG. 7. Regressions with respect to PC1 and the reversed CP index from 1967 to 2012. (a) Regression of the annual mean precipitation (shading; 10^{-2} Pa s^{-1}) onto PC1 from 1967 to 2012. Anomalies exceeding the 10% significance level are indicated by white dots. (b) Regression of the 850-hPa streamfunction anomalies (contours; 10^6 m^2 s^{-1}) onto the reversed CP SST anomaly index from 1967 to 2012. Anomalies exceeding the 10% significance level are indicated by black dots. The black box indicates the CP SST index region.

FIG. 8. Atmospheric forcing from the MC responsible for the EOF2 mode. (a) Annual mean SST (shading; °C) and 850-hPa wind anomalies (m s^{-1}) regressed onto the normalized PC2 time series from 1900 to 2012. (b) Annual mean precipitation (shading; 10^{-2} Pa s^{-1}) regressed onto PC2 from 1900 to 2012. Anomalies exceeding the 10% significance level are indicated by white dots, and thick vectors represent wind whose zonal and meridional components exceed the 10% significance level. The black boxes indicate the MC region.
resides in the sinking branch of the local Hadley circulation, triggered by enhanced convection over the MC. The warm SST anomalies under the anomalous anticyclone may be regarded as a passive response to this atmospheric forcing (Chung et al. 2011). To examine this hypothesized mechanism, we regressed the 850-hPa wind and SST anomalies onto the MC SST anomaly index (Fig. 9a). The results show an anomalous anticyclone centered over the Philippine Sea, which is similar to the regression of the 850-hPa wind anomalies onto PC2 (Fig. 8a). To further reveal the impact of the MC SST anomalies on the enhanced anomalous anticyclonic circulation, we examine the regressions of the decadal MC index onto the divergent wind at both 850 and 250 hPa. It is found that warm MC SST anomalies induce convergence (divergence) in the Philippine Sea at high (low) levels and divergence (convergence) in the MC region at high (low) levels (Figs. 9b,c).

The meridional overturning circulation (MOC) induced by the MC SST anomalies is further revealed by the regressed zonally averaged vertical velocity and meridional divergent wind at each pressure level in the region of 110°–140°E (Fig. 10). Consistent with the regressed divergent wind fields, the flow is upward over the tropical region from 10°S to the equator. This upward motion causes upper tropospheric divergent flows toward the Philippine Sea (at approximately 10°N) where the downward motion is pronounced. Therefore, our analysis indicates that the EOF2 mode is established by strengthening of the regional MOC from the MC region into the Philippine Sea region.

6. Conclusions and discussion

a. Conclusions

The WNPAC has an important influence on East Asian climate; however, previous studies of the WNPAC have been confined to interannual time scale and WNPAC variability on decadal time scale is unknown. In the present paper, we have identified decadal modes of the WNPAC and investigated their relationships with the PDO and SST variations. Our decadal EOF analysis shows that the first mode (EOF1), accounting for 41% of the total variance, is characterized by an anomalous anticyclone centered over the WNPAC, which is similar to the regression of the 850-hPa wind anomalies onto PC1 (Fig. 9a). The results show an anomalous anticyclone centered over the Philippine Sea, which is similar to the regression of the 850-hPa wind anomalies onto PC2 (Fig. 8a). To further reveal the impact of the MC SST anomalies on the enhanced anomalous anticyclonic circulation, we examine the regressions of the decadal MC index onto the divergent wind at both 850 and 250 hPa. It is found that warm MC SST anomalies induce convergence (divergence) in the Philippine Sea at high (low) levels and divergence (convergence) in the MC region at high (low) levels (Figs. 9b,c).

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a. Conclusions

The WNPAC has an important influence on East Asian climate; however, previous studies of the WNPAC have been confined to interannual time scale and WNPAC variability on decadal time scale is unknown. In the present paper, we have identified decadal modes of the WNPAC and investigated their relationships with the PDO and SST variations. Our decadal EOF analysis shows that the first mode (EOF1), accounting for 41% of the total variance, is characterized by an anomalous anticyclone centered over the WNPAC, which is similar to the regression of the 850-hPa wind anomalies onto PC1 (Fig. 9a). The results show an anomalous anticyclone centered over the Philippine Sea, which is similar to the regression of the 850-hPa wind anomalies onto PC2 (Fig. 8a). To further reveal the impact of the MC SST anomalies on the enhanced anomalous anticyclonic circulation, we examine the regressions of the decadal MC index onto the divergent wind at both 850 and 250 hPa. It is found that warm MC SST anomalies induce convergence (divergence) in the Philippine Sea at high (low) levels and divergence (convergence) in the MC region at high (low) levels (Figs. 9b,c).

The meridional overturning circulation (MOC) induced by the MC SST anomalies is further revealed by the regressed zonally averaged vertical velocity and meridional divergent wind at each pressure level in the region of 110°–140°E (Fig. 10). Consistent with the regressed divergent wind fields, the flow is upward over the tropical region from 10°S to the equator. This upward motion causes upper tropospheric divergent flows toward the Philippine Sea (at approximately 10°N) where the downward motion is pronounced. Therefore, our analysis indicates that the EOF2 mode is established by strengthening of the regional MOC from the MC region into the Philippine Sea region.
phase of the PDO was characterized by a strengthened Aleutian low over the western midlatitude Pacific and warming of the southern Indian Ocean (Fig. 11a). The strengthened Aleutian low could affect the WNPAC through meridional atmospheric circulation, leading to anomalous divergence over the subtropical western Pacific. Meanwhile, the southern Indian Ocean warming suppressed convection over the WNP and thereby strengthened the WNPAC. As a result, the anomalous anticyclone from 1900 to 1966 was maintained by the effects of both the strengthened Aleutian low and the Indian Ocean warming. Thus, PC1 varied in phase with the PDO from 1900 to 1966.

In contrast, from 1967 to 2012, the PDO is associated with the eastward shift of the strengthened Aleutian low and the fading of the southern Indian Ocean warming, and the disappearance of the anticyclone over the tropical western Pacific (Fig. 4d). The map of the SST regressed onto PC1 from 1967 to 2012 exhibits feature corresponding to the negative phase of the PDO (Fig. 4c); thus, PC1 varied out of phase with the PDO from 1967 to 2012. Our analysis further suggests that from 1967 to 2012, the WNPAC was a Rossby wave response to negative heating anomalies induced by the cold SST anomalies over the tropical CP region during the negative phase of the PDO (Fig. 11b).

The second mode (EOF2) of the decadal EOF analysis is characterized by an anomalous anticyclone extending from southeastern China to the Philippine Sea and accounts for 31% of the total variance. As illustrated in Fig. 10, this anticyclone resides in the sinking branch of the local Hadley circulation, triggered by enhanced convection over the MC due to warming from 1900 to 2012. Our study has shown that the PDO and MC can both be viewed as major drivers of decadal variability of the WNPAC as a result of their atmospheric link. Furthermore, our present study emphasizes that the different patterns of the PDO in the two periods before and after 1966 led to distinct atmospheric responses in the WNP, causing the relationship between the PDO and PC1 to shift from in phase to out of phase after 1966.

Recently, the decadal variations in the Indian and Pacific Oceans have been a topic of intense discussion (Han et al. 2014b; Zhang et al. 2018). Prior to the 1980s, the decadal IOBM was positively correlated with the PDO (Han et al. 2014a). Our study has further shown that the positive relationship between the PDO and the decadal IOBM can induce an anticyclone in the WNP, which influences East Asian climate. In addition, we note that the in-phase relationship between the EOF2 mode and the MC may indicate an active role

Fig. 11. Schematic diagrams of mechanisms responsible for the first decadal mode (EOF1) of the WNPAC. (a) The mechanism responsible for the decadal WNPAC from 1900 to 1966 when the PDO and the EOF1 mode are in phase. The anticyclone was maintained by the effects of both the strengthened Aleutian low through meridional atmospheric forcing, and the warming of the tropical Indian Ocean through zonal thermodynamic circulation. (b) As in (a), but from 1967 to 2012 when the PDO and the EOF1 mode are out of phase. The anticyclone was a Rossby wave response to the negative heating induced by the cold SST anomalies over the central equatorial Pacific in the negative phase of the PDO. The letters A and C represent anticyclone and cyclone, respectively.
of the MC SST in modulating East Asian climate. The MC could be viewed as a major source of decadal climate variability in the WNP.

b. Discussion

1) RESULTS FROM OTHER DATASETS

To test the reliability of the decadal modes derived from the 20CR dataset, we applied the same EOF analysis to another long-term reanalysis dataset, ERA-20C, which ranges from 1900 to 2010 (Figs. 12a,b). For this dataset, the first two decadal modes account for 54% and 26% of the total variance, respectively. The predominant features of the first mode derived from the ERA-20C dataset, which shows an anomalous anticyclone centered over the WNP, are similar to those from the 20CR dataset. For the second mode, however, the spatial pattern derived from ERA-20C shows some differences with respect to those derived from the 20CR. Specifically, the anomalous anticyclonic circulation pattern seems to only appear in the southern South China Sea in the ERA-20C dataset (Fig. 12b). This may be due to the systematic error between these two independent datasets, which is inevitable. The similar results between the two datasets make us believe that the decadal modes derived from the 20CR dataset are realistic.

To further check the robustness of the second EOF mode, we compare the circulation anomalies from the 20CR with those from the JRA-55 and ERA-40 datasets (Fig. 13). Because the EOF2 mode is triggered by the decadal variation of convective heating over the MC, composites were computed in terms of the MC SST index, with positive (negative) phase being selected when the MC index is of greater (less) than ±0.5 standard deviations. The composited plots are calculated based on the positive minus negative phases of the MC index. For the comparison with the JRA-55, we focus on the time period from 1958 to 2012 during which two datasets overlap. Both the composites are characterized by an anomalous anticyclone extending from southeastern China to the Philippine Sea. The composite of the ERA-40 dataset from 1958 to 2002 also shows an anticyclone over the southern South China Sea. These results from different datasets indicate that the second decadal mode does exist.

2) UNCERTAINTY OF DECADAL VARIABILITY OF THE PDO

As noted in section 4, the spatial pattern of the PDO is quite different for the two periods of 1900–66 and 1967–2012. For both periods, the positive phase of the PDO is characterized by positive SST anomalies in the tropical central-eastern Pacific.
and negative SST anomalies in the midlatitude North Pacific. However, from the 1960s to the 2010s, the negative SST anomalies in the midlatitude Pacific shifted eastward toward the central Pacific compared to the former period from the 1900s to the 1960s. At present, we do not know what causes this shift, which deserves further study in the future. Meanwhile, as discussed in the previous sections, both the strengthened Aleutian low and the Indian Ocean warming in association with the PDO during 1900 to 1966 may have significant impacts on decadal variability of the WNPAC. Their relative roles, however, remain to be clarified, which also deserves further studies with numerical model experiments.

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