

Indo-Pacific climate during the decaying phase of the 2015/16 El Niño: role of southeast tropical Indian Ocean warming

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Abstract This study investigates the influence of southeast tropical Indian Ocean (SETIO) sea surface temperature (SST) warming on Indo-Pacific climate during the decaying phase of the 2015/16 El Niño by using observations and model experiments. The results show that the SETIO SST warming in spring 2016 enhanced local convection and forced a “C-shape” wind anomaly pattern in the lower troposphere. The “C-shape” wind anomaly pattern over the eastern tropical Indian Ocean consists of anomalous westerly flow south of the equator and anomalous easterly flow north of the equator. The anomalous easterly flow then extended eastward into the western North Pacific (WNP) and facilitates the development or the maintenance of an anomalous anticyclone over the South China Sea (SCS). Correspondingly, the eastern part of the Bay of Bengal, the SCS and the WNP suffered less rainfall. Such precipitation features and the associated “C-shape” wind anomaly pattern shifted northward about five latitudes in summer 2016. Additionally, the SETIO warming can induce local meridional circulation anomalies, which directly affect Indo-Pacific climate. Numerical model experiments further confirm that the SETIO SST warming plays an important role in modulating Indo-Pacific climate.

Keywords SETIO SST warming · 2015/16 El Niño · Anomalous anticyclone · “C-shape” wind anomaly pattern · Indo-Pacific climate

1 Introduction

El Niño-Southern Oscillation (ENSO) is a dominant mode of interannual variability in the tropics. ENSO can significantly affect tropical and extratropical climate (e.g. Ropelewski and Halpert 1987; Trenberth et al. 1998; Webster et al. 1998; Wang 2002; Chen et al. 2014). Previous works have pointed out that ENSO can affect the strength of the East Asian summer monsoon (EASM) in the following year (e.g. Huang and Wu 1989; Zhang et al. 1996; Lau and Nath 2003; Chen 2002; Wang et al. 2000; Wu et al. 2003; Yim et al. 2008; Chen et al. 2016a). The pronounced low-level anomalous anticyclone/cyclone (WNPAC/WNPC) over the western North Pacific (WNP) (Zhang et al. 1996; Weisberg and Wang 1997; Wang et al. 1999) plays an important role in ENSO and ENSO’s climate. For example, the WNPAC induces the easterly wind anomalies in the equatorial western Pacific, which in turn terminates ENSO and serves as a negative feedback in the ENSO western Pacific oscillator (Weisberg and Wang 1997; Wang et al. 1999). During the El Niño decaying phase, the anomalous southwesterly on the northwestern flank of the WNPAC may strengthen the EASM and enhance the moisture transport from the tropics to subtropical frontal region, thus increasing the rainfall over Yangtze River valley, South Korea, and Japan (Zhang et al. 1999; Chen 2002; Lee et al. 2006).

Wang et al. (2000) showed that the WNPAC can arise from atmospheric Rossby wave response to suppressed convective heating, which is induced by local ocean surface cooling and subsidence forced remotely by the central

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to eastern Pacific sea surface temperature (SST) warming. Even though the warming in the tropical Pacific decays and vanishes in summer, the WNPAC can sustain via the local air-sea interaction during El Niño decaying year (Wang et al. 2000). It is known that El Niño can induce tropical Indian Ocean (TIO) SST warming by atmospheric bridge (e.g. Klein et al. 1999) and oceanic processes (e.g. Xie et al. 2002; Liu and Alexander 2007; Du et al. 2009), like a battery charging a capacitor. However, with the decay of El Niño, the TIO warming unleashes its influence in summer via eastward propagating Kelvin wave, like a discharging capacitor (Yang et al. 2007). The surface friction drives northeasterly wind into the equatorial low pressure in the baroclinic Kelvin wave, and induces surface convergence on the equator and divergence off the equator, thereby triggering suppressed deep convection and anomalous anticyclone over the western North Pacific (Xie et al. 2009). Xie et al. (2016) provided an overview of a coupled ocean-atmosphere mode over the Indo-Pacific called Indo-western Pacific ocean capacitor (IPOC), which combines the views of local air-sea interaction (Wang et al. 2000) and of Indian Ocean capacitor effect (Xie et al. 2009). In spring, the Northwest Pacific cooling and low level atmospheric Rossby wave (anomalous anticyclone) are coupled via wind-evaporation-SST feedback in the presence of trade winds, and such local SST cooling can trigger a summer feedback that arises from the interaction of the anomalous anticyclone and the North Indian Ocean warming in the Asian monsoon season (Xie et al. 2016). Recently, Xie and Zhou (2017) also provided a unified view of seasonal modulations of El Niño-related atmospheric variability in the Indo-Pacific.

A super El Niño event occurred in 2015–2016 with its maximum intensity in winter 2015 (Fig. 1b). This El Niño event was fully established in spring 2015, and rapidly developed into one of the three strongest El Niño episodes in record. Due to the impact of such super El Niño event, along with global warming background, the global surface temperature and air temperature over China in 2015 broke the observational record (Zhai et al. 2016). During the mature phase of the 2015/16 El Niño, an anomalous anticyclonic circulation in the lower troposphere prevailed over the Philippines, enhancing the southwesterly wind and substantially increasing precipitation in southern China (Zhai et al. 2016; Chen et al. 2016b).

Historically, La Niña events always follow several (but not all) strong El Niño events, including the 1997/98 El Niño. Some climate models indicated that La Niña development was possible in the third quarter of 2016 and its intensity was likely to be weak. However, the strong 2015/16 El Niño ended in May 2016 (Fig. 1b). The La Niña condition was not well established in the central to eastern Pacific (Fig. 1b). More importantly, there was no obvious anomalous anticyclonic circulation in the lower troposphere over

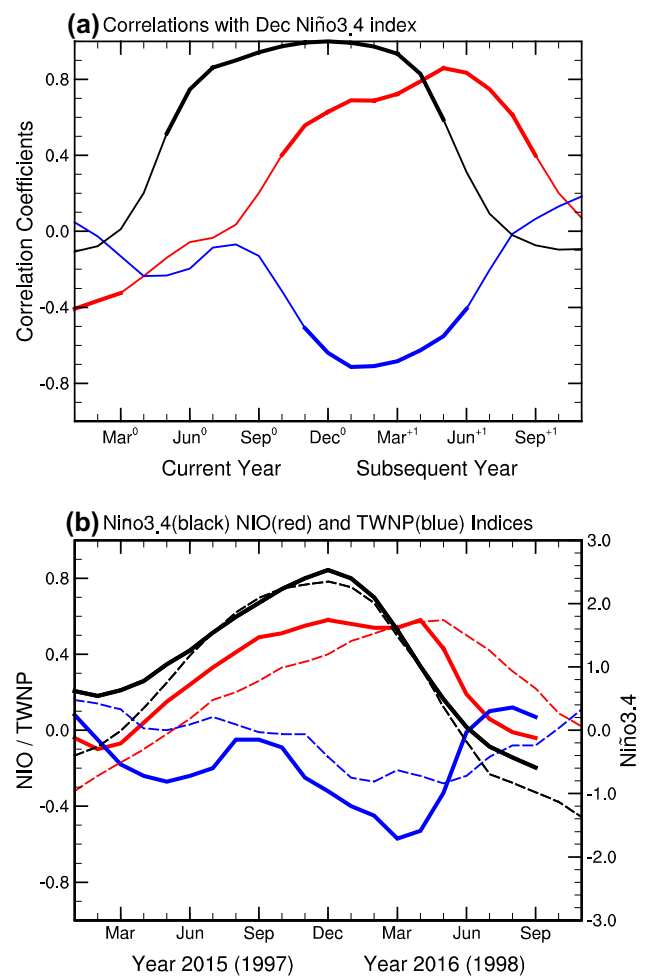


Fig. 1 **a** Correlations with December Niño3.4 SST index and **b** SST Anomalies in three ocean regions for 2015–2016 (solid line) and 1997–1998 (dash line): Niño3.4 region (5°S – 5°N , 170°W – 120°W ; black), North Indian Ocean (0 – 20°N ; 40°E – 100°E ; red) and tropical western North Pacific (10° – 20°N , 150°E – 170°E ; blue). Thick curves in **a** indicate the correlations are significant at 95% confidence level, based on the student's *t* test. The HadISST1 dataset for 1979–2016 has been detrended before computing the SST indices. The SST indices are smoothed by 3 month running means. The superscripts “0” and “+1” denote current year and subsequent year, respectively

the WNP in summer (Fig. 2d). Such feature was so different from that in 1997/98 El Niño decaying summer (e.g. Wang and Weisberg 2000). In 1998, the intensity of WNPAC was very strong in summer (Figs. 2h, 3h), enhancing the strength of EASM, resulting in serious flooding over most part of southern China (Zhang et al. 1999). Natural questions are: Why the intensity of WNPAC was so weak in this super El Niño decaying summer? What was the role of Indo-Pacific SST anomalies in maintaining the WNPAC from spring to summer in 2016?

Previous studies noticed that the TIO SST anomalies can affect the Indo-Pacific climate (e.g. Du et al. 2011; He et al.

SST & 925-hPa Wind Anomalies

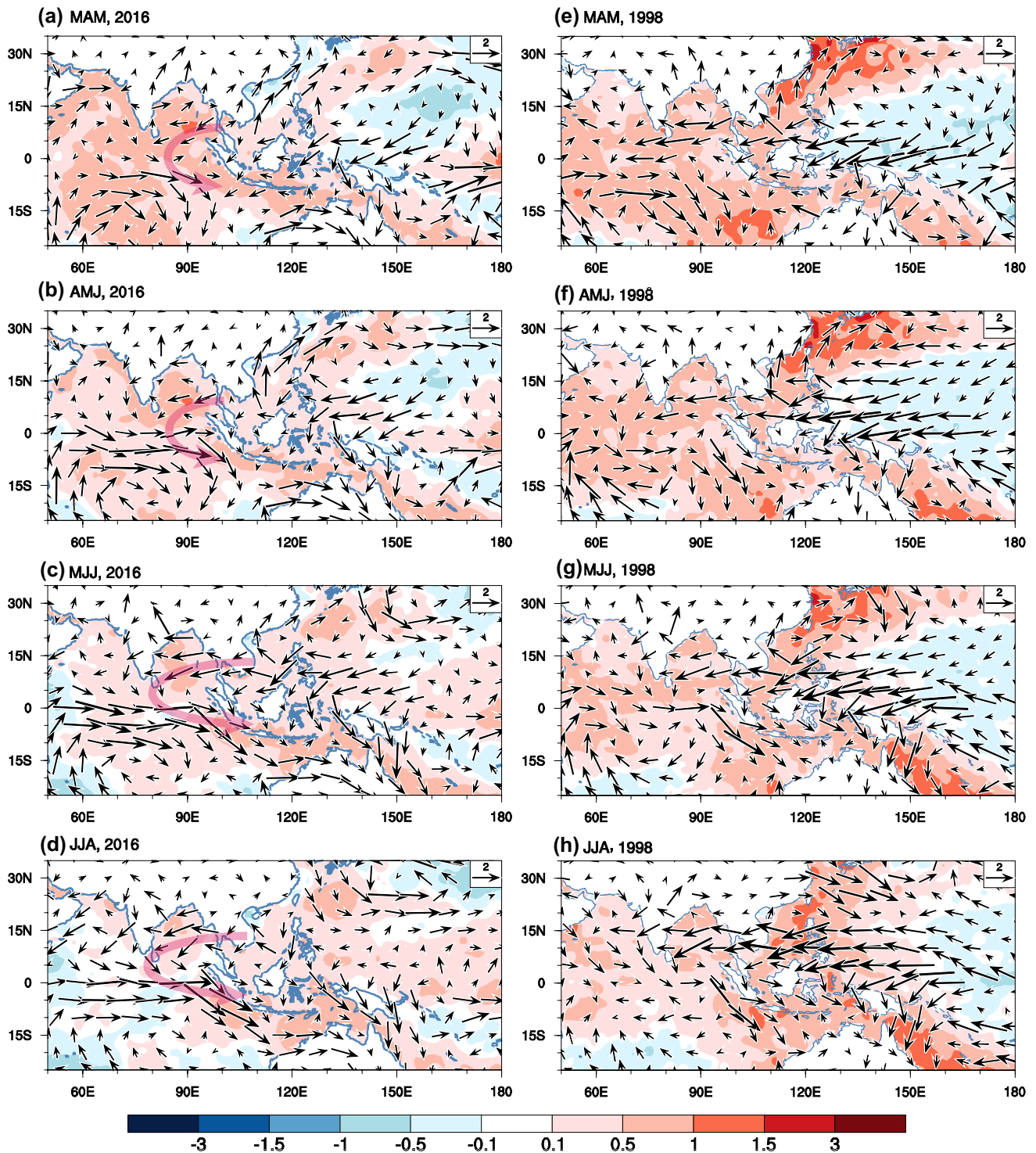


Fig. 2 SST ($^{\circ}\text{C}$, shading) and low-level wind (vectors) anomalies from March-April-May (MAM) to June-July-August (JJA) in year 2016 (left panels) and year 1998 (right panels)

2015; Hu et al. 2014; He and Wu 2014; Wu et al. 2012; Zhan et al. 2011, 2014). For example, Zhan et al. (2011) argued that the eastern TIO summer SST anomalies could

significantly influence the western Pacific summer monsoon and the equatorial Kelvin wave activity over the western Pacific, thus affecting the tropical cyclone genesis in

925-hPa Wind & Precipitation Anomalies

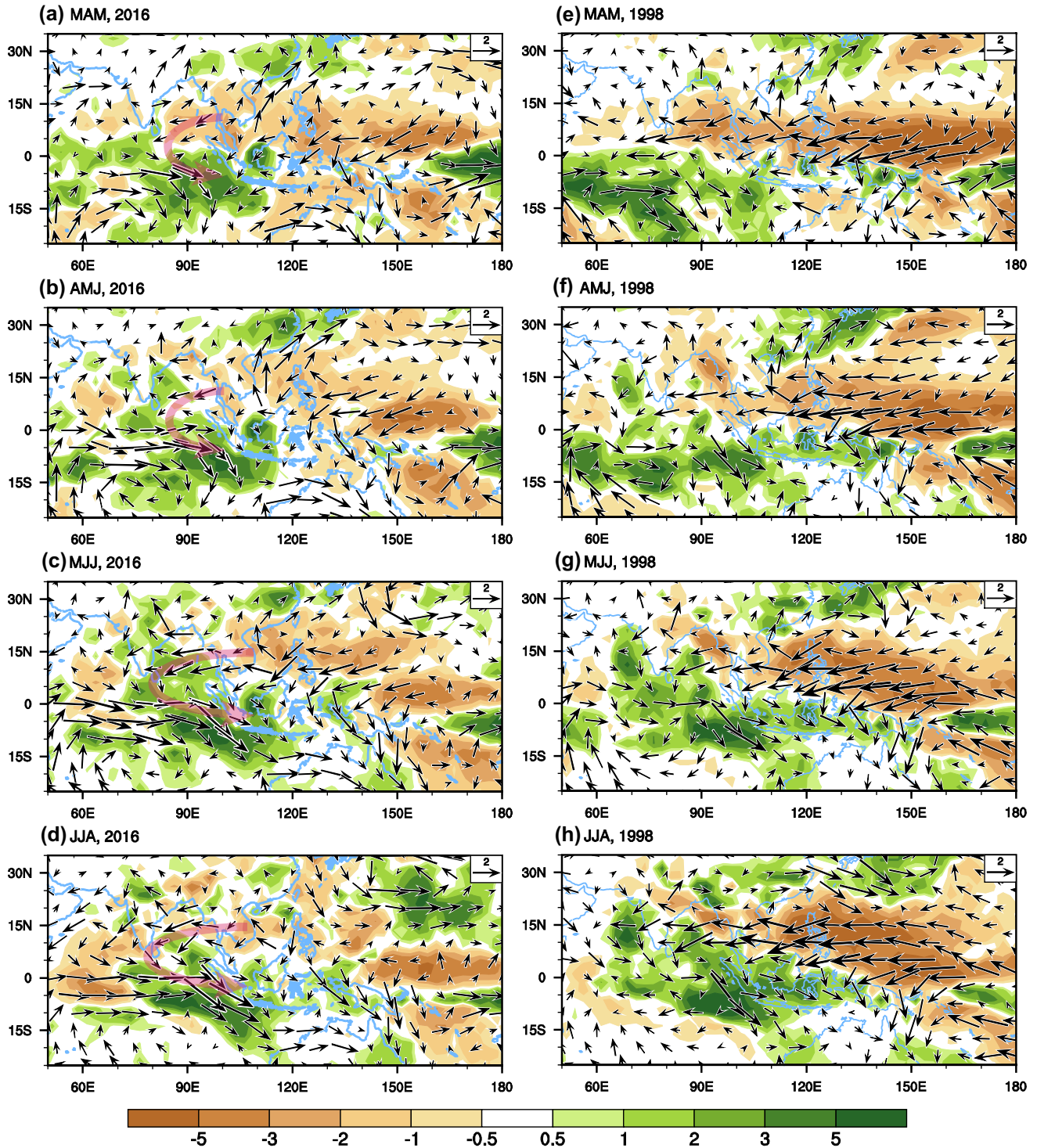


Fig. 3 Low-level wind (m/s, vectors) and precipitation (mm/day, shading) anomalies from MAM to JJA in year 2016 (left panels) and year 1998 (right panels)

the WNP and largely determining the number of tropical cyclones. Wu et al. (2012) investigated the interdecadal change in the relationship between southern China summer

rainfall and tropical Indo-Pacific SST. Comparisons were made between the 1950–1960s and the 1980–1990s, and they found that a larger southeast TIO SST forcing coupled

with a stronger and more extensive WNP subtropical high in recent decades would induce circulation anomalies reaching higher latitude, influencing South China directly.

In this study, we focus on the decaying phase of the 2015/16 El Niño. The objective of this paper is to reveal that the southeast tropical Indian Ocean (SETIO) plays a role in modulating the anticyclonic circulation over the South China Sea (SCS) and the northeast Indian Ocean during the El Niño decaying year. The evolution of SST anomalies in the 2015/16 El Niño provides insights into the influence of SETIO SST variability on Indo-Pacific climate. The rest of the paper is organized as follow. Section 2 describes the dataset, method and climate model utilized in this study. Section 3 presents the observed SST, precipitation and atmospheric circulation anomalies during the decaying phase of the 2015/16 El Niño. Section 4 clarifies the influence of the SETIO on East Asian Climate through numerical model experiments. Section 5 gives the concluding remarks and discussions.

2 Data and methodology

The following datasets were used in this study: (1) National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996) with a horizontal resolution of 2.5° longitude \times 2.5° latitude; (2) Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997) data on a $2.5^\circ \times 2.5^\circ$ grid; (3) the monthly SST data on a $1^\circ \times 1^\circ$ grid from the Met Office Hadley Center (HadISST1, Rayner et al. 2003); (4) the monthly surface latent heat flux data on a $1^\circ \times 1^\circ$ grid from objectively analyzed air–sea fluxes (OAFlux) products (Yu et al. 2008). The NCEP/NCAR reanalysis data and CMAP precipitation data are provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, and downloaded from the web at <http://www.esrl.noaa.gov/psd/>. Above monthly datasets are available from January 1979 to October 2016. The seasonal anomalies were derived by subtracting the corresponding seasonal mean climatology for the period 1979–2016. In addition, the long-term linear trend was removed from all the datasets.

To extract the leading mode of East Asian climate, we used the multivariate empirical orthogonal function (MV-EOF) analysis on a set of meteorological fields (i.e. precipitation, 925-hPa zonal and meridional winds) in April–May–June (AMJ) for the period 1979–2016. The analysis was performed within a domain including both East Asia and WNP (i.e. 5°N – 40°N , 95°E – 150°E). Anomalies were firstly calculated by removing the climatological mean and then normalized with respect to each variable so that each variable gets equal weight in the MV-EOF analysis. The three input fields of normalized AMJ anomalies for

each year were concatenated into an N-dimensional vector as input vector. N is three times the number of grid points in the selected domain, and the number of all input vectors is 38 in this study. Finally, an area-weighted covariance matrix was constructed for the combined fields to carry out the MV-EOF analysis. More details can be found in Wang (1992). By using MV-EOF method, we can capture the spatial coherent anomaly pattern between low-level circulation and precipitation in East Asia.

The Community Atmosphere Model Version 4 (CAM4), which was developed with significant community collaboration at NCAR, was used in this study. CAM4 is the atmospheric component of Community Climate System Model Version 4 (CCSM4) that was released in 2010 (Gent et al. 2011). The CAM4 simulations used finite-volume dynamic core (Lin 2004) on a horizontal resolution roughly equivalent to 0.9° latitude \times 1.25° longitude, with 26 vertical levels in a hybrid sigma-pressure coordinate system extending from the surface to approximately 3.5-hPa. A general overview of CAM4 mean climate simulation can be found in Neale et al. (2013).

In order to clarify the role of SETIO SST anomalies in modulating East Asian climate during the decaying phase of the 2015/16 El Niño, we conducted two sets of model experiment. One is control run (CTRL run), which was forced by climatological mean annual cycle of SSTs. The climatological SSTs in CTL run were from the merged HadISST1-OI.v2 SST products, which were specifically developed as surface forcing datasets for CAM simulations (Taylor et al. 2000; Hurrell et al. 2008). The monthly climatological SSTs in CAM4 model were computed during the period 1982–2001 (Hurrell et al. 2008). The other one was forced by the warm SST anomalies (Fig. 7) in the SETIO added to the climatological mean annual cycle of SST (SETIO run). The SST anomalies shown in Fig. 7 are detrended monthly SST anomalies for 2016. We only extracted the positive SST anomalies from February to August in SETIO. In the SETIO run, the monthly SST was set to the respective climatological mean for months other than those shown in Fig. 7. Each run is a 35-year continuous simulation and the last 30-year results are analyzed in this study. A student's t test is utilized to examine the statistical significance of the difference between the SETIO run and CTRL run.

3 Indo-Pacific climate variations during the decaying phase of the 2015/16 El Niño

In MAM 2016, cold SST anomalies appeared in the WNP and warm SST anomalies were located in the North Indian Ocean (Fig. 2a). The cooling over the WNP might suppress the deep convection there and maintain the WNPAC

(Fig. 3a). However, the North Indian Ocean warming corresponds to in-situ below normal precipitation (Fig. 3a), which indicates that the North Indian Ocean SST anomalies were likely a response to the atmospheric change instead of a forcing of the atmosphere in spring (Wu et al. 2008; Wu and Yeh 2010).

The anomalous anticyclone over the Indo-Pacific was obvious from MAM to AMJ in 2016 (Figs. 2a, b, 3a, b). In summer (JJA), its intensity was weak, and only weak anticyclonic circulation appeared over the SCS (Figs. 2d, 3d). This is very different from the evolution of WNPAC in the following summer of the 1997/98 El Niño (Figs. 2h, 3h). From spring to summer, there was a low-level “C-shape” wind anomaly pattern with anomalous easterly wind in the north and anomalous westerly wind in the south over the eastern TIO (Figs. 2, 3). In spring, this “C-shape” wind anomaly was asymmetric along the equator with northeasterly wind anomaly in the north and northwesterly wind anomaly in the south (Figs. 2a, 3a). After that, it moved northward about five latitudes and further noticeable, especially in summer (Figs. 2d, 3d).

The SST cooling in the WNP gradually decayed from MAM to JJA and disappears in summer (Fig. 2). This result is consistent with former studies, which argued that with the retreat of easterly trade winds in the Asian monsoon season, the positive thermodynamic feedback between the WNPAC and the underlying SST turns to be a negative feedback (Chou et al. 2009), thus decreasing the negative SST anomalies in the WNP and its local forcing effect (Wu et al. 2010).

Typically, after the mature phase of El Niño, the North Indian Ocean displays a double-peak warming (Fig. 1a). The second peak is larger in magnitude, and can persist into summer (Du et al. 2009) as the first notice in the SCS (Wang et al. 2006). In 2016, the North Indian Ocean warming persisted from spring to summer with its intensity gradually weakening (Fig. 1b). From AMJ to JJA, the southern part of the Bay of Bengal received above normal precipitation, which suggests that the North Indian Ocean was discharging at that time (Fig. 3b–d). However, the summertime North Indian Ocean warming in 2016 was much weaker than that in 1998 (Fig. 1b), thus its remote forcing effect on the WNPAC may be weak in 2016. Since the local SST anomalies decayed quickly and vanished in summer, and the North Indian Ocean warming was weak (Fig. 1b), the intensity of the WNPAC in summer 2016 was weak. Besides, the lack of following La Niña development might also partly explain the weak intensity of WNPAC in summer 2016 (e.g. Fan et al. 2013; Chen et al. 2016a).

The strongest positive precipitation signal in the Indo-Pacific region in 2016 was over the SETIO (Fig. 3). Corresponding to such strong positive precipitation anomalies, the positive SST anomalies persisted from spring to summer in the SETIO (Figs. 2a–d, 3a–d). Besides, lower level westerly

wind anomalies prevailed over the southern TIO from spring to summer 2016 (Figs. 2a–d, 3a–d).

To provide more evidence for the asymmetric anomaly pattern over the eastern TIO, we computed the zonal mean SST, precipitation and 925-hPa wind anomalies between 95°E and 110°E (Fig. 4). From late spring to early summer in 2016, the asymmetric wind anomaly pattern along the equator was rather clear in the eastern TIO. Although both the southern part and northern part of SST anomalies within the East Indian Ocean were positive, the SST anomalies in the SETIO were warmer than those in the northeast tropical Indian Ocean during February–March–April (FMA) 2016.

At the same time, the convection over the southeast Indian Ocean gradually enhanced. The meridional thermal gradient within the East Indian Ocean might induce anomalous ascent in the southern hemisphere and anomalous northerly crossing the equator, which were favorable for the formation of “C-shape” wind anomalies in lower troposphere over the eastern TIO (Fig. 4). This point is further supported by Fig. 5, which shows the latitude-height section plots of anomalous vertical motion and specific humidity averaged over 95°E–110°E. Clearly, from spring to early summer, the specific humidity anomaly displayed a dipole pattern with wet condition in the south of the equator and dry condition in the north of the equator. In addition, there was an anomalous vertical cell over the eastern TIO. The anomalous vertical circulation directly connected the descent over Indochina Peninsula, eastern part of the Bay of Bengal and western part of the SCS to the ascent over the SETIO (Figs. 3a–d, 5).

Furthermore, we investigated the origin of the SST warming in the SETIO. The SETIO SST warming began in boreal autumn in 2015 (Fig. 6). At the same time, the

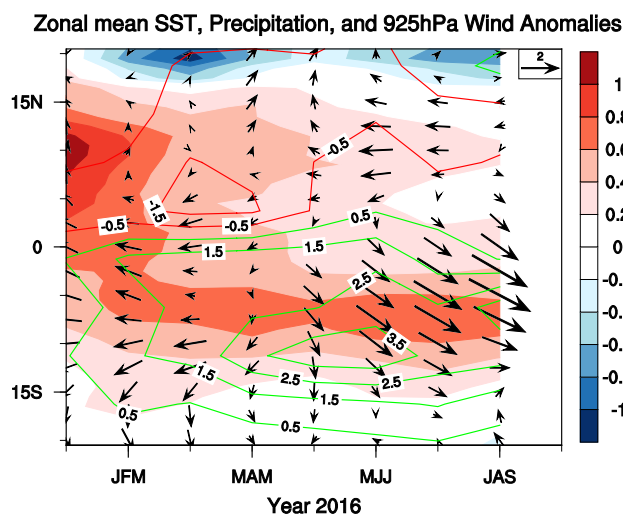


Fig. 4 Zonal mean SST (°C, shading) precipitation (mm/day, contours) and 925-hPa wind (m/s, vectors) anomalies in the East Indian Ocean (95°E–110°E). The contour levels for precipitation anomalies are -1.5 , -0.5 , 0.5 , 1.5 , 2.5 , and 3.5 mm/day, respectively

Fig. 5 Meridional circulation and specific humidity (g/kg, shading) anomalies averaged over 95°E–110°E from MAM to JJA in year 2016. The p-velocity (i.e. omega, Pa/s) anomalies are multiplied by -50

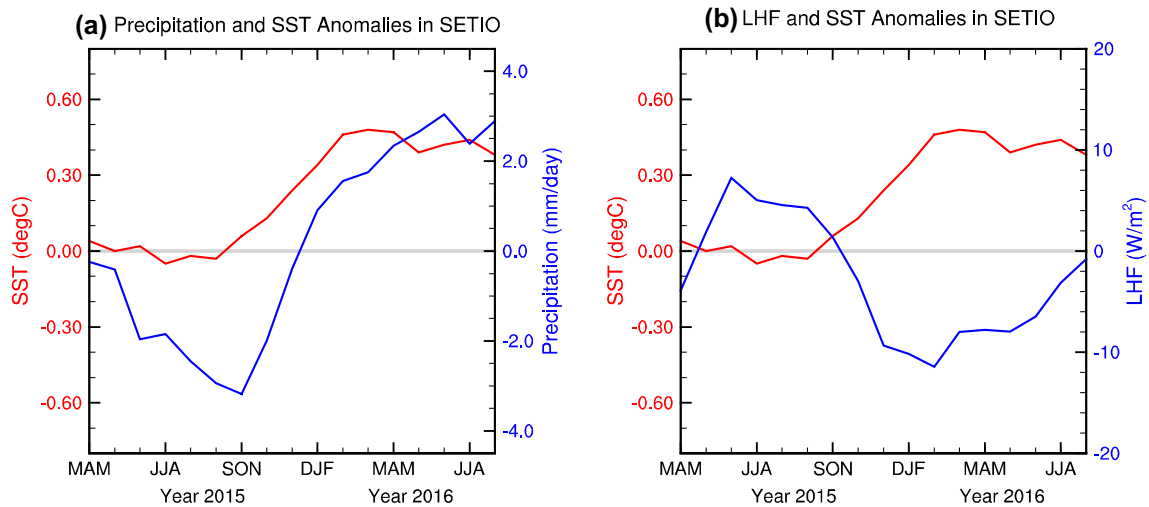
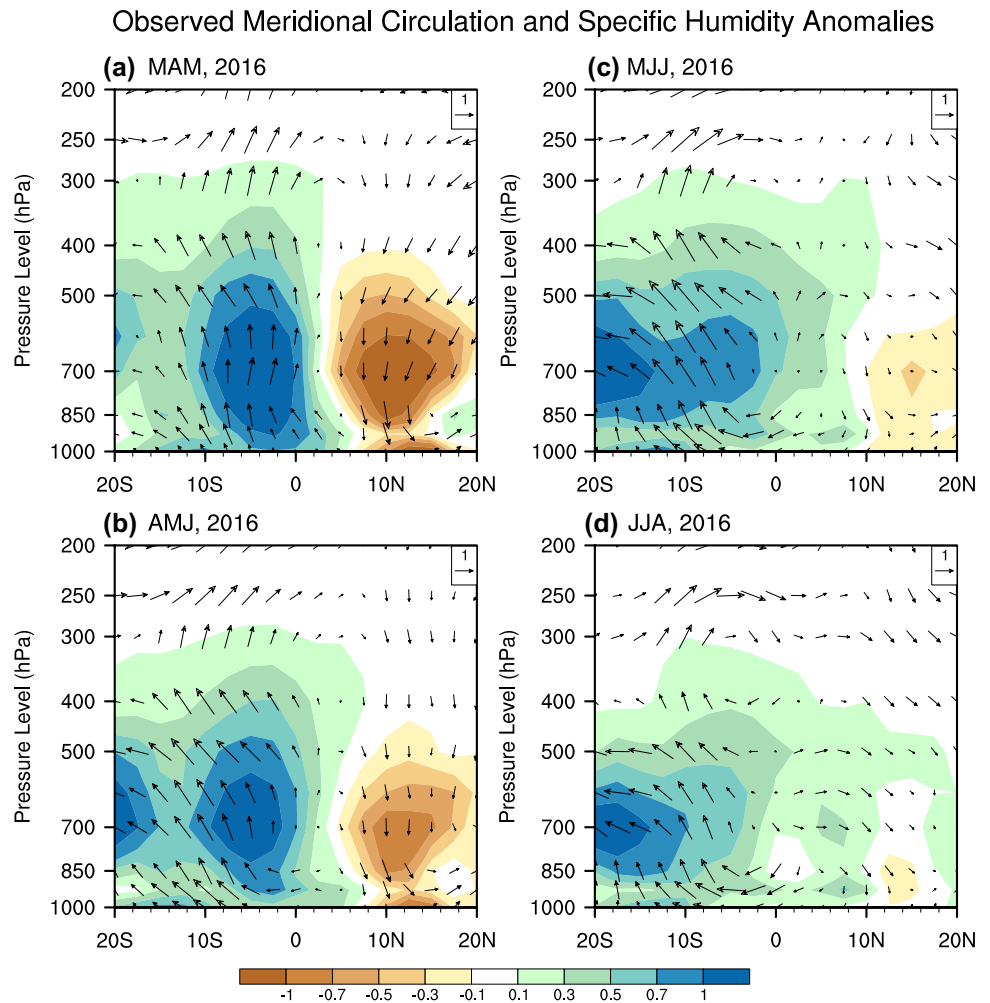


Fig. 6 Temporal evolution of anomalies in the SETIO (90°E–110°E, 15°S–0). **a** Precipitation (blue line) and SST (red line) anomalies. **b** Surface latent heat flux (blue line) and SST (red line) anomalies

convection in situ was suppressed with more shortwave radiation into the surface, triggering the SST warming in the SETIO (Fig. 6a). Then, the SETIO SST warming gradually developed and peaked in boreal spring in 2016 (Fig. 6). The negative latent heat flux anomalies show that the ocean reduced the heat release into the atmosphere (Fig. 6b), which help the development or the maintenance of the SETIO SST warming.

4 Role of the SETIO in Indo-Pacific climate

The above analyses suggest that the SETIO SST anomalies may play a role in influencing regional climate. The strong updraft induced by positive SST anomalies in the SETIO causes the formation of an anomalous vertical circulation

with lower level cross-equatorial southward flow and upper level cross equatorial northward flow. As revealed by previous works (e.g. Wu et al. 2012; Hu et al. 2014), such a vertical circulation links SCS climate variability to the SST variability off the Sumatra coast. As the SETIO warming can induce anomalous sinking motion over the SCS, so the suppressed convection may partly contribute to the maintenance of anomalous anticyclonic circulation over the SCS.

Besides, we have computed the lead-lag correlation between SST and precipitation. The simultaneous correlation coefficient between SST and precipitation in the SETIO is positive (about 0.42). The SETIO maximum SST anomalies lead the precipitation anomalies by about 2 months (Figure not shown), indicating that the SETIO SST can force the atmosphere. Since there were North Indian Ocean warming and WNP cooling during spring to early summer in 2016,

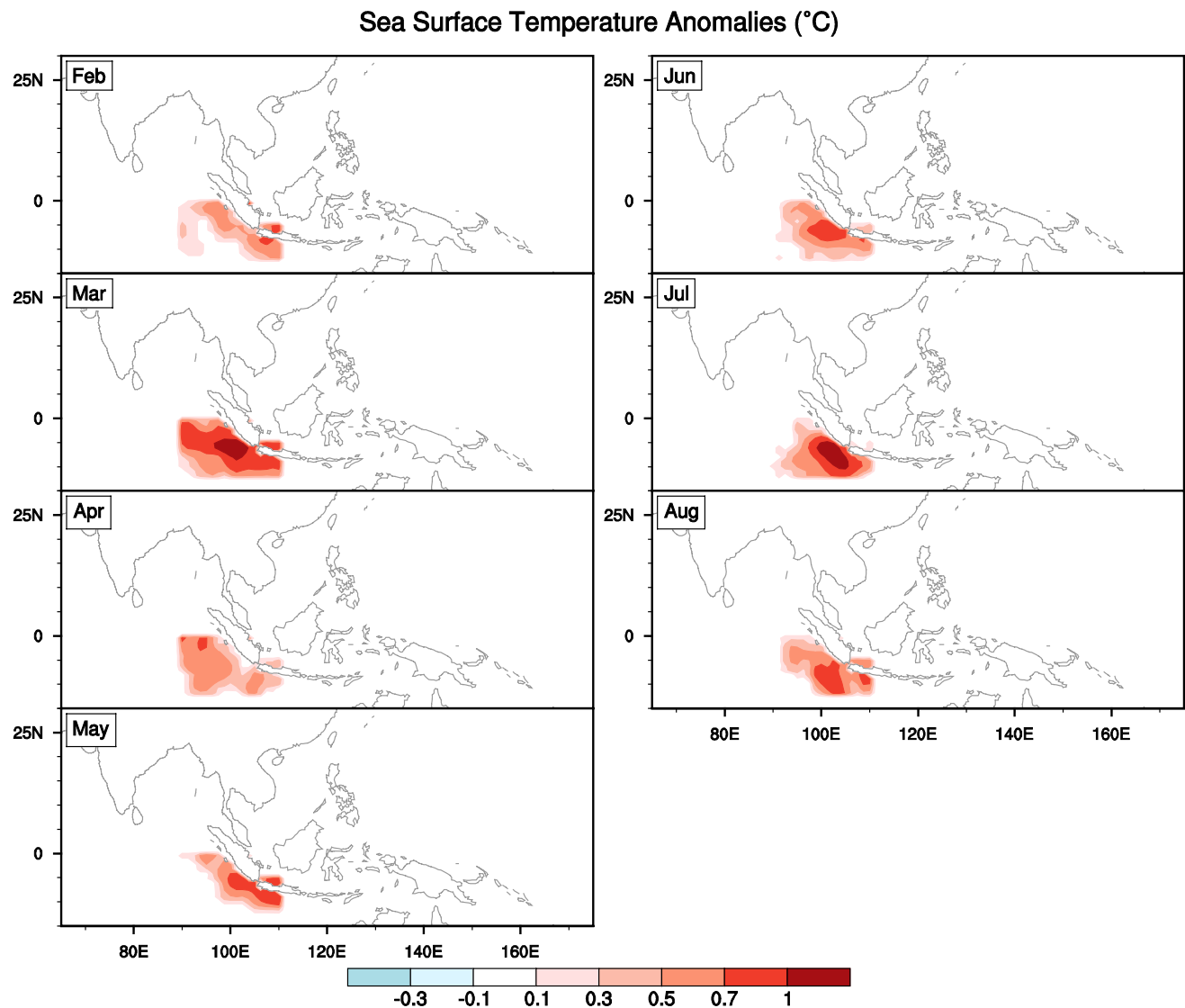


Fig. 7 SST anomalies from Feb to Aug used in SETIO run

we may probably overestimate the influence of the SETIO warming in modulating the WNPAC from observations. To further reveal the impacts of the SETIO, two idealized CAM4 numerical experiments (i.e. CTRL run and SETIO run) are conducted. The model runs are designed to identify the role of SETIO SST anomalies (Fig. 7) in modulating Indo-Pacific climate. The forcing effect of the SETIO warming can be evaluated by analyzing the ensemble mean difference between SETIO run and CTRL run.

The simulated precipitation and 925-hPa wind difference between SETIO run and CTRL run are shown in Fig. 8. In response to the positive SST anomaly in the SETIO, the convection in situ is significantly enhanced from spring to summer. Negative precipitation anomaly appears north of the positive precipitation anomaly in the SETIO. The SCS, the eastern part of the Bay of Bengal, and the Philippine Sea suffer less rainfall. A “C-shape” wind anomaly pattern forms in spring over the eastern TIO with anomalous northeasterly in the northern hemisphere and northwesterly in the southern hemisphere. This “C-shape” wind anomaly pattern shifts northward about five latitudes in summer. Such numerical results are similar to the observational findings shown by Fig. 3. To the north of the “C-shape” circulation

anomaly pattern, there is an anomalous anticyclone over the SCS (Fig. 8). The southwesterly wind anomalies in the northwest flank of the anomalous anticyclone enhances the water vapor transport in the subtropical frontal region in East Asia. Thus, there is an above normal rain band extending from the lower reach of the Yangtze River Valley to the south of Japan Islands. Besides, most part of southern China has more rainfall from spring to summer (Fig. 8). In our sensitivity experiment, we put the SST forcing in the SETIO. In fact, the response stands for or is equivalent to an atmospheric response to meridional cross-equatorial SST gradient, which has been investigated in the tropical Atlantic (Xie and Carton 2004). The atmospheric response to meridional cross-equatorial SST gradient may be similar in different ocean basins. For example, when exploring the failure factors of 2014 El Niño prediction, Zhu et al. (2016) put the negative SST anomalies in the southeastern tropical Pacific in their experiments and they found a similar wind response to that in our study related to the SETIO SST warming.

Figure 9 illustrates the response of mid-level vertical velocity, high-level velocity potential and divergent wind to the SETIO warming. The 200-hPa velocity potential anomalies display a north–south dipole pattern over the East Indian

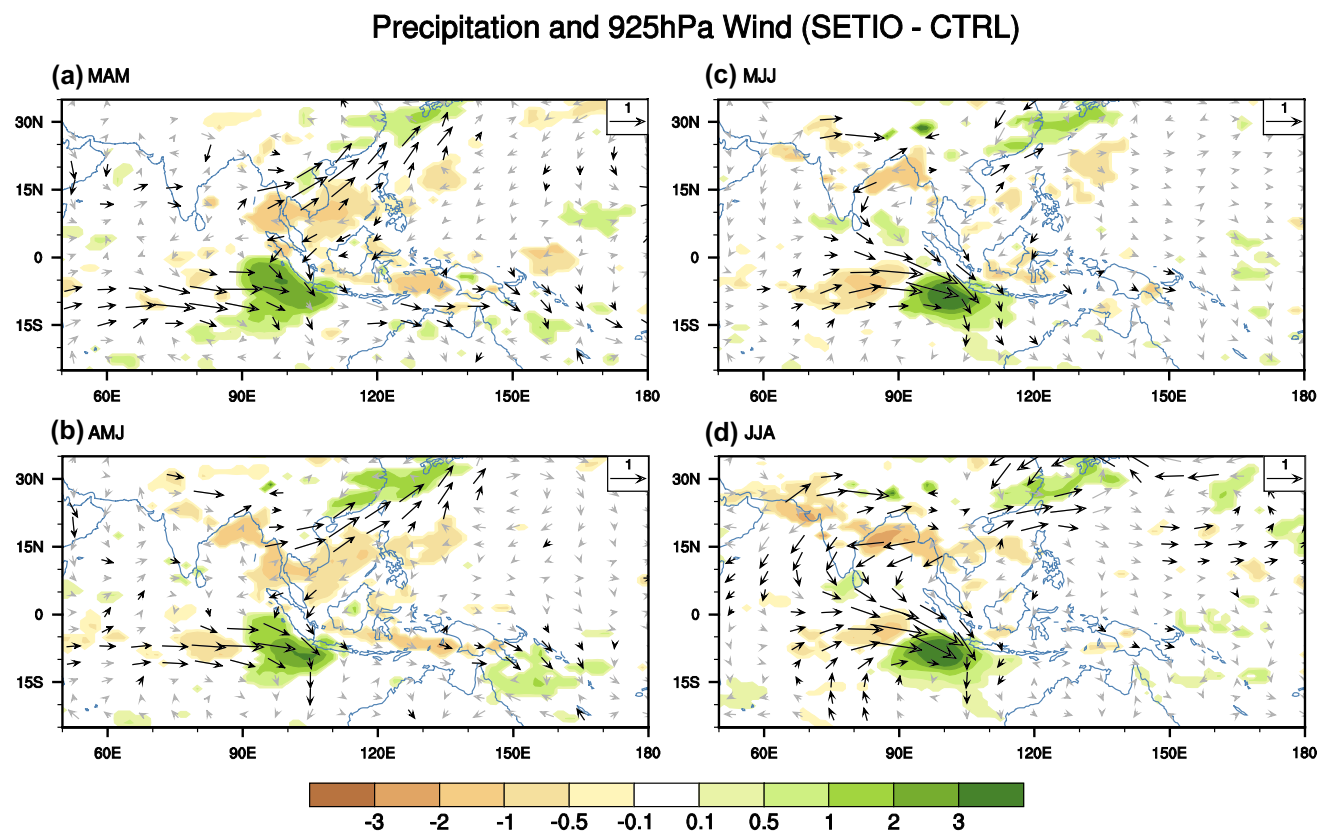


Fig. 8 Simulated precipitation (mm/day, shading) and 925-hPa wind (m/s, vectors) difference between SETIO run and CTRL run. The only precipitation anomalies that are significant at 90% confidence

level are plotted. The black vectors denote that the wind anomalies are significant at 90% confidence level according to student’s t test

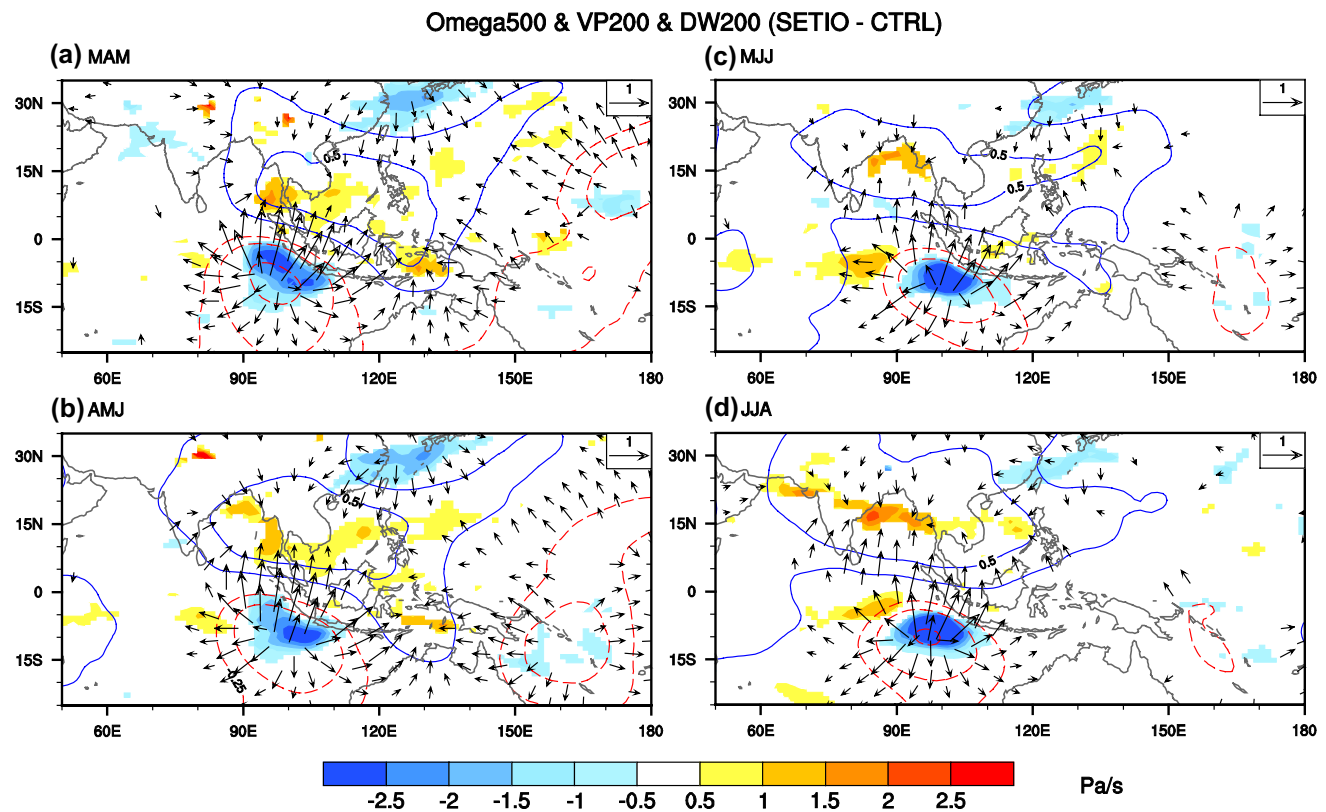


Fig. 9 Simulated 500-hPa omega (Pa/s, multiplied by 100, shading), 200-hPa velocity potential ($10^6 \text{m}^2 \text{s}^{-1}$, contours) and divergent wind (m/s, vector) differences between SETIO run and CTL run. The con-

tour levels for velocity potential anomalies are -1.0 , -0.5 , -0.25 , 0.25 , 0.5 and 1.0 , respectively. The only omega and divergent wind anomalies that are significant at 90% confidence level are plotted

Ocean with negative value in the south and positive value in the north. Corresponding to the high-level velocity potential anomaly pattern, there is anomalous upward vertical motion over the SETIO, which is accompanied by high-level divergence in situ. Meanwhile, anomalous downward vertical motion appears near the Bay of Bengal, Indochina Peninsula and the SCS, which corresponds to high-level convergence.

The anomalous meridional circulation in the East Indian Ocean links the Bay of Bengal, Indochina Peninsula and SCS climate to the SETIO SST anomalies (Fig. 10). The numerical results of SETIO run further confirm that the SETIO SST anomalies from spring to summer 2016 play an important role in modulating Indo-Pacific climate.

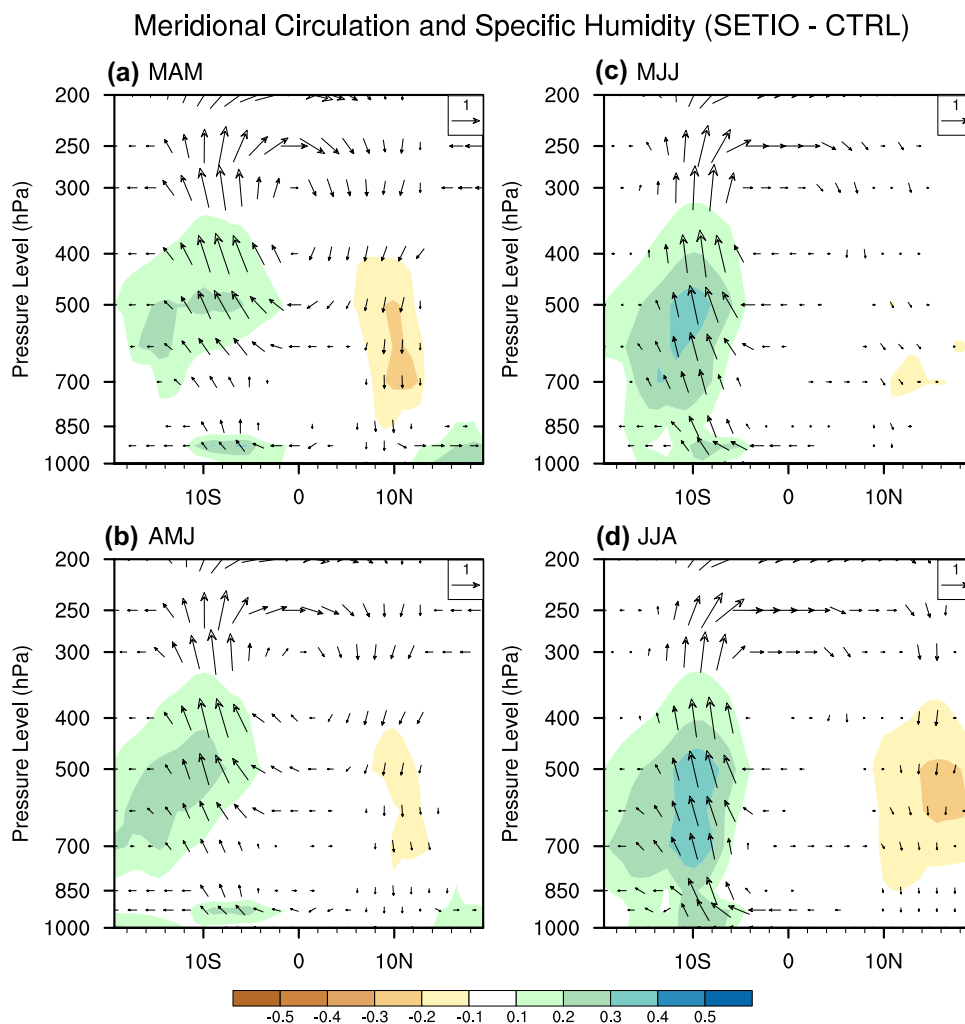
5 Summary and discussion

In this study, we investigate the role of SETIO SST warming in modulating Indo-Pacific climate during the decaying phase of the 2015/16 El Niño. For this super El Niño event, although the related positive SST anomalies within the central to eastern Pacific were strong in its mature phase (previous winter), its intensity decayed quickly and

transited into a normal condition in the following summer. The cooling in the WNP was obvious in spring; however, with the decay of the 2015/16 El Niño and the onset of the Asian summer monsoon, such cooling nearly vanished in summer. There was a North Indian Ocean warming during spring to summer in 2016. In spring, the positive SST anomalies in the North Indian Ocean was more like a passive response to atmosphere change (less rainfall and more solar radiation, Fig. 3a), rather than an atmospheric forcing. In summer, the North Indian Ocean warming might unleash its influence on Indo-Pacific climate (Hu et al. 2011; Kosaka et al. 2013; Xie et al. 2016), but its forcing effect seemed to be weak as its warming intensity was weak. During spring to early summer of this extreme El Niño decaying phase, there was an anomalous anticyclone over the WNP (WNPAC). The WNPAC covered a larger area and was stronger in spring compared to that in summer. To the northwest flank of the WNPAC, the anomalous southwesterly in the lower troposphere brought more water vapor to the subtropical frontal region, thus most part of South China suffered more rainfall.

Although the results are based on a case study, the influence of SETIO SST anomalies is not just confined to this

Fig. 10 Simulated meridional circulation and specific humidity (g/kg , shading) differences averaged over 95°E – 110°E between SETIO run and CTRL run. The p-velocity (i.e. ω , Pa/s) anomalies are multiplied by -50



super El Niño event. Figure 11 shows the regressions of precipitation and wind onto the SETIO SST index. In general, the AMJ SETIO warming induces above-normal precipitation over the south tropical Indian Ocean and below-normal precipitation over the eastern part of the Bay of Bengal, most part of the SCS and WNP (Fig. 11a). Correspondingly, the low-level wind anomalies over the eastern TIO feature “C-shape” flows with anomalous westerly in the south of equator and anomalous easterly north of the equator. The anomalous easterly extends into the western Pacific and forms an anomalous anticyclone over the SCS and WNP (Fig. 11a). In JJA, the regression results over the East Indian Ocean and western North Pacific are similar to those in AMJ, except that the regression pattern shifts northward about five latitudes (Fig. 11b). These features well match the results shown in our case study and numerical model experiments.

We also find that the SST over the SETIO has a close relationship with East Asian Climate during the transition period from spring to summer (AMJ). Figure 12 presents the

leading mode of multivariate EOF analysis (MV-EOF) on a set of three meteorological fields (including precipitation, the zonal and meridional winds at 925-hPa) in AMJ. The leading mode accounts for about 21.5% of the total variance for all three fields together. The spatial pattern of the leading MV-EOF mode shows a north–south dipole pattern with dry anomalies over the Indochina Peninsula, the SCS and Philippine Sea, and, wet condition along the Yangtze River valley to southern Japan. At lower troposphere, a dominant feature is an anomalous anticyclone with enhanced southwesterly winds prevailing on its northwestern flank from the northern SCS to the middle and lower reaches of the Yangtze River and enhanced easterly winds between 5°N and 20°N . The correlation between the AMJ SETIO SST index and time series of leading principal component (PC1) is significantly high (about 0.51), which indicates that the SST in the SETIO can be a predictor to East Asian climate in AMJ. Additionally, the correlation between previous winter (November–December–January) Niño 3.4 SST index and following late spring (AMJ) SETIO SST index is also significantly high

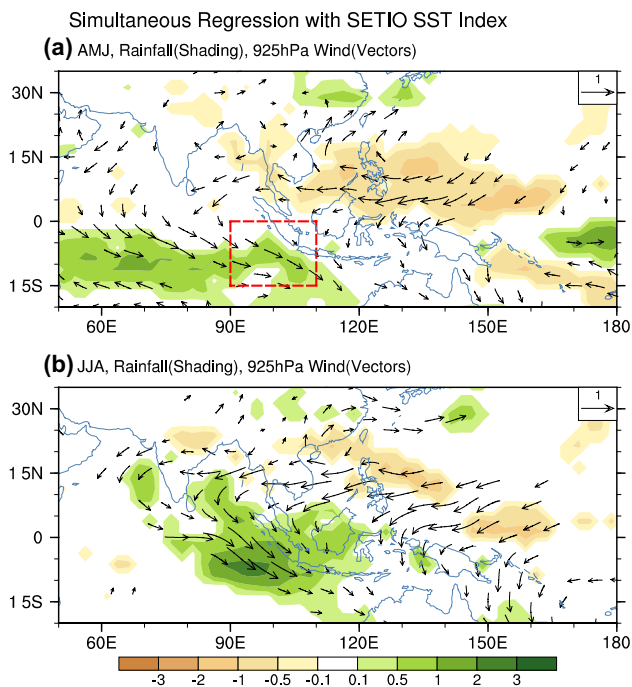


Fig. 11 Regression with the standardized SETIO SST index: precipitation (shading) and 925-hPa wind (vectors): **a** for AMJ, and **b** for JJA. The SETIO SST index is defined as the SST anomalies in the southeast tropical Indian Ocean (90°E–110°E, 15°S–0°)

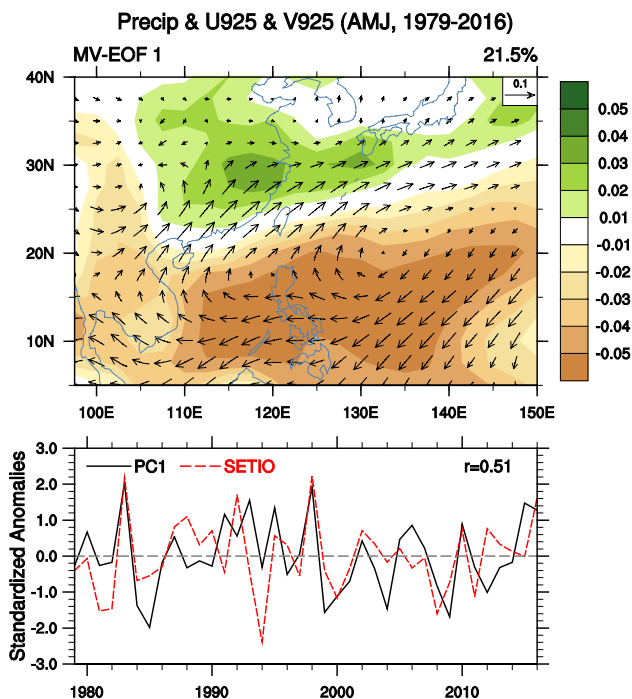


Fig. 12 Spatial pattern of leading MV-EOF mode of precipitation and 925-hPa wind in East Asia (5°N–40°N, 95°E–150°E) in AMJ (top panel). The principal component (black solid line) and SETIO SST index (red dash line) for the period 1979 to 2016 (low panel)

(about 0.65). The result indicates that the SETIO SST warming and cooling usually follow an ENSO event in the Pacific.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Chen W (2002) Impacts of El Niño and La Niña on the cycle of the East Asian winter and summer monsoon. *Chin J Atmos Sci (Chinese)* 26:595–610
- Chen Z, Wen Z, Wu R, Zhao P, Cao J (2014) Influence of two types of El Niños on the East Asian climate during boreal summer: a numerical study. *Clim Dyn* 43:469–481. doi:10.1007/s00382-013-1943-1
- Chen Z, Wen Z, Wu R, Lin X, Wang J (2016a) Relative importance of tropical SST anomalies in maintaining the western north pacific anomalous anticyclone during El Niño to La Niña transition years. *Clim Dyn* 46:1027–1041. doi:10.1007/s00382-015-2630-1
- Chen J, Wen Z, Wang X (2016b) Analysis of winter and spring precipitation over Southern China during 2015/2016 extreme El Niño. *Trans Atmos Sci (Chinese)* 39:813–826 b)
- Chou C, Huang L-F, Tu J-Y, Tseng L, Hsueh Y-C (2009) El Niño impacts on precipitation in the western North Pacific-East Asian sector. *J Clim* 22:2039–2057
- Du Y, Xie S-P, Huang G, Hu K-M (2009) Role of air-sea interaction in the long persistence of El Niño-induced North Indian Ocean warming. *J Clim* 22:2023–2038
- Du Y, Yang L, Xie S-P (2011) Tropical Indian Ocean influence on Northwest Pacific tropical cyclones in summer following strong El Niño. *J Clim* 24:315–322
- Fan L, Shin S-I, Liu Q, Liu Z (2013) Relative Importance of Tropical SST anomalies in forcing East Asian summer monsoon circulation. *Geophys Res Lett* 40:2471–2477. doi:10.1002/grl.50494
- Gent PR, Danabasoglu G, Donner LJ et al (2011) The Community climate system model version 4. *J Clim* 24: 4973–4991. doi:10.1175/2011JCLI4083.1
- He Z, Wu R (2014) Indo-Pacific remote forcing in summer rainfall variability over the South China Sea. *Clim Dyn* 42:2323–2337. doi:10.1007/s00382-014-2123-7
- He Z, Wu R, Wang W (2015) Signals of the South China Sea summer rainfall variability in the Indian Ocean. *Clim Dyn* 46:3181–3195. doi:10.1007/s00382-015-2760-5
- Hu KM, Huang G, Huang RH (2011) The impact of tropical Indian Ocean variability on summer surface air temperature in China. *J Clim* 24:5365–5377
- Hu W, Wu R, Liu Y (2014) Relation of the South China Sea precipitation variability to tropical indo-pacific SST anomalies during spring-to-summer transition. *J Clim* 27:5451–5467

- Huang R-H, Wu Y-F (1989) The influence of ENSO on the summer climate change in China and its mechanism. *Adv Atmos Sci* 6:21–32
- Hurrell JW, Hack JJ, Shea D, Caron JM, Rosinski J (2008) A new sea surface temperature and sea ice boundary dataset for community atmosphere model. *J Clim* 21:5145–5153. doi:10.1175/2008JCLI2292.1
- Kalnay E, Kanamitsu M, Kistler R et al (1996) The NCEP/NCAR 40-year reanalysis project. *Bull Am Meteor Soc* 77:437–471
- Klein SA, Soden BJ, Lau N-C (1999) Remote sea surface temperature variations during ENSO: evidence for a tropical atmospheric bridge. *J Clim* 12:917–932
- Kosaka Y, Xie S-P, Lau N-C, Vecchi GA (2013) Origin of seasonal predictability for summer climate over the Northwestern Pacific. *Proc Natl Acad Sci* 110:7574–7579
- Lau N-C, Nath MJ (2003) Atmosphere–ocean variations in the Indo Pacific sector during ENSO episodes. *J Clim* 16:3–20
- Lee EJ, Yeh SW, Jhun JG, Moon BK (2006) Seasonal change in anomalous WNPSH associated with the strong East Asian summer monsoon. *Geophys Res Lett* 33:L21702. doi:10.1029/2006GL027474
- Lin SJ (2004) A “vertically Lagrangian” finite-volume dynamical core for global models. *Mon Wea Rev* 132: 2293–2307. doi:10.1175/1520-0493(2004)132,2293:AVLFDC.2.0.CO;2
- Liu Z, Alexander MA (2007) Atmospheric bridge, oceanic tunnel and global climatic teleconnections. *Rev Geophys* 45:RG2005. doi:10.1029/2005RG000172
- Neale RB, Richter J, Park S, Lauritzen PH, Vavrus SJ, Rasch PJ, Zhang M (2013) The mean climate of the Community Atmosphere Model (CAM4) in forced SST and fully coupled experiments. *J Clim* 26:5150–5168. doi:10.1175/JCLI-D-12-00236.1
- Rayner NA, Parker DE, Horton EB et al (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J Geophys Res-Atmos*. doi:10.1029/2002JD002670
- Ropelewski CF, Halpert MS (1987) Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon Wea Rev* 115:1606–1626
- Taylor KE, Williamson D, Zwiers F (2000) The sea surface temperature and sea-ice concentration boundary conditions for AMIP II simulations. *PCMDI Rep* 60:28. <http://www-pcmdi.llnl.gov/publications/ab60.html>.
- Trenberth KE, Branstator GW, Karoly D, Kumar A, Lau N-C, Ropelewski CW (1998) Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *J Geophys Res* 103(C7):14291–14324
- Wang B (1992) The vertical structure and development of the ENSO anomaly mode during 1979–1989. *J Atmos Sci* 49:698–712
- Wang C (2002) Atmospheric circulation cells associated with the El Niño Southern Oscillation. *J Clim* 15:399–419
- Wang C, Weisberg RH (2000) The 1997–98 El Niño evolution relative to previous El Niño events. *J Clim* 13:488–501
- Wang C, Weisberg RH, Virmani J (1999) Western Pacific interannual variability associated with the El Niño–Southern Oscillation. *J Geophys Res* 104:5131–5149
- Wang B, Wu R, Fu X (2000) Pacific–East Asian teleconnection: how does ENSO affect East Asian climate? *J Clim* 13:1517–1536
- Wang C, Wang W, Wang D, Wang Q (2006) Interannual variability of the South China Sea associated with El Niño. *J Geophys Res* 111: C03023, doi:10.1029/2005JC003333
- Webster PJ, Magana VO, Palmer TN, Shukla J, Tomas RA, Yanai M, Yasunari T (1998) Monsoons: processes, predictability, and the prospects for prediction. *J Geophys Res* 103:14451–14510
- Weisberg RH, Wang C (1997) A western Pacific oscillator paradigm for the El Niño–Southern Oscillation. *Geophys Res Lett* 24:779–782
- Wu R, Yeh SW (2010) A further study of the tropical Indian Ocean asymmetric mode in boreal spring. *J Geophys Res* 115:D08101. doi:10.1029/2009JD012999
- Wu R, Hu Z-Z, Kirtman BP (2003) Evolution of ENSO related rainfall anomalies in East Asia. *J Clim* 16:3742–3758
- Wu R, Kirtman BP, Krishnamurthy V (2008) An asymmetric mode of tropical Indian Ocean rainfall variability in boreal spring. *J Geophys Res* 113:D05104. doi:10.1029/2007JD009316
- Wu B, Li T, Zhou T-J (2010) Relative contributions of the Indian Ocean and local SST anomalies to the maintenance of the Western North Pacific anomalous anticyclone during the El Niño Decaying Summer. *J Clim* 23:2974–2986
- Wu R, Yang S, Wen Z, Huang G, Hu K (2012) Interdecadal change in the relationship of southern China summer rainfall with tropical Indo-Pacific SST. *Theor Appl Climatol* 108:119–133. doi:10.1007/s00704-011-0519-4
- Xie P, Arkin PA (1997) Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull Am Meteor Soc* 78:2539–2558
- Xie S-P, Carton JA (2004) Tropical Atlantic variability: patterns, mechanisms, and impacts. Earth’s climate: the ocean–atmosphere interaction. *Geophys Monogr* 147:121–142
- Xie S-P, Zhou ZQ (2017) Seasonal modulations of El Niño-related atmospheric variability: Indo-western Pacific ocean feedback. *J Clim*. doi:10.1175/JCLI-D-16-0713.1
- Xie S-P, Annamalai H, Schott FA, McCreary JP (2002) Structure and mechanisms of south Indian Ocean climate variability. *J Clim* 15:867–878
- Xie S-P, Hu KM, Hafner J, Tokinaga H, Du Y, Huang G, Sampe T (2009) Indian Ocean capacitor effect on Indo-Western Pacific climate during the summer following El Niño. *J Clim* 22:730–747
- Xie S-P, Kosaka Y, Du Y, Hu KM, Chowdary J, Huang G (2016) Indowestern Pacific Ocean capacitor and coherent climate anomalies in post-ENSO summer: a review. *Adv Atmos Sci* 33:411–432. doi:10.1007/s00376-015-5192-6
- Yang J, Liu Q, Xie S-P, Liu Z, Wu L (2007) Impact of the Indian Ocean SST basin mode on the Asian summer monsoon. *Geophys Res Lett* 34:L02708. doi:10.1029/2006GL028571
- Yim SY, Yeh SW, Wu R, Jhun JG (2008) The Influence of ENSO on decadal variations in the relationship between the East Asian and Western North Pacific summer monsoons. *J Clim* 21:3165–3179
- Yu L, Jin X, Weller RA (2008) Multidecade Global Flux Datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables. Woods Hole Oceanographic Institution, OAFlux Project Tech. Rep. OA-2008-01, p 64
- Zhai P, Yu R, Guo Y, Li Q, Ren X, Wang Y, Xu W, Liu Y, Ding Y (2016) The strong El Niño in 2015/2016 and its dominant impacts on global and China’s climate. *Acta Meteorol Sin (Chinese)* 74:309–321. doi:10.11676/qxxb2016.049
- Zhan R, Wang Y, Lei X (2011) Contributions of ENSO and East Indian Ocean SSTA to the interannual variability of Northwest Pacific tropical cyclone frequency. *J Clim* 24:509–521
- Zhan R, Wang Y, Tao L (2014) Intensified Impact of East Indian Ocean SST Anomaly on tropical cyclone genesis frequency over the Western North Pacific. *J Clim* 27:8724–8739
- Zhang R, Sumi A, Kimoto M (1996) Impact of El Niño on the East Asian monsoon: a diagnostic study of the ‘86/87 and ‘91/92 events. *J Meteor Soc Jpn* 74:49–62
- Zhang R, Sumi A, Kimoto M (1999) A diagnostic study of the impact of El Niño on the precipitation in China. *Adv Atmos Sci* 16:229–241
- Zhu J, Kumar A, Huang B, Balmaseda MA, Hu Z-Z, Marx L, Kinter JL III (2016) The role of off-equatorial surface temperature anomalies in the 2014 El Niño prediction. *Sci Rep* 6:19677. doi:10.1038/srep19677