Strengthened Relationship between Eastern ENSO and Summer Precipitation over Northeastern China

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ABSTRACT

This paper reveals a strengthened relationship between the spring eastern ENSO and summer precipitation over northeastern China (NEC) after the late 1990s. The relationship of the spring eastern ENSO with summer NEC precipitation is insignificant during 1983–97, whereas it becomes significantly positive during 1998–2012. In the earlier period, a zonal tripolar pattern in the middle to high latitudes of the North Asia–Pacific region and an anomalous anticyclone over Japan are the main factors responsible for NEC summer precipitation, although these atmospheric patterns have a weak correlation with the spring eastern ENSO. However, the atmospheric circulation that influences precipitation in NEC develops into the Siberian high and an anomalous cyclone over NEC after the late 1990s, which are strongly correlated with the spring eastern ENSO. The changes in associated atmospheric circulation partially contribute to the strengthening of the eastern ENSO–precipitation relationship. Additionally, the eastern ENSO signals persist from spring to summer via the tropical Indian Ocean (TIO) and a dramatic warming trend occurs in the TIO after the late 1990s. Observations and numerical simulations indicate that the circulation anomaly induced by warming in the TIO acts as a bridge linking the eastern ENSO and precipitation after the late 1990s. The northern Hadley and Ferrell cell anomalies associated with the TIO SST anomaly are much more significant and extend farther north to the midlatitudes, and the associated divergence anomalies centers shift from the tropical central Pacific to western Pacific; those further influence the NEC precipitation through modulation to the atmosphere circulation (e.g., geopotential height, horizontal wind, and moisture transport).

1. Introduction

El Niño–Southern Oscillation (ENSO) refers to a cycle of anomalous warm and cold sea surface temperatures (SSTs) in the tropical central and eastern Pacific. Previous studies have shown a close relationship between ENSO and East Asian climate (Li 1989; Liu and Ding 1992; Gong and Wang 1999; Wang 2000; Huang et al. 2004; Lau and Nath 2006; Su et al. 2013). Li (1990) reported that anomalous atmospheric circulation caused by El Niño events contributes to a weaker East Asian winter monsoon (EAWM) and that a strong EAWM might in turn cause an El Niño event. Using observed data, both Huang and Wu (1989) and Jin and Tao (1999) showed the effects of different stages of the ENSO cycle on summer precipitation in east China. Earlier studies have also shown that the influence of ENSO on precipitation in China varies between different subregions (Lau and Weng 2001; Wu et al. 2003). Furthermore, ENSO might affect the mei-yu precipitation in the...
Yangtze River valley through the East Asian–Pacific (EAP) teleconnection pattern (Zong et al. 2008). Zhou et al. (2010) reported that ENSO dominates winter precipitation over south China by inducing upper-level temperature anomalies. Based on data analysis and simple ocean data simulations, Chen et al. (2012) noted that the ENSO cycle influences climate anomalies within China through heat transport in zonal and meridional directions via an “atmospheric bridge” and that, during the mature and decaying phases of an El Niño event, precipitation in northern China decreases significantly. Liang et al. (2013) showed that ENSO influences the onset of the South China Sea summer monsoon through the modulation of the western Pacific subtropical high and associated convection.

Gu et al. (2009) examined the interdecadal changes in the relationship between the North Atlantic Oscillation and east China’s summer precipitation patterns occurring in 1905, 1925, and 1950. Additionally, recent studies have revealed significant changes in summer meridional teleconnection over western North Pacific and East Asia (Lin et al. 2010), as well as in the summer moisture circulation over China (Li et al. 2011) in the late 1970s. Recently, there has been increasing interest in the decadal changes in the relationship between ENSO and climatic variability in East Asia (Wang 2002; Yim et al. 2008; Ye and Lu 2011; He et al. 2013). For example, both Wang and He (2012) and Wang et al. (2013) discussed the weakening of the EAWM–ENSO relationship around the mid-1970s, based on observational analyses and model simulations. Analysis of long-term data has indicated that the EAWM–ENSO relationship exhibits a low-frequency oscillation (Zhou et al. 2007). He and Wang (2013) attributed this oscillating relationship to the combined effects of the Pacific decadal oscillation (PDO) and the Atlantic multidecadal oscillation. Additionally, the East Asian summer monsoon circulation associated with ENSO has undergone a remarkable decadal change (Wang 2001). Previous work has shown that instabilities exist in the relationship between ENSO and the summer climate in China (Wang 2002). Hui et al. (2006) detected a weak connection between ENSO and summer precipitation in China after the 1980s. Su and Wang (2007) revealed decadal changes in the correlation between ENSO and variations in droughts and wet spells in China. Recently, Zong et al. (2010) explored the links between summer precipitation in China and ENSO, and they found that such links are more unstable in northeastern and northwestern China than in eastern China. Such unstable relationships make predictions of summer precipitation in China challenging.

Precipitation in northeastern China (NEC) is generally affected by signals from the middle and high latitudes as well as from the tropical oceans. Previous studies have shown that cold vortices, the northwestern Pacific subtropical high, and the East Asian summer monsoon are important contributors to summer precipitation in NEC (Sun et al. 2007; Zhao and Sun 2007; Shen et al. 2011; Han et al. 2015). Zhu (2011) proposed that the soil moisture content in northwestern Eurasia and the 500-hPa geopotential height over NEC during the preceding spring are good indicators for predicting summer precipitation in NEC. Moreover, it has been suggested that antecedent SST anomalies in some critical areas (e.g., the southwest Indian Ocean, the northern and equatorial Atlantic Ocean, and the North Pacific) have an influence on summer precipitation in NEC (Bai 2001; Feng et al. 2006). ENSO is also considered a principal factor in the climatic variability of NEC (Sun and Wang 2006). Furthermore, Wu et al. (2003) revealed that the correlation of ENSO with seasonal mean precipitation in NEC is unstable. Chen et al. (2006) found that summer precipitation in southern parts of NEC was closely associated with concurrent SST anomalies in the tropical central and eastern Pacific. Nevertheless, based on atmospheric general circulation model experiments, Chang et al. (2013) noted that summer precipitation in northeast Asia has a slight linear variation in association with the variation of SST in the central to eastern tropical Pacific. Therefore, it is of particular importance to investigate the relationship between ENSO and summer precipitation in NEC. Given that winter ENSO has a weak correlation with precipitation in NEC (figure not shown), the focus of this paper is on spring ENSO.

The remainder of this paper is structured as follows. Section 2 introduces the datasets used. Section 3 illustrates the strengthening of the ENSO–precipitation relationship and the associated atmospheric and oceanic circulation anomalies. Possible reasons for the strengthened relationship and the results of numerical simulations are analyzed in sections 4 and 5, respectively. Finally, brief conclusions and discussions are presented in section 6.

2. Data

We use global monthly atmospheric reanalysis data for 1948–2012, with a resolution of 2.5° × 2.5°, from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996). Horizontal wind, geopotential height, specific humidity, vertical velocity, divergence, vertically integrated moisture flux, precipitable water vapor, and total cloud cover were analyzed. The National Oceanic and Atmosphere Administration (NOAA) Extended Reconstructed SST
V3b for 1854–2012 (Smith et al. 2008) with a 2.0° × 2.0° latitude/longitude grid was used for the monthly SST dataset. An advanced monthly precipitation observation dataset over China (CN05.1; Wu and Gao 2013), was also used in the study. This dataset is constructed for 1961–2012 based on an interpolation from over 2400 observation stations in China and has a relatively high resolution of 0.5° × 0.5°. A second precipitation dataset, NOAA's Precipitation Reconstruction over Land (PREC/L) with a resolution of 1.0° × 1.0° for 1948–2012 (Chen et al. 2002) was also used. The common period adopted in this study was 1961–2012.

The NEC summer precipitation index (hereafter shortened to “Precip index”) is defined by the normalized, area-averaged summer precipitation within NEC (38°–55°N, 115°–135°E), based on the CN05.1 dataset. Given that SST anomalies associated with precipitation are mainly restricted to the tropical eastern Pacific (figure not shown), the spring Niño-3 index is computed as the area-averaged SST in spring over the tropical eastern Pacific (5°S–5°N, 150°–90°W), and it is used to describe eastern ENSO events (available at https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Niño3/). Spring and summer in this study were defined as the means for the months of March–May and June–August, respectively. The Student’s t test was used to detect statistical significance. Additionally, linear trends were eliminated before performing the correlation and regression analyses.

3. Strengthening of the eastern ENSO–precipitation relationship

The time evolutions of the spring Niño-3 and the summer precipitation indices are presented in Fig. 1a. The correlation coefficient between the two indices is low (0.19) over the period 1961–2012, implying that the eastern ENSO–precipitation relationship is weak. Further analysis shows that strong in-phase variability between the two indices can be identified after the late 1990s. Figure 1b depicts the 15-yr sliding correlation coefficients between the two indices. This figure shows that the correlation between NEC summer precipitation and spring Niño-3 indices varies with time and that the positive correlation becomes statistically significant after the late 1990s (R = 0.73, significant at the 99% confidence level). The 17- and 19-yr sliding correlations both show similar results (figures not shown), confirming that the strengthened eastern ENSO–precipitation relationship in the late 1990s is robust.

Two periods, 1983–97 (P1) and 1998–2012 (P2), were selected based on Fig. 1 to examine the spatial distribution of correlation coefficients between the spring Niño-3 index and NEC summer precipitation, using the CN05.1 gridded data and the PREC/L reanalysis data, respectively. Consistent changes can be observed between these two datasets (Fig. 2). During P1, the correlations do not show any large-scale areas of significance over NEC in response to a positive Niño-3 index, whereas during P2 significant positive correlations are present over most of NEC. These results demonstrate the enhanced influence of the spring eastern ENSO on summer precipitation in NEC after the late 1990s.

Figure 3 depicts the linear regression patterns of summer 850-hPa horizontal wind and 500-hPa geopotential height with the spring Niño-3 index for the two sub-periods. During P1, a positive Niño-3 index is characterized by a meridional dipolar pattern of wind anomalies over the western North Pacific in the lower troposphere (Fig. 3c). Anomalous northerlies dominate western NEC and prevent the transport of subtropical water vapor to NEC. In the middle troposphere, significant negative height anomalies stretch from eastern NEC to the North Pacific, accompanied by zonally positive anomalies over the region south of 30°N (Fig. 3a). During 1983–97, a positive precipitation anomaly coincides with a zonal tri-polar circulation pattern in the middle to high latitudes over the North Asia–Pacific region, characterized by
anomalous highs over central Siberia and the Aleutian Islands and an anomalous depression over the Okhotsk Sea (Fig. 4a). An anticyclone over Japan also influences NEC summer precipitation. Comparatively, the spring Niño-3-related circulation pattern differs from that associated with the NEC summer precipitation, demonstrating a weak relationship between the eastern ENSO and NEC precipitation.

Marked changes occurred during P2. In the lower troposphere, the meridional dipolar wind pattern over the western North Pacific shifts westward, with cyclonic wind anomalies over NEC and anticyclonic wind anomalies over the Philippines (Fig. 3d). The south-easterly flow in the southwest flank of the anticyclone centered over the North Pacific extends westward over NEC, favoring the transport of water vapor from the North Pacific to NEC. In the midtroposphere, the abnormal positive geopotential height over Siberia is spatially broader and quantitatively larger than during P1 (Fig. 3b). The midtroposphere also experiences significant positive anomalies in the tropics and weak negative values over NEC. In 1998–2012, when precipitation shows a positive anomaly, a pattern of positive–negative–positive anomalies can also be observed along East Asia in the midtroposphere (Fig. 4b), together with a cyclone centered over western NEC in the lower troposphere (Fig. 4d). The spring Niño-3-related circulation pattern agrees with that associated with NEC summer precipitation anomaly. Therefore, the relationship between the eastern ENSO and summer precipitation in NEC becomes significant after the late 1990s.

The anomalous circulation pattern is strongly linked to anomalous divergence circulation. The eastern ENSO-related divergence circulation patterns in the lower and upper troposphere in summer appear to undergo remarkable changes over different periods. During P1, when an eastern Pacific El Niño occurs, the lower- and upper-level divergence circulation anomalies are both insignificant over NEC, with no evident vertical
motion produced (figures not shown). During P2, the most remarkable changes are the occurrences of significant lower-level convergence and upper-level divergence over NEC (Figs. 5a,b). Accordingly, the anomalous divergence circulation patterns further excite strong anomalies of ascent over NEC according to the continuity equation (Fig. 5c). Enhanced upward motion and increased moisture content (Fig. 6d) lead to increased total cloud cover (Fig. 5d), which generally leads to enhanced summer precipitation over NEC.

![Figure 3](image-url)  
**FIG. 3.** Regression maps of summer (a),(b) 500-hPa geopotential height (HGT500; m) and (c),(d) 850-hPa wind field (UV850; m s⁻¹) against the spring Niño-3 index during (left) 1983–97 and (right) 1998–2012. Dark (light) shading indicates significant values at 95% (90%) confidence level based on the Student’s t test.

![Figure 4](image-url)  
**FIG. 4.** As in Fig. 3, but for precipitation.
We also investigated changes in the eastern ENSO-related moisture conditions in summer. During P1, a positive Niño-3 index is followed by anomalous moisture divergence over the subtropical western Pacific, together with anomalous southwesterly flows prevailing over the Yangtze River valley and South China (Fig. 6a). The significant northerly flow is positioned only over southern NEC. Therefore, the anomalous lower-level specific humidity and precipitable water content are insignificant over NEC, excluding the small southeast region (Figs. 6c,e). During P2, an anomalous moisture convergence center occupies southern NEC and moisture divergence centers over the South China Sea (Fig. 6b), which is concordant with the anomalous wind field in the lower troposphere (Fig. 3d). Thus, lower-level specific humidity and precipitable water vapor increase significantly over NEC (Figs. 6d,f).

The results presented here indicate a strengthened relationship between the spring eastern ENSO and summer precipitation over NEC in the late 1990s. There is a weak correlation between the two factors in 1983–97 and a significant in-phase relationship in 1998–2012. Such changes can be detected in the ENSO-related horizontal winds, geopotential height, divergence circulation, vertical movement, total cloud cover, and moisture conditions over NEC. The results based on the NCEP–NCAR reanalysis dataset are similar to those based on the ERA-Interim reanalysis dataset (figures not shown).

4. Possible mechanisms for the strengthened eastern ENSO–precipitation relationship

a. Changes in regimes influential to NEC summer precipitation

Figures 7a and 7c depict the first two principal empirical orthogonal function (EOF) modes of 500-hPa geopotential height (HGT500) over the East Asia–Pacific...
FIG. 6. Regression maps of summer (a),(b) vertically integrated moisture flux \( \text{kg m}^{-3} \text{s}^{-1} \), (c),(d) 850-hPa specific humidity \( \text{g kg}^{-1} \), and (e),(f) precipitable water content \( \text{kg m}^{-2} \) against the spring Niño-3 index for (left) 1983–97 and (right) 1998–2012. Dark (light) shading indicates significant values at 95% (90%) confidence level based on the Student’s \( t \) test.
The purpose of EOF analyses is to reduce the dimensionality of a dataset while preserving the majority of the variation (Jolliffe 2002). The leading EOFs should describe the spatially coherent pattern that maximizes its variance. Here, the first EOF (EOF1) mode features higher (lower) geopotential height anomalies than normal in the Arctic (Aleutian Islands) and relatively weak positive anomalies in the tropics (Fig. 7a). The second EOF (EOF2) mode displays a zonal tripolar pattern in the middle to high latitudes (Fig. 7c). In addition, during P1, the atmospheric anomalies associated with summer precipitation also display a zonal tripolar pattern in the middle to high latitudes of the East Asia–Pacific region (Fig. 4a), consistent with the EOF2 mode. The spring Niño-3-related signals are mainly restricted to the tropical to midlatitude oceans (Fig. 3a). Therefore, the connection between the spring ENSO and NEC summer precipitation is weak before the late 1990s.

The EOF1 and EOF2 of HGT500 during P2 show quite different patterns from those during P1. The most conspicuous feature of the EOF1 is the appearance of negative–positive–negative–positive height anomalies from the Arctic to the tropics (Fig. 7b). The EOF2 mode is characterized by a zonal tripolar pattern in the high latitudes of the East Asia–Pacific region, with positive anomalies in the Arctic and in the tropics (Fig. 7d). In addition, during P2, the Siberian high and the cyclone centered over western NEC strongly impact NEC summer precipitation (Figs. 4b,d). Comparatively, the EOF1 mode is consistent with the main regimes influencing NEC summer precipitation. The spring Niño-3-related signals expand westward to East Asia and northward to North Asia (Figs. 3b,d), followed by significant height anomalies over Siberia and wind anomalies over NEC. The changes in precipitation-related atmospheric circulation pattern contribute to the strengthened connection between the spring eastern ENSO and summer precipitation over NEC after the late 1990s.

### b. Role of tropical Indian Ocean SST

We examined the eastern ENSO-related SST anomalies by regressing SST onto the spring Niño-3 index (Figs. 8a,b). For both periods, a positive Niño-3 index is characterized by warm SST anomalies in the equatorial central–eastern Pacific and cool anomalies in the western region during P1. The purpose of EOF analyses is to reduce the dimensionality of a dataset while preserving the majority of the variation (Jolliffe 2002). The leading EOFs should describe the spatially coherent pattern that maximizes its variance. Here, the first EOF (EOF1) mode features higher (lower) geopotential height anomalies than normal in the Arctic (Aleutian Islands) and relatively weak positive anomalies in the tropics (Fig. 7a). The second EOF (EOF2) mode displays a zonal tripolar pattern in the middle to high latitudes (Fig. 7c). In addition, during P1, the atmospheric anomalies associated with summer precipitation also display a zonal tripolar pattern in the middle to high latitudes of the East Asia–Pacific region (Fig. 4a), consistent with the EOF2 mode. The spring Niño-3-related signals are mainly restricted to the tropical to midlatitude oceans (Fig. 3a). Therefore, the connection between the spring ENSO and NEC summer precipitation is weak before the late 1990s.

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Pacific. Such SST anomalies in the equatorial Pacific are maintained well into summer during P1 but weaken substantially during P2 (Figs. 8c,d). We hypothesize that SST elsewhere may conserve the eastern ENSO signals into summer during P2. Figure 8 suggests that SST in the tropical Indian Ocean has an intimate link with the eastern ENSO events, which is consistent with previous studies (Nigam and Shen 1993; Klein et al. 1999). Sea surface temperature anomalies during spring are stronger and expand longitudinally in the tropical Indian Ocean (TIO) during P2 than during P1 (Figs. 8a,b). We defined the spring and summer SST_Indian indices as the normalized area-averaged SST during spring and summer in the TIO (rectangles in Figs. 8b,d), respectively. The correlation coefficient between the two SST_Indian indices is 0.73 throughout the entire period. The 15-yr sliding correlation coefficients between these two indices also imply strong persistence of SST anomalies in the TIO from spring to summer (Fig. 9a). On the other hand, the 15-yr sliding correlation between the Niño-3 and summer SST_Indian indices shows a consistent in-phase variability after the 1970s, with a correlation coefficient of approximately 0.59 for 1961–2012 (Fig. 9b). In addition, the sliding correlation coefficients between the precipitation and summer SST_Indian indices are negative and not significant from the mid-1970s to the 1990s, but become positive after the 1990s. The positive correlation coefficients increase sharply and become significant. These results indicate that the eastern ENSO signals persist from spring to the following summer via the TIO, while

![Fig. 8. Regression maps of (a),(b) spring and (c),(d) summer SST (°C) against the spring Niño-3 index during (left) 1983–97 and (right) 1998–2012. Dark (light) shading indicates significant values at 95% (90%) confidence level based on the Student’s t test.](image)

![Fig. 9. (a) The 15-yr sliding correlation coefficients between the spring and summer SST in the tropical Indian Ocean indices. (b) The 15-yr sliding correlation coefficients between the spring Niño-3 and summer SST in the tropical Indian Ocean (SST_Indian) indices (dotted line) and between the precipitation and summer SST_Indian indices (solid line). The horizontal dashed lines indicate the standard for 95% significance, as estimated by the Student’s t test.](image)
the summer TIO SST has an intensified linkage to the simultaneous precipitation in NEC after the late 1990s. Therefore, the spring eastern ENSO exerts an enhanced influence on NEC precipitation during the following summer after the late 1990s.

To further illustrate the strong influence of the TIO SST anomaly on NEC summer precipitation after the late 1990s, we examined the atmospheric circulation anomalies associated with the summer SST_Indian index in this section (Fig. 10). During P2, a positive SST_Indian index is associated with significant positive height anomalies over Siberia and the tropics and weak negative height anomalies over NEC (Fig. 10a). Additionally, a zonally elongated anticyclonic wind anomaly in the lower troposphere is observed over the subtropical western Pacific (Fig. 10b). To the north of this anticyclone is an anomalous cyclone around NEC. This anomalous anticyclone and cyclone pair determines moisture transport (Fig. 10c). Accordingly, moisture convergence over NEC is induced by the anomalous northwesterly and southeasterly winds. Meanwhile, moisture divergence over the Philippines is formed. The SST_Indian-associated regimes agree with those related to the Niño-3 index, which influence precipitation over NEC after the late 1990s. When the eastern ENSO effect is removed, these SST_Indian-associated atmospheric anomalies are also exhibited (Fig. 11). Thus, the eastern ENSO exerts an impact on the NEC precipitation in the following summer via the tropical Indian Ocean in the latter period.

A relevant question is therefore raised: what accounts for the decadal strengthened influence of the TIO on the atmospheric circulations associated with NEC precipitation? Figure 12 displays the linear regression of the zonal mean mass streamfunction against the summer SST_Indian index for the two subperiods. In the following analysis of the possible mechanism by which the SST_Indian influences NEC precipitation, we removed the eastern ENSO effect by excluding the linear regression with regard to the spring Niño-3 index. During P1, the positive summer SST_Indian index is concurrent with insignificant northern Hadley and Ferrell cells. By contrast, during P2, the northern Hadley cell is quantitatively larger and spatially broader. Notably, the northern Ferrell cell becomes significant and expands poleward. This implies that the SST_Indian may have an enhanced effect on the atmospheric circulation associated with NEC precipitation through northern cell circulations, which favors the connection between the tropical and midlatitude systems. Figure 13 illustrates features of the anomalous velocity potential and divergent winds in the lower and upper troposphere related to the summer SST_Indian index. During P1, the positive summer SST_Indian

FIG. 10. Regression maps of summer (a) HGT500 (m), (b) UV850 (m s$^{-1}$), and (c) vertical integral of moisture flux (kg m$^{-1}$ s$^{-1}$) against the summer SST_Indian index during 1998–2012. Dark (light) shading indicates significant values at 95% (90%) confidence level based on the Student’s $t$ test.
index features a prominent convergent center over the tropical central Pacific and a divergent center over the tropical western Indian Ocean in the upper troposphere (Fig. 13a). Correspondingly, a dominant divergent center is present over the tropical central Pacific and a convergent center is located over the Arabian Sea in the lower troposphere (Fig. 13b). During P2, the anomalous upper-level convergent center and lower-level divergent center shift westward from the tropical central Pacific to the tropical western Pacific (Figs. 13c,d), which induce the westward shift of anomalous wind field and moisture divergence anomalies above it (Figs. 3d, 6b, 10b,c, and 11b,c), and thus the Niño-3-related signals expands westward.

It is speculated that the decadal change in background SST in the TIO may be responsible for the changes in the SST_Indian-related atmospheric circulation anomalies. Figures 14a and 14b show the EOF1 mode of the background SST during spring in the TIO and the time series of the first principal component (PC1). The SST EOF1 mode features uniform variability in the TIO. The PC1 shifts to a positive phase after the late 1980s. Notably, a dramatic upward trend occurs after the late

**Fig. 11.** After removing the linear influence of ENSO, the regression maps of summer (a) HGT500 (m), (b) UV850 (m s$^{-1}$), and (c) vertical integral of moisture flux (kg m$^{-1}$ s$^{-1}$) against the summer SST_Indian index during 1998–2012. Dark (light) shading indicates significant values at 95% (90%) confidence level based on the Student’s t test.

**Fig. 12.** After removing the linear influence of ENSO, the regression maps of summer zonal mean streamfunction ($10^7$ kg s$^{-1}$) against the summer SST_Indian index during (a) 1983–97 and (b) 1998–2012. Dark (light) shading indicates significant values at 95% (90%) confidence level based on Student’s t test.
1990s, implying a warming trend occurring in the TIO after that. The difference in spring and summer SSTs also show profound warming in the TIO (Figs. 14c,d). The change in the mean SST may be one of the possible reasons that lead to the strengthening of the TIO’s influence on the atmospheric circulations associated with NEC precipitation. The role of TIO warming will be tested using numerical simulation in the next section.

5. Numerical simulations

We conducted simulations to test the role of warming in the TIO using the global Community Atmosphere Model version 4 (CAM4) (Gent et al. 2011). CAM4 is the atmospheric component of the Community Earth System Model, with finite-volume dynamics and 26 hybrid sigma pressure levels. The “F_2000” component set was chosen with prescribed climatological SST and sea ice for the period 1981–2001, and with an active land model. The atmospheric composition was held constant at year 2000 values, with an atmospheric CO$_2$ concentration of 367 ppm throughout the simulation. One control run was performed using the model’s climatological SST and sea ice as boundaries. One sensitivity experiment was similar to the control run, but it was superposed with the differences in spring and summer SSTs between 1998–2012 and 1983–97 in the tropical Indian Ocean (i.e., SST anomalies in the area surrounded by the thick lines in Figs. 8b,d). Each run was integrated for 30 years, and the results for the last 15 years were analyzed.

Figure 15 illustrates the differences between the sensitivity and control experiments for the midlevel geopotential height, lower-level horizontal wind, moisture divergence, specific humidity, vertical velocity, total cloud, and total precipitable water in summer. The model is able to reproduce the main features of the strong positive height over Siberia in the middle layer and the cyclonic wind field over NEC in the lower layer. Convergence of moisture flux is detected over NEC, especially over the eastern region. Additionally, greater humidity and ascent facilitate increased total cloud cover over NEC, leading to enhanced formation of precipitable water, which are also reproduced in the simulation. The simulated circulation is qualitatively similar to the observations. The simulation confirms that warming in the TIO after the late 1990s leads to the strengthening of the eastern ENSO–precipitation relationship through anomalous atmospheric circulations influencing the NEC precipitation.

The discrepancy between the model simulation and observations might be attributable to the differences between the idealized SST used in the simulation and the real SST variability. Nevertheless, the simulation generally reproduces the major features of the circulation over East Asia, forced by the SST anomalies in the tropical Indian Ocean.

6. Discussion and conclusions

This investigation analyzed the strengthening of the relationship between the spring eastern ENSO and summer
precipitation in NEC after the late 1990s. Their correlation is not significant during 1983–1997 (P1), whereas it becomes statistically significant during 1998–2012 (P2). The related atmospheric circulation patterns are also analyzed. During P1, the contributors to summer precipitation over NEC are the anomalous anticyclone centered over Japan and the zonal tripolar pattern in the middle to high latitudes of the Asia–Pacific region, which is consistent with the EOF2 mode of atmospheric circulation over the East Asia–Pacific region. The spring Niño-3-related signals are mainly confined to the tropical to midlatitude oceans. Therefore, the circulation pattern associated with precipitation is weakly related to the spring eastern ENSO. Comparatively, during P2, the atmospheric circulation regimes governing NEC summer precipitation develop to the Siberian high and a cyclone centered over western NEC, which is consistent with the EOF1 mode of atmospheric circulation over the East Asia–Pacific region. Meanwhile, the spring Niño-3-related signals expand westward to East Asia and northward to North Asia. The precipitation-related regimes are closely linked to the spring eastern ENSO. Additionally, the eastern ENSO-related divergence circulation, vertical movement, total cloud cover, and moisture conditions also exert considerable influence on summer NEC precipitation. Changes in the spring Niño-3- and precipitation-related atmospheric circulation patterns contribute partially to the strengthened connection between the spring eastern ENSO and summer NEC precipitation after the late 1990s.

The eastern ENSO-related SST anomalies weaken substantially in the tropical eastern Pacific during P2, which may persist to summer via the TIO. A dramatic warming trend occurs in the tropical Indian Ocean after the late 1990s. Numerical simulation results and observations show that the warming in the TIO leads to the strengthening of the east ENSO–precipitation relationship through the anomalous atmospheric circulations associated with NEC precipitation (e.g., geopotential height, horizontal wind, moisture transport), which is associated with the poleward expansion and intensification of the TIO-related Hadley and Ferrell cells in the Northern Hemisphere and the westward shift of the associated divergence anomalies centers from the tropical central Pacific to the tropical western Pacific. Together, these conditions contribute to the strengthened influence of the spring eastern ENSO on summer precipitation in NEC.

In addition, the interdecadal Pacific Oscillation (IPO), or the PDO, is the ENSO-like multidecadal climate variation (Zhang et al. 1997; Mantua et al. 1997). The IPO and PDO possess essentially the same decadal variability (Deser et al. 2004), with the IPO covering the whole Pacific basin and the PDO defined within the North Pacific. ENSO’s impacts on regional climate can be modulated by the IPO or PDO (Gershunov and Barnett 1998;
As suggested by Wang et al. (2008), when the PDO is in its low (high) phase, the ENSO-related midlatitude atmospheric responses are strong (weak) and significant (insignificant). Previous studies showed that both the IPO and PDO changed from a warm to a cold phase in the late 1990s (Deser et al. 2004; Zhu et al. 2011), which might partially contribute to the strengthened influence of ENSO on the atmospheric circulation pattern influencing NEC precipitation. As illustrated in Fig. 3, after the late 1990s, the spring Niño-3 index is followed by significant circulation anomalies over the middle to high latitudes of the East Asia–Pacific region. The related issue is beyond the scope of this study, and needs to be investigated further.
Global mean surface warming has stalled after the late 1990s (Allan et al. 2014). Previous studies showed that the ocean stores the heat missing from the atmosphere (Loeb et al. 2012; Drijfhout et al. 2014). Recently, Lee et al. (2015) proposed that during this hiatus, easterly trade winds over the eastern Pacific strengthened, leading to the accumulation of warm water in the western Pacific. This water seeped into the Indian Ocean via the Indonesian Throughflow, conveying heat with it. Consequently, Indian Ocean heat content increased abruptly and has accounted for more than 70% of the global ocean heat gain in the upper ocean during the past decade. It is speculated that the increased heat content might partially contribute to a warming trend in the TIO. However, the reasons for the warming trend in the TIO are complex. This interesting issue deserves further exploration but is beyond the scope of the present study.

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REFERENCES


