Decadal Transition of the Leading Mode of Interannual Moisture Circulation over East Asia–Western North Pacific: Bonding to Different Evolution of ENSO

XIUZHEN LI
Center for Monsoon and Environment Research and Department of Atmospheric Sciences, Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Guangzhou, and Jiangsu Collaborative Innovation Center for Climate Change, Nanjing, China

ZHIPING WEN
Institute of Atmospheric Sciences, Fudan University, Shanghai, and Center for Monsoon and Environment Research and School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou, and Jiangsu Collaborative Innovation Center for Climate Change, Nanjing, China

DELIANG CHEN
Regional Climate Group, Department of Earth Science, University of Gothenburg, Gothenburg, Sweden

ZESHENG CHEN
State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China

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ABSTRACT

The El Niño–Southern Oscillation (ENSO) cycle has a great impact on the summer moisture circulation over East Asia (EA) and the western North Pacific [WNP (EA-WNP)] on an interannual time scale, and its modulation is mainly embedded in the leading mode. In contrast to the stable influence of the mature phase of ENSO, the impact of synchronous eastern Pacific sea surface temperature anomalies (SSTAs) on summer moisture circulation is negligible during the 1970s–80s, while it intensifies after 1991. In response, the interannual variation of moisture circulation exhibits a much more widespread anticyclonic/cyclonic pattern over the subtropical WNP and a weaker counterpart to the north after 1991. Abnormal moisture moves farther northward with the enhanced moisture convergence, and thus precipitation shifts from the Yangtze River to the Huai River valley. The decadal shift in the modulation of ENSO on moisture circulation arises from a more rapid evolution of the bonding ENSO cycle and its stronger coupling with circulation over the Indian Ocean after 1991. The rapid development of cooling SSTAs over the central-eastern Pacific, and warming SSTAs to the west over the eastern Indian Ocean–Maritime Continent (EIO-MC) in summer, stimulates abnormal descending motion over the western-central Pacific and ascending motion over the EIO-MC. The former excites an anticyclone over the WNP as a Rossby wave response, sustaining and intensifying the WNP anticyclone; the latter helps anchor the anticyclone over the tropical–subtropical WNP via an abnormal southwest–northeast vertical circulation between EIO-MC and WNP.

1. Introduction

Summer precipitation over East Asia is extremely complex. In the past few decades, summer precipitation over East China has shown a dramatic interdecadal variation accompanied by a weak East Asian summer monsoon, with an anomalous rain belt retreating from North and northeastern China to the Yangtze River valley in the late 1970s and to South China in the early 1990s (Ding et al. 2008, 2009; Gong and Ho 2003; Li et al. 2011). After the late 1990s, the mei-yu rain belt tends to move northward again from south of the Yangtze River valley to the Huai River valley (Liu et al. 2012; Si et al. 2009). Concurrent with this decadal shift of the rain belt, an interdecadal transition in the leading mode of
precipitation also occurs, shifting from a meridional “− + −” structure to a dipole “+ − −” pattern. This indicates a possible transition in the precipitation regime during the last few decades (Ding et al. 2008; Sun and Wang 2015; Si and Ding 2013). Although the decadal southward shift of the rain belt has been intensively investigated and attributed mainly to the weakness of the Asian monsoon, the cause of the transition of the interannual mode of precipitation has not been well addressed.

Precipitation variation over East Asia is closely associated with moisture circulation over East Asia (EA) and the western North Pacific [WNP (EA-WNP); Li et al. 2011, 2012; Sun and Wang 2015], which is influenced jointly by three Asian summer monsoon subsystems and the western Pacific subtropical high (WPSH; e.g., Chen et al. 1992; Murakami and Matsumoto 1994; Ueda and Yasunari 1996). By performing an EOF analysis based on vertically integrated water vapor flux anomalies in summer, Li and Zhou (2012) found that variation in moisture circulation over EA-WNP is characterized by an “anticyclone–cyclone” dipole structure, which is responsible for the abnormal elongated convergence from the Yangtze River valley to southern Japan. This illustrates the vigorous variation of the mei-yu–baiu rain belt. A recent study by Sun and Wang (2015) shows that this anticyclone–cyclone dipole-structured moisture circulation is replaced by an anticyclonic monopole structure with a much larger spatial domain over the WNP after 2000, as the main rain belt centered along the Yangtze River valley shifts northward to the region between the Yangtze and Yellow Rivers. Thus, concurrent with the interdecadal transition in the leading mode of summer precipitation, the moisture circulation pattern over EA-WNP is seen to change.

Many external factors, including El Niño–Southern Oscillation (ENSO), tropical Indian Ocean SST, snow cover/depth on the Tibetan Plateau, Arctic sea ice, Arctic Oscillation (AO), and Antarctic Oscillation, are known to have impacts on the variability of circulation over East Asia (Wang et al. 2000; Xie et al. 2009; Wu and Qian 2003; Wu and Kirtman 2007; Duan et al. 2013; Huang et al. 1995; Gong and Ho 2003; Nan et al. 2009), and the impact of ENSO is emphasized on interannual time scale (e.g., Huang and Wu 1989; Chang et al. 2000; Wang et al. 2000, 2001; Chen 2002; Wu and Wang 2002; Wu et al. 2003; Li et al. 2014, 2015). In the case of El Niño, an anomalous cyclone is triggered in the lower troposphere over the WNP in the developing summer by enhanced convection over the tropical central Pacific via the Gill–Matsumo mechanism (Gill 1980; Matsumo 1966; Wu et al. 2003), while an abnormal anticyclone is formed [western North Pacific anticyclone (WNPAC)] in the decaying summer through the Indian Ocean capacitor mechanism (Xie et al. 2009) and local air–sea interaction (Wang et al. 2000; Wang and Zhang 2002) when the positive sea surface temperature anomalies (SSTAs) in the tropical central-eastern Pacific diminish (Wang et al. 2003; Wang and Wu 2012). The anticyclone–cyclone dipole-structured moisture circulation tends to appear over EA-WNP in the transitional summer between a decaying El Niño and a developing La Niña (Li and Zhou 2012). Moreover, recent studies have proposed that the speed at which El Niño transforms to La Niña could modulate the summer circulation over East Asia (Fan et al. 2013; Chen et al. 2016). When it shifts quickly, as cooling develops over the central-eastern Pacific from spring to summer, it starts to influence the maintenance and intensification of the WNPAC in summer (Chen et al. 2016).

The modulation of these external signals may change on decadal time scales. In the past few decades, a shift in the relationship between ENSO and the East Asian summer monsoon and thus China rainfall has been detected (Wu and Wang 2002). As for the cause, Wu and Wang (2002) emphasize the role of variability of the summer SSTAs over the Indian Ocean and WNP. During the 1970s–90s, when summer SST increased over the Philippine Sea, convection over the WNP intensified and moved northward, and the cyclonic anomaly over Japan shifted eastward. This resulted in an anticyclone–cyclone dipole-structured anomalous moisture circulation. After the 1990s, the interannual variability of tropical SSTs over both the Indian and Pacific Oceans diminishes and fails to excite the dipole-structured anomalous moisture circulation (Sun and Wang 2015). Modulation of the relationship by the Pacific decadal oscillation (PDO) is also proposed (Feng et al. 2014). However, only the synchronous summer SSTAs are emphasized in their studies (Wu and Wang 2002; Sun and Wang 2015).

Questions remain regarding how the interannual variations of moisture circulation and thus precipitation have changed in the past few decades and whether the ENSO signal has played a role. If so, what characteristics of ENSO are responsible for such variations, the amplitude, evolution, or its coherence with the SSTAs over other regions? This paper addresses these questions. Sections are organized as follows: The data used in this study are introduced in section 2. The decadal shift of the interannual variation of moisture circulation modulated by SSTAs is investigated in section 3. The role played by the ENSO signal, especially its evolution speed, is examined in detail in section 4. The underlying physical processes responsible for the decadal change in
the modulation of the ENSO revolution on moisture circulation over EA-WNP are studied in section 5, and a discussion and conclusion are provided in section 6.

2. Data and methodology

Daily precipitation data from 756 stations in China, collected and subjected to quality-control procedures by the China Meteorological Administration (Bao 2007), are employed. The key dataset applied in this study is the Japanese 55-year Reanalysis (JRA-55), the second global reanalysis constructed by the Japan Meteorological Agency (JMA; Kobayashi et al. 2015; Harada et al. 2016). It is the first to apply four-dimensional variational analysis in the last half-century. Its main objectives are to address issues found in the previous reanalysis and to produce a comprehensive atmospheric dataset suitable for studying multidecadal variability and climate change (Kobayashi et al. 2015; Harada et al. 2016). Improvements are found in JRA-55 in its representations of the phenomena on a wide range of space–time scales, such as equatorial waves and transient eddies in storm track regions (Kobayashi and Iwasaki 2016). Moreover, temporal consistency is improved in JRA-55 compared with the older reanalysis (JRA-25) throughout the reanalysis period. It is similar to ERA-40 in its spatial patterns, as well as in the magnitude of its moisture convergence and divergence, which are comparable to those of the Special Sensor Microwave Imager (SSM/I; Park et al. 2007). It covers the period starting in 1958 when regular radiosonde observations begin on a global basis. The variables employed are monthly wind fields, vertical velocity, and vertically integrated water vapor flux. The monthly Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al. 2003), with a resolution of 1° latitude × 1° longitude, is also included to study the variation in SSTAs and their impact on the moisture circulation. The period of all datasets spans 1961–2012. The mature winter (WIN) and decaying spring (SPR) and summer (SUM) of ENSO are represented as WIN(0), SPR(+1), SUM(+1) for short.

The Community Atmosphere Model, version 4 (CAM4), the atmospheric component of the Community Climate System Model, version 4 (CCSM4; Gent et al. 2011), developed with significant community collaboration at the National Center for Atmospheric Research (Neale et al. 2013), is employed in this study to explore the atmospheric response over EA-WNP to the SSTA evolution over the tropical eastern Pacific. It reasonably captures the spatial features of the summer climate in observations, though with some infidelity (e.g., Neale et al. 2013; Chen et al. 2014). By modifying deep-convection processes, CAM4 reduces many of the model biases, resulting in significant improvement in the Hadley circulation. It also enhances estimations of the phase, amplitude, and spatial anomaly patterns of the modeled El Niño. A more comprehensive and detailed description about CAM4 can be found in Neale et al. (2010). In this study, the CAM4 model uses a finite-volume dynamic core and is run for a period of 20 years at a horizontal resolution roughly equivalent to 1.9° latitude × 1.25° longitude, with 26 vertical levels in a hybrid sigma–pressure coordinate system extending from the surface to approximately 3.5 hPa.

3. Decadal shift of the interannual variation of moisture circulation

a. Leading mode of moisture circulation and its relationship with ENSO

EOF analysis is applied to the summer vertically integrated water vapor flux during 1962–2013 to examine the interannual variation of moisture circulation over EA-WNP. The leading mode, which explains 36.8% of the total variance, nearly triple that of the second mode, is depicted in Fig. 1 together with the principal component (PC1). An anticyclone–cyclone dipole-structured pattern features the moisture circulation over EA-WNP. In positive-phase years, a widespread anticyclonic moisture circulation prevails over the subtropical WNP; abnormal moisture diverging over the tropical–subtropical WNP is advected by the peripheral flow of the anticyclone to East China. To the south, abnormal easterly moisture transport dominates the tropical western Pacific, implying a weaker-than-normal climatological westerly moisture transport from the Indian Ocean. To the north, a cyclonic moisture circulation controls the mid-latitudes, with abnormal northerly transport west to Japan. In comparison with its anticyclonic counterpart, the cyclonic moisture circulation is much weaker in both intensity and spatial extent. In this mode, the abnormal moisture transport over East Asia converges at around 30°N over the Yangtze River valley instead of moving northward. This leading mode represents variations mainly on an interannual time scale. The interannual component of the corresponding PC1 explains a majority of the variance (>80%), together with a weak interdecadal variation and a nearly negligible long-term trend. With this consideration in mind, only the interannual component is investigated in this study. All variables are filtered by applying a 9-yr high-pass Lanczos filter before further analysis.

This leading mode of moisture circulation was proposed in our previous studies (Li and Zhou 2012) to be modulated by the ENSO signal to a great extent, and its positive phase was apparent in the transitional summer
from an El Niño to a La Niña event. To examine whether such modulation is stable over the past few decades, a 13-yr running correlation between PC1 and the Niño-3.4 index is examined (Fig. 2). The Niño-3.4 index is calculated based on SSTAs in the previous winter, the synchronous summer, and the following winter to observe the possible impact of ENSO evolution. Several dramatic features are evident in Fig. 2. First, the PC1 of the moisture circulation over EA-WNP is positively correlated with the prewinter Niño-3.4 index and negatively with the postwinter Niño-3.4 index. This supports the preference of the anticyclone–cyclone dipole-structured moisture circulation in the transitional summer between an El Niño and a La Niña. Second, and interestingly, the influence of eastern Pacific SSTAs in the synchronous summer shows a strong decadal variation. The correlation between PC1 and the synchronous Niño-3.4 index is weak and insignificant during the 1970s–80s, while it intensifies and remains strongly negative after 1991, with a correlation coefficient even higher than that of the prewinter Niño-3.4 index. The causes of such a decadal shift in this relationship are still unknown. It has been widely accepted that the direct influence of eastern Pacific summer SSTAs on the climate over East Asia is weak as the ENSO signal diminishes. However, a recent study by Chen et al. (2016) argues that because an El Niño event can transition into either a La Niña event or a neutral or persistent warming condition in the succeeding summer, composite analysis by previous studies might conceal the impact of synchronous SSTAs over the eastern Pacific. The rapid development of synchronous cooling over the central-eastern Pacific may sustain the WNPAC by stimulating a Rossby wave response to its northwest. A similar enhanced decadal relationship also appears between PCI and the postwinter Niño-3.4 index. In sum, compared to the stable influence from the previous winter, the influence of synchronous eastern Pacific SSTAs on summer moisture circulation over EA-WNP intensifies after 1991.
**b. Shift in the interannual coherence of moisture circulation and ENSO**

As the modulation of synchronous tropical SSTAs over the eastern Pacific changes, decadal variation might also appear in the corresponding moisture circulation. To address this question, the interannual variation of the moisture circulation and its coupling with tropical SSTAs are examined for the periods of 1971–90 and 1991–2013, when the correlation coefficient between the PC1 of moisture circulation and the synchronous Niño-3.4 index is insignificant and significantly negative, respectively. The coupling between the ENSO signal and the moisture circulation over the EA-WNP may be embedded in not just the first leading mode. A singular value decomposition (SVD) is applied to the summer moisture circulation over the EA-WNP and the tropical SSTAs in the previous winter (Fig. 3) in order to address this issue. The fields of moisture circulation ($Q_{uw}$) and SSTAs in the first SVD mode (SVD1) are referred to as SVD1($Q_{uw}$) and SVD1(SST), respectively. The squared covariance fractions (SCF) accounted for by SVD1, the correlation coefficients of the corresponding expansion coefficients (ECs) between $Q_{uw}$ and SSTAs (EC$_R$), and the spatial correlation of $Q_{uw}$/SST between EOF1 and SVD1 ( Spa$_{EOF_{SVD_{Q_{uw}}}}$/Spa$_{EOF_{SVD_{SST}}}$) are exhibited in Table 1. It is interesting to note that the SCFs for SVD1 are quite high during the two periods (95.3% and 85.5%). In addition, the spatial patterns of the outputs from SVD show high similarities with that of EOF (correlation coefficients > 0.7), with a widespread anticyclonic moisture circulation lying over the EA-WNP and an El Niño signal dominating the winter SSTAs (Fig. 3). These results illustrate that the ENSO signal exerts a strong influence on moisture circulation over the EA-WNP, and its modulation is embedded mainly in the leading mode of the moisture circulation. In other words, interannual variation of summer moisture circulation over the EA-WNP is dominated by the ENSO signal.

The SVD1(SST)s in the two periods are characterized by a typical El Niño pattern with maximum warming over the eastern Pacific, cooling of the “U shape” to the west, basin-wide warming over the Indian Ocean, and a zonal “warm–cool” contrast over the South China Sea (SCS) and WNP (Figs. 3d,e). In contrast to the small decadal variation in the prewinter SSTA pattern (Fig. 3f), a decadal shift occurs in the leading mode of moisture circulation over EA-WNP (Fig. 3c). In the positive phase, dramatic discrepancies can be seen in the location, spatial extent of the anticyclonic moisture circulation over the subtropical EA-WNP, and its concurrence with the cyclonic moisture circulation to the north over Japan. Before 1990, the abnormal anticyclonic moisture circulation over the subtropical WNP is much smaller in its meridional extent, and the cyclonic moisture circulation to the north is strong. Abnormal northerly transport to the west of the cyclonic anomaly dominates the midlatitude WNP, and southerly transport anomaly to the west of the anticyclonic anomaly turns eastward at around 30°N instead of penetrating further. This results in abnormal moisture convergence over South China, the Yangtze River valley, and the region south to Japan, whereas abnormal moisture divergence occurs to the north over the Korean Peninsula and Japan (Fig. 3a). As a result, the corresponding precipitation anomalies are enhanced mainly over the Yangtze River valley and the western part of southeastern China (Fig. 4a). The correlation between the corresponding expansion coefficient of the SVD1($Q_{uw}$) (EC1$_{Q_{uw}}$) and the Yangtze River valley summer precipitation during 1971–90 reaches 0.66, significant at the 99.9% confidence level (Fig. 4c). Hence, the ENSO signal in the previous winter exerted a great influence on precipitation over the Yangtze River valley during 1971–90 by modulating moisture circulation.

After 1991, the anticyclonic moisture circulation over the subtropical WNP shows a larger meridional expansion compared to a zonally elongated shape during 1971–90, while the cyclonic moisture circulation to the north is weak. As a result, moisture from the lower latitudes invades northward, and the stronger moisture convergence shifts northward to the Huai River valley, extending northeastward from the upper reaches of the Yangtze River valley to the Korean Peninsula and Japan, with enhanced moisture divergence to the south over South China (Fig. 3b). In response to this abnormal moisture circulation pattern, the precipitation intensifies and shifts northward from the Yangtze River valley to the Huai River valley and weakens over most parts of South China (Fig. 4b). The correlation between EC1$_{Q_{uw}}$ and summer precipitation increases from 0.13 to 0.51 (significant at the 95% confidence
level) over the Huai River valley after 1991, while it decreases from 0.66 to 0.44 over the Yangtze River valley (Figs. 4c,d).

The tropical Indian Ocean and western Pacific experience a decadal shift not only in the moisture circulation over EA-WNP but also in covariance with moisture circulation. Before 1990, the anticyclonic moisture circulation over the subtropical WNP was concurrent with weakened westerly moisture circulation to its south over the eastern Indian Ocean–Philippine Sea, but the resulting moisture divergence is weak and scattered (Fig. 3a). The leading mode of moisture circulation over EA-WNP during 1991–2013 shows a stronger coupling with moisture circulation over tropical regions. Abnormal easterly moisture transport dominates the tropical central-western Pacific with abnormal moisture divergence over the tropical central

Table 1. SCF accounted for by SVD1, the correlation coefficients between EC\textsubscript{R} of moisture circulation and tropical SST\textsubscript{As}, and the spatial correlations of \textit{Q}_{\text{Moist}}/SST\textsubscript{As} between EOF1 and SVD1 (\textit{Spa\textsubscript{R}_{EOF,SVD_{\textit{Q}_{\text{Moist}}}}}/\textit{Spa\textsubscript{R}_{EOF,SVD_{SST}}}) during 1971–90 and 1991–2013; ** indicates significance at the 99% confidence level.

<table>
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<th></th>
<th>SCF</th>
<th>EC\textsubscript{R}_{\text{Moist},SST}</th>
<th>\textit{Spa\textsubscript{R}<em>{EOF,SVD</em>{\textit{Q}_{\text{Moist}}}}}</th>
<th>\textit{Spa\textsubscript{R}<em>{EOF,SVD</em>{SST}}}</th>
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<tr>
<td>1971–90</td>
<td>95.3%</td>
<td>0.71</td>
<td>(0.91**, 0.70**)</td>
<td>0.97**</td>
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<tr>
<td>1991–2013</td>
<td>85.5%</td>
<td>0.71</td>
<td>(0.97**, 0.88**)</td>
<td>0.98**</td>
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FIG. 4. Regression of summer precipitation (mm) based on the EC1_Quv during (a) 1971–90 and (b) 1991–2013. Results above the 90% confidence level are marked. The blue boxes in (a) and (b) represent the Yangtze River valley (28°–32°N, 107°–122°E) and the Huai River valley (31°–35°N, 114°–120°E), respectively. Time series of regional summer precipitation over (c) the Yangtze River valley (28°–32°N, 107°–122°E) and (d) the Huai River valley (31°–35°N, 114°–120°E) are shown together with EC1_Quv during 1971–90 and 1991–2013.
Pacific and convergence over the Maritime Continent (Fig. 3b). In addition, a C-shaped moisture circulation occurs in the tropical Indian Ocean, with abnormal moisture converging over the eastern Indian Ocean south to the equator. This C-shaped circulation in the surface winds has been described by Xie et al. (2009) as a typical response to antisympmetric convective heating about the equator, even though the SSTAs are more or less symmetrical. This C-shaped moisture circulation is hardly ever found before 1990, illustrating the enhancement of the coupling between the leading mode of moisture circulation over EA-WNP and the circulation over the Indian Ocean after 1991. This will be investigated further in next section. In the differential panel (Fig. 3c), the aforementioned weakness of the cyclonic moisture circulation north to 30°N, the intensification of the easterly transport from the central Pacific to the Maritime Continent, and the existence of the C-shaped moisture circulation over the Indian Ocean after 1991 are even more robust. In other words, the influence of tropical SSTAs on the interannual variation of moisture circulation lies more southward over tropical–subtropical regions rather than in midlatitude regions after 1991.

4. Modulation from the evolution of ENSO

Given the similarity in the prewinter SVD1(SST) between the two periods and the stable relationship between the prewinter El Niño index and the leading mode of the moisture circulation (Figs. 2, 3), the decadal shift of the moisture circulation over EA-WNP bonding to the ENSO signal might be caused by the change in the SSTA evolution and the intensification of the modulation from synchronous SSTAs. The evolution of SSTAs may act to amend the impact of the prewinter ENSO signal.

a. Faster evolution of ENSO

To verify this hypothesis, SSTAs and 850-hPa streamfunction and 500-hPa vertical velocity in the decaying phases are regressed by the corresponding expansion coefficients of EC_1(SST), and their spatial pattern and temporal evolution (5°S–5°N mean) are displayed in Figs. 5 and 6. In the mature winter, responding to warming SSTAs over the eastern Pacific, an abnormal Walker circulation dominates the tropical Pacific (Fig. 7). Abnormal ascending motion appears over the tropical central-eastern Pacific, whereas descending motion occurs to the west over the tropical western Pacific. They stimulate a pair of cyclones and anticyclones on their northern and southern sides, which is nearly symmetrical about the equator (Figs. 6a,d). Consistent with SSTAs, common features are also found in the corresponding circulations in WIN(0) during the two periods with the exception of a slight difference in the anticyclone over the WNP, which is referred to as the Philippine Sea anticyclone (PSAC). The PSAC has aroused much attention for its key role in bridging the ENSO signal and the abnormal climate over East Asia from the mature winter to the decaying summer. It is characterized by a more westward displacement after 1991, with its center over the Philippines shifting to the SCS.

In contrast to the similarity in prewinter SSTAs, the evolution of El Niño during the two periods shows dramatic differences. Before 1990, the abnormal SSTAs over the tropical Pacific start to decay in the spring, develop into a neutral condition in the late summer, and evolve further into a La Niña in the following winter. This is concurrent with the persistence of Indian Ocean basin-wide warming (IOBW) from the mature winter to the decaying summer (Figs. 5a–d). The prewinter strong abnormal rising motion over the tropical eastern Pacific weakens concurrently in early spring and decays rapidly into the neutral condition afterward. Its counterpart over the western Pacific lies asymmetrically about the equator, over the WNP, and to the east of Australia in the decaying spring. The descending motion over the WNP couples well with the WNP anticyclone, which extends eastward in SPR(+1) and shifts northward and diminishes in SUM(+1).

After 1991, the development of La Niña is seen to be much faster. The tropical eastern Pacific warming evolves into abnormal cooling instead of a neutral condition in SUM(+1). This is concurrent with the reversal of the SSTAs over the tropical western Pacific from negative to significantly positive (Figs. 5f,h). The IOBW persists to SPR(+1) and begins to diminish in SUM(+1) as the warming SSTAs develop over the eastern Indian Ocean, Maritime Continent, and the WNP. The atmospheric response over the Pacific in the decaying spring is similar to that before 1990, while it shows a distinct seasonal reversal in the decaying summer consistent with the SSTAs. This will be discussed further in section 4c.

b. Intensified effect of IOBW in the mature winter and decaying spring of ENSO

As previously mentioned, concurrent with prewinter El Niño, IOBW dominates the Indian Ocean and persists to late summer before the 1990s, while it disappears faster in early summer after the 1990s. Though the tropical Indian Ocean warms up with a similar pattern and intensity in the mature winter and decaying spring during the two periods, a dramatic atmospheric response can be seen only after 1991 (Figs. 6, 7). Abnormal upward motion
Fig. 5. (a)–(j) Regression of seasonal SSTAs (K) from the mature winter to the following winter based on the EC1_SSTAs. (k),(l) The temporal evolution of the regressed tropical (5°S–5°N averaged) SSTAs. Results above the 90% confidence level are marked. The panels (a)–(e) and (k) are for the period of 1971–90 and (f)–(j) and (l) are for the period of 1991–2013.
features the tropical western and central Indian Ocean, accompanying the abnormal downward motion over the western Pacific (Fig. 6d) and lower-level easterly and upper-level westerly anomalies, forming an anti-Walker circulation over the Indian Ocean–western Pacific (Fig. 7d). This is counter to the scattered and insignificant signals before 1990. The descending motion over the western Pacific, a common downward branch of Walker circulation over the tropical Pacific and anti-Walker circulation over the tropical Indian Ocean, intensifies and...
extends southwestward after 1991 (Fig. 7d) and so does the PSAC (Fig. 6d). In the decaying spring, abnormal upward motion over the Indian Ocean migrates eastward and lies south to the equator (Fig. 6e), with the bonding lower-tropospheric circulation characterized by C-shaped wind anomalies (figure not shown). The anti-Walker circulation over the Indian Ocean remains, though its counterpart over the Pacific weakens to be insignificant (Fig. 7e). However, this teleconnection between the tropical Indian Ocean and the western Pacific could hardly be found in the regressed zonal circulation before 1990 (Figs. 7a,b).

To further reveal the decadal change in atmospheric response of the IOBW and its teleconnection with the

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**Fig. 7.** Regression of seasonal tropical (10°S–10°N averaged) zonal circulation (vector) and 500-hPa vertical velocity (shading, 10^2 hPa s^-1) in the (a),(d) mature winter, (b),(e) decaying spring, and (c),(f) summer based on the EC1_SSTAs. Only the results of vertical velocity significant at the 90% confidence level are shown. The panels (a)–(c) are for the period of 1971–90 and (d)–(f) are for the period of 1991–2013.
circulation over the WNP, divergent and rotational winds in both the lower and upper troposphere are regressed based on EC_1(SST) (Figs. 8, 9). Before 1990, descending motion accompanied by lower-level divergence and upper-level convergence occurs in the circulation over the WNP, with the opposite over Southeast China and the central Pacific in WIN(0) and SPR(+1), indicating a possible linkage between the WNP anticyclone and precipitation over Southeast China. The atmospheric teleconnection between the WNP and the Indian Ocean is weak and insignificant, except in the decaying spring when the circulation departs from the southeastern Indian Ocean to the WNP in the upper level (Fig. 8d). In contrast, the airflow ascends over the western Indian Ocean, goes eastward to the WNP in the upper troposphere, sinks over the WNP, and returns to the western Indian Ocean in the lower troposphere in WIN(0) after 1991 (Figs. 9a,b). The signal over the Indian Ocean shifts southwestward to the central Indian Ocean south of the equator in the following spring, forming a southwest–northeast teleconnection between the Indian Ocean and WNP (Figs. 9c,d). It helps anchor the abnormal widespread anticyclone over the tropical–subtropical WNP. The intensification of this teleconnection between the Indian Ocean and WNP is proposed as one of the causes of the widespread anticyclonic moisture circulation after 1991.

FIG. 8. Regression of 500-hPa vertical motion (shading; hPa s$^{-1}$), divergent wind (vectors; m s$^{-1}$), and velocity potential (contours; $10^5$ m$^2$ s$^{-1}$) at (a),(c),(e) 850 hPa and (b),(d),(f) 200 hPa from previous winter to summer based on the EC1_SSTAs during 1971–90. Only the results of divergent wind and vertical motion significant at the 90% confidence level are shown.
This decadal intensification of the IOBW effect has also been proposed by other studies. In recent decades, air–sea interaction over the tropical Indian Ocean has enhanced, including an ENSO-induced downwelling Rossby wave, southwestern Indian Ocean warming, the antisymmetric C-shaped wind pattern, and its coupling with the WNPAC (Xie et al. 2010; Huang et al. 2010; Zheng et al. 2011). As pointed out by Luffman et al. (2010), the SST over the Indian Ocean has increased at a rate of 0.7°C during the past century, and the western Indian Ocean especially has warmed faster than any other tropical ocean region. Ding et al. (2010) argues that the summer SSTAs superposed on a higher mean SST contribute to a stronger response of the atmospheric circulation to SSTA forcing. By using numerical modeling, Zheng et al. (2011) proposes that the “capacitor effect” of IOBW enhances in response to global warming even though ENSO itself weakened. Further work is needed to illustrate how the air–sea interaction and thus the atmospheric response change under global warming given the comparable SSTAs over the Indian Ocean in both periods.

c. Role of simultaneous eastern Pacific cooling

In summer, responding to the rapid establishment of cooling over the eastern Pacific and warming over the eastern Indian Ocean–Maritime Continent (EIO-MC), abnormal descending motion begins to dominate the western-central Pacific in early summer. It is concurrent with abnormal ascending motion to the west over the EIO-MC (Figs. 6f,h). This indicates an establishment of an anti-Walker circulation between the EIO-MC and
central Pacific, the atmospheric counterpart of rapidly developing La Niña in summer after 1991 (Fig. 7f). The suppressed convection over the tropical western-central Pacific excites a pair of anticyclones to its northwest over the WNP and southwest to the east of northeast Australia apart from the equator as a Rossby wave response via the Gill–Matsumo mechanism (Fig. 6f). The northwest anticyclone tends to be superimposed upon and thus enhances the WNPAC excited by the preceding El Niño. A similar result is found in Chen et al. (2016) via numerical experiments forced by tropical eastern Pacific cooling. However, these regressed circulation anomalies cannot be found before 1990 accompanying neutral SSTAs in the tropical eastern Pacific in the decaying summer of El Niño (Figs. 6c, g, 7c).

The aforementioned abnormal vertical circulation can be found not only in a west–east direction between EIO-MC and the tropical western Pacific, but also in a southwest–northeast direction between the EIO-MC and the subtropical WNP in the rotational and divergent wind fields after 1991 (Figs. 9e, f). The airflow ascends over the EIO-MC, and diverges northeastward in the upper level to the WNP, where it descends to the lower level and returns to the EIO-MC. This is consistent with He and Wu (2014), in which such southwest–northeast vertical circulation is proposed as an alternative mechanism for the Indian Ocean SST influence on the SCS climate other than the Kelvin wave–induced Ekman divergence mechanism (Wu et al. 2012; He and Wu 2014).

Hence, the rapid development of cooling SSTAs over the central and eastern Pacific and warming SSTAs over EIO-MC appear to act in concert to stimulate a west–east teleconnection with abnormal downward motion over the western-central Pacific and upward motion over the EIO-MC. The former excites an anticyclone over the WNP, sustaining and intensifying the WNPAC; the latter helps anchor the WNPAC via the abnormal southwest–northeast vertical circulation between the EIO-MC and WNP. In response, a more widespread anticyclonic moisture circulation prevails in the tropical–subtropical western Pacific, with the northward shift of abnormal moisture convergence over East Asia and precipitation enhancement over the Huai River valley instead of the Yangtze River valley in China. That is, the different speed of evolution from the prewinter El Niño to La Niña tends to amend the leading mode of moisture circulation over EA-WNP.

The decadal change of the covariance between the moisture circulation over WNP and the SSTAs over the eastern Pacific and EIO-MC is also supported by the cases studied. The regional SSTAs in abnormal years when the EC1_Qw is significantly anomalous during two subperiods are listed in Table 2. All positive/negative anomalous cases are preceded by tropical eastern Pacific warming/cooling. However, in contrast to the higher possibility of reversal instead of maintenance of the eastern Pacific SSTAs from winter to summer during 1991–2013, the possibility is evenly distributed during 1971–90. That is why the leading mode of moisture circulation concurs with the reversal of ENSO signal in summer after 1991, while with neutral conditions in summer before 1990 in the regression analysis. For the SSTAs over the EIO-MC, comparing to the 3 out of 4 cases in the pre-1990 period, all cases in the post-1991 period occur in line with the regression results. Hence, the modulation from the summer SSTAs is not stable in the pre-1990 period, while it is relatively stable in the post-1990 period.

d. Numerical experiments

To evaluate the impact of a different transforming speed of El Niño to La Niña on the circulation over EA-WNP, three idealized numerical experiments are designed and

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conducted. One is a control (CTL) run in which the model is forced by repeating climatological annual cycles of SST and sea ice. The other two idealized experiments are designed with climatological SST superposed by the SSTAs over the tropical central-eastern Pacific \((20^\circ S–20^\circ N, 160^\circ E–80^\circ W)\) regressed during the period of 1971–90 when the transforming of El Niño is slow (EP_pre90) and during the period of 1991–2013 when the transforming of El Niño is fast (EP_post90). Only the regressed SSTAs significant at the 90% confidence level are superposed (Figs. 6, 11). The last 19 ensembles’ mean results from winter to summer are analyzed.

The difference of the simulated lower-level circulation and midlevel vertical motion between the EP_pre90/EP_post90 and CTL runs are shown in Fig. 10. Similar atmospheric response is found in boreal winter in both simulations, as the enforcing SSTAs in WIN(0) are more or less alike (Figs. 10a,d). When it comes to spring, in the EP_pre90 run, as the eastern Pacific warming is sustained, upward motion dominates the central-eastern Pacific with its counterpart over the western Pacific; a weak anticyclonic circulation appears over the western Pacific and the SCS (Fig. 10b). Responding to the fast decay of El Niño in the EP_post90 run, both the upward and downward motions over the tropical Pacific weaken to a large extent and so does the anticyclone over the SCS-WNP (Fig. 11d). In boreal summer, as the eastern Pacific SST turns to be neutral in the EP_pre90 run, the atmospheric response over the WNP dissipates (Fig. 11c); whereas in the EP_post90 run, an anticyclonic circulation is stimulated over the WNP and SCS as the cooling SSTAs over the tropical eastern Pacific and abnormal descent to its west are established (Fig. 11f). These results validate the importance of the early establishment of eastern Pacific cooling in intensifying the simultaneous WNPAC in summer after 1991.

The upward motion over the EIO-MC is proposed to be directly triggered by the local simultaneous warming SSTAs (He and Wu 2014). To evaluate the individual role of the EIO-MC warming and also its combined effect with the eastern Pacific cooling, two additional experiments are conducted with the SSTAs specified around the EIO-MC region (EIO-MC_post91; \(15^\circ S–5^\circ N, 90^\circ E–160^\circ W\)) and both the EIO-MC and eastern Pacific region (EP&EIO-MC_post91) during 1991–2013, and the circulation in summer is shown in Fig. 11. In the EIO-MC_post91 run, though the stimulated low-level circulation is not significant, an anticyclonic circulation could still be found over the WNP. The airflow ascends over the EIO-MC, diverges northward to the SCS-WNP in the upper level, then descends and returns to the EIO-MC in the lower level, forming an abnormal meridional circulation. With the SSTAs over the eastern Pacific superposed, the WNP anticyclone is enhanced and enlarged; the meridional circulation shifts southwest–northeastward, and the west–east teleconnection between the EIO-MC and mid-Pacific is found. Hence, with the EIO-MC warming and the eastern Pacific cooling acting in concert, the WNPAC

![Fig. 10. Difference of the simulated 850-hPa wind (vector; m s\(^{-1}\)) and 500-hPa omega (shading; 10\(^{-2}\) hPa s\(^{-1}\)) between the (a)–(c) EP_pre90 run, (d)–(f) EP_post90 run, and the CTL run in the (a),(d) previous winter, (b),(e) previous spring, and (c),(f) summer. Only the results significant at the 90% confidence level are shown for omega and in black vector for wind. The red/blue contours with the interval of 0.3 K indicate the SSTAs over the tropical eastern Pacific imposed in the stimulation.](image-url)
is enhanced and enlarged in the transitional summer between El Niño and La Niña.

**5. Conclusions and discussion**

The leading mode of summer moisture circulation over EA-WNP, characterized by an “anticyclone–cyclone” dipole structure, is likely to take place in the transitional summer from an El Niño to La Niña event. In the past few decades, its modulation by the prewinter tropical eastern Pacific SSTAs was stable, while the influence of synchronous eastern Pacific SSTAs intensified after 1991. As a result, the zonally elongated anticyclonic moisture circulation over the subtropical WNP enhances and shows a much larger meridional expansion, while the cyclonic moisture circulation to the north weakens after 1991. As a result, stronger moisture invades northward and the associated convergence shifts from the Yangtze River valley to the Huai River valley, as does the precipitation.

The possible shift in the modulation of ENSO might arise in its evolution. After 1991, the prewinter El Niño decays and reverses to be cooling, concurrent with the replacement of IOBW by the EIO-MC warming in the decaying summer. Such rapid development of La Niña stimulates abnormal descending motion over the western-central Pacific and ascending motion over the EIO-MC. The former excites a pair of anticyclones over the western Pacific, sustaining and intensifying the WNP anticyclone. The latter helps in anchoring the WNP anticyclone via the southwest–northeast circulation between the EIO-MC and WNP. Numerical experiments using CAM4 enforced by the regressed SSTAs over the tropical central-eastern Pacific and EIO-MC verify these results. In addition, the influence of the IOBW shows a decadal variation. Though the

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**FIG. 11.** Difference of the simulated 500-hPa omega (shading; $10^{-2}$ hPa s$^{-1}$) and (a),(d) 850-hPa wind (vector; m s$^{-1}$), (b),(c),(e),(f) divergent wind (vectors; m s$^{-1}$) and velocity potential (contours; $10^5$ m$^2$ s$^{-1}$) wind between the (a)–(c) EIO-MC_post90 run, (d)–(f) EP&EIO-MC_post90 run, and the CTL run in summer. Only the results significant at the 90% confidence level are shown for omega and in black vector for wind. The red/blue contours with the interval of 0.1 K indicate the SSTAs imposed in the stimulation.
tropical Indian Ocean warms up with a similar pattern and intensity in the mature winter and decaying spring of El Niño during the two periods, apparent atmospheric response could be found only after 1991.

Besides the wider expansion of anticyclonic moisture circulation over the WNP, decadal change is also manifested in the weakness of the cyclonic moisture circulation to the north in the positive phase of the leading mode. The cyclonic moisture circulation is strong before 1990, lying east to Japan, together with the anticyclonic circulation over the WNP, implying the modulation of the “East Asia–Pacific” teleconnection or “Pacific–Japan pattern” on the moisture circulation (Nitta 1987). However, it weakens to a large extent after 1991. Huang and Sun (1992) suggested that this East Asia–Pacific teleconnection, characterized by the meridional propagation of quasi-stationary planetary waves, was forced by heat sources around the Philippines (Hoskins and Karoly 1981). To examine the possible causes of the weakness of the cyclone over Japan, the wave activity fluxes, and the quasigeostrophic streamfunction (Takaya and Nakamura 2001) in the lower and upper troposphere, characterized by the meridional propagation of quasi-stationary planetary waves, was forced by heat sources around the Philippines (Hoskins and Karoly 1981). To examine the possible causes of the weakness of the cyclone over Japan, the wave activity fluxes, and the quasigeostrophic streamfunction (Takaya and Nakamura 2001) in the lower and upper troposphere, characterized by the meridional propagation of quasi-stationary planetary waves, was forced by heat sources around the Philippines (Hoskins and Karoly 1981). To examine the possible causes of the weakness of the cyclone over Japan, the wave activity fluxes, and the quasigeostrophic streamfunction (Takaya and Nakamura 2001) in the lower and upper troposphere, characterized by the meridional propagation of quasi-stationary planetary waves, was forced by heat sources around the Philippines (Hoskins and Karoly 1981). To examine the possible causes of the weakness of the cyclone over Japan, the wave activity fluxes, and the quasigeostrophic streamfunction (Takaya and Nakamura 2001) in the lower and upper troposphere, characterized by the meridional propagation of quasi-stationary planetary waves, was forced by heat sources around the Philippines (Hoskins and Karoly 1981).

The cyclone is significant before 1990 and shows a quasi-barotropic vertical structure, with its location shifting slightly northeastward in the upper level. In the lower troposphere, its variation is closely associated with the northward propagation of wave activity fluxes from the subtropical WNP, implying possible forcing from the lower latitudes (Huang and Sun 1992; Kosaka and Nakamura 2006). The wave activity flux ascends over the region where the cyclone lies. In addition, it couples well with a barotropic wave train from the high latitudes, which could be traced back to the Arctic Ocean. The wave activity flux from the high latitudes propagates along the wave train in the upper troposphere and descends to the lower level over the Sea of Okhotsk north to the midlatitude cyclone. That is, the cyclone over Japan is the joint result of wave propagation from lower latitudes in the lower troposphere and from higher latitudes in the upper troposphere. In contrast, after 1991, the wave activity forced by the convection over the tropical–subtropical western Pacific is constrained in the lower latitudes. Meanwhile, the wave train from higher latitudes cannot be found. The underlying processes and mechanisms for such decadal variation remain unknown at this stage. Other signals besides tropical SSTAs could also play a role in the decadal variation of the atmosphere and thus moisture circulation over EA-WNP.

In this study, the decadal shift in 1990/91 is focused on as the relationship between the moisture circulation over the EA-WNP and the eastern equatorial Pacific SSTAs in summer shifts to be significantly negative. It is proposed to be caused by the rapid transforming of ENSO, which starts to play roles in summer. In cases studied (Table 2), we found that such rapid transforming also appears before 1990; however, it takes place with equal chance as slow transforming cases, while it appears much more often than the slow cases after 1990. For the causes, many recent studies propose that the Pacific decadal oscillation (PDO) could modulate the decaying speed of

FIG. 12. Regression of the quasigeostrophic streamfunction (shading; $10^6 \text{m}^2 \text{s}^{-1}$), horizontal (vectors; $\text{m}^2 \text{s}^{-2}$) and vertical (contours; $10^{-4} \text{Pa m s}^{-2}$) wave activity flux proposed by Takaya and Nakamura (2001) averaged between (a),(b) 500 and 200 hPa and (c),(d) 1000 and 550 hPa for the periods of (a),(c) 1971–90 and (b),(d) 1991–2013. Only the results significant at the 90% confidence level are shown.
ENSO and its impact on the global climate (e.g., Gershunov and Barnett 1998; Chen et al. 2013; Feng et al. 2014). The climate response of El Niño is likely to be stronger when the PDO is highly positive; in contrast, the climate response of La Niña is stronger when the PDO is highly negative (Gershunov and Barnett 1998). During high-PDO phases, El Niño decays slowly and has a strong anchor in the north Indian Ocean warming; comparatively, during low-PDO phases, El Niño decays rapidly and La Niña develops in summer. As a result, the anomalous WNPAC has a zonal band structure spanning southern China–WNP during the positive PDO phases, while it has a much larger spatial domain with meridional elongated structure from the tropics to the midlatitudes during the negative PDO phases (Chen et al. 2013; Feng et al. 2014). Hence, the more rapid evolution speed of ENSO and its impact on the moisture circulation over EA-WNP after 1991 proposed in this study might also be related to the change of the PDO phases. However, it is found that a decadal shift of the PDO from positive to negative phase tends to appear in late 1990 instead of early 1990, though two short terms of negative PDO phase appear in 1989–91 and mid-1990s (figure not shown). Whether the decadal shift of the relationship between the ENSO and moisture circulation could be attributed to the PDO signal requires further investigation.

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