Changing Impact of ENSO Events on the Following Summer Rainfall in Eastern China since the 1950s

LINYUAN SUN,a XIU-QUN YANG,a LINGFENG TAO,a JIABEI FANG,a AND XUGUANG SUNa

* China Meteorological Administration–Nanjing University Joint Laboratory for Climate Prediction Studies, School of Atmospheric Sciences, Nanjing University, Nanjing, China

(Manuscript received 9 January 2021, in final form 26 May 2021)

ABSTRACT: El Niño–Southern Oscillation (ENSO) events, which generally mature in winter, profoundly affect the following summer rainfall in eastern China (ECSR), but such an impact can change significantly with decadal background. This study examines how the impact has changed since the 1950s by running correlation and regression analyses. It is found that ENSO’s impact on ECSR has undergone two decadal shifts, one in the late 1970s and the other in the 1990s. Sequentially, three distinct ENSO-induced ECSR anomaly patterns are categorized, which exhibit both robust and changeable sides. The robust side manifests generally as more precipitation in the Yangtze River basin affected by the anomalous tropical western North Pacific anticyclone (WNPAC) in the post–El Niño summer. The changeable side is reflected in the more variable ENSO-induced rainfall anomalies north of the Yangtze River, due to the different ENSO-induced East Asian midlatitude circulation anomalies. Meanwhile, the El Niño–induced drought in South China has been enhanced since the late 1970s with the intensification of the anomalous WNPAC. ENSO’s changing impact on the ECSR stems from the changes of ENSO-induced tropical and midlatitude circulation anomalies over East Asia, which are associated with different zonal (from the tropical Pacific to the Indian Ocean) and meridional (from the tropical Pacific to the midlatitude North Pacific) teleconnections of ENSO-induced SST anomalies. The former affects the intensity and location of the anomalous WNPAC by affecting the Indian Ocean capacitor effect and convection anomalies over the tropical Indo-western Pacific. The latter modulates the ocean-to-atmosphere feedback in the mid-latitude North Pacific, contributes to different local geopotential anomaly sources, and then directly or indirectly through the Rossby wave train affects the East Asian midlatitude circulation.

KEYWORDS: ENSO; Rainfall; Interannual variability; Teleconnections; Sea surface temperature; Atmospheric circulation

1. Introduction

Eastern China is located in the East Asian monsoon region. Modulated by the East Asian summer monsoon (EASM), the interannual variability of eastern China summer rainfall (ECSR) is large and can frequently cause droughts and floods, seriously affecting the economic and social development of eastern China. Accordingly, research on the mechanism and prediction of the ECSR’s interannual variability has been highly emphasized (Tao and Chen 1987; Ding 1992; Chen et al. 2004; Wu et al. 2009; Huang et al. 2012; Sun et al. 2017). As the most prominent interannual climate variability with global impacts (Bjerknes 1969; Rasmusson and Wallace 1983; Wang et al. 1999), El Niño–Southern Oscillation (ENSO) has great precursory significance on the EASM, and is regarded as the leading predictor for the ECSR anomalies (Zhang et al. 1996; Wang et al. 2000; Lau and Nath 2006).

Many previous research studies identified the impact of ENSO on ECSR, which is associated with the developing or decaying phase of an ENSO event (Huang and Wu 1989; Gong and Wang 1999; Lau and Weng 2001). Based on eight El Niño events during 1950–80, Huang and Wu (1989) reported a tri-pole rainfall anomaly pattern in the El Niño decaying summer, with drought in the Huaihe River basin and flooding in the Yangtze River basin and North China, while this tri-pole pattern is nearly reversed in the El Niño developing summer. Chang et al. (2000) further confirmed that the intense mei-yu front and more summer rainfall occurred in the Yangtze River basin after the preceding winter El Niño. Using nearly 50 years of data, Chen (2002) and Wu et al. (2003) also obtained consistent results by composite and correlation analysis, respectively. Following these pioneering studies, consensus can be reached that significant positive rainfall anomalies tend to occur over the Yangtze River basin in the post–El Niño summer, and this provides a key precursor for the summer rainfall prediction in China.

One of the linkages between ENSO and the following ECSR anomalies is the anomalous western North Pacific anticyclone (WNPAC) (Zhang et al. 1996; Wang et al. 2000; Lau and Nath 2006), which is the important circulation system that conveys the El Niño signal to affect the subsequent summer East Asian climate (Li et al. 2017). In the post–El Niño summer, the anomalous WNPAC indicates the intensification and westward extension of the western Pacific subtropical high. The southwesterly wind anomalies to its northwestern flank can strengthen the southwest monsoon flow and increase the northward moisture transport, thus causing enhanced mei-yu frontal rainfall along the Yangtze River basin (Zhang et al. 1996; Chang et al. 2000). Meanwhile, the anomalous WNPAC is also considered the tropical part of a meridional wave train along the East Asian coast, namely the Pacific–Japan (PJ) (Nitta 1987) or East Asia–Pacific (EAP) pattern (Huang and Li 1987), which connects the tropical and the midlatitude East Asian climate anomalies. Accordingly, various hypotheses

DOI: 10.1175/JCLI-D-21-0018.1

© 2021 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
are proposed to explain the formation and maintenance of the anomalous WNPAC, including the local air–sea interaction in the tropical northwestern Pacific (Wang et al. 2000), the capacitor effect induced by the positive sea surface temperature (SST) anomaly in the tropical Indian Ocean (Yang et al. 2007; Xie et al. 2009) and North Atlantic (Rong et al. 2010), the combination mode theory (Stuecker et al. 2015), and the moist enthalpy advection theory (Wu et al. 2017a,b). Recently, Zhang et al. (2017) and Li et al. (2017) both reviewed this issue and made a thorough summary and discussion of this topic.

However, with the changing decadal background, recent studies have revealed that the impact of ENSO on ECSR is changeable on interdecadal time scales (Wu and Wang 2002; Zong et al. 2010; Jin et al. 2016). One such change is that the relationship between ECSR and the preceding winter Niño-3 index has weakened since the 1970s, and ENSO’s predictive signature on the ECSR anomalies has also decreased remarkably (Gao et al. 2006). Zhu et al. (2007) investigated the interdecadal variation of the relationship between ENSO and summer climate variability in China, and found that after the late 1970s North China changed from wetter to dryer during the El Niño decaying phase while the Huaihe River basin changed from dryer to normal. Similarly, such a decadal shift also exists in the relationship between ENSO and the simultaneous summer Niño-3 index (Guo and Lang 2017), while the predictive significance revealed by simultaneous correlation is limited. All of these studies indicate that ENSO’s impact on ECSR has experienced obvious decadal shifts, thereby bringing great challenges to ENSO-based ECSR prediction.

Since the ECSR anomalies are directly affected by the variation of EASM circulation, the changing ENSO–ECSR relationship essentially reflects the interdecadal variation of interannual relation between ENSO and EASM (Kinter et al. 2002; Wang 2002; Yim et al. 2008; Shi and Wang 2019). Wu and Wang (2002) compared the different ENSO-related EASM anomalies between 1962–77 and 1978–93 and found that the rainfall in eastern North China during the post–El Niño summer changed from above to below normal in the latter epoch, while the associated anomalous WNPAC is enhanced and shifted to higher latitudes. Wang et al. (2008) further clarified an enhanced relation between the Asian-Australian monsoon and ENSO since the late 1970s, in which one important feature is the stronger anomalous WNPAC in the EASM region. In situ gauge observation and a 1000-yr simulation with a coupled climate model were also used to identify the interdecadal change in the ENSO–EASM relationship (Chowdary et al. 2012; Liu et al. 2018). Furthermore, the enhanced ENSO-related anomalous WNPAC is attributed to the stronger Indian Ocean capacitor effect in which the tropical Indian Ocean response to slowly decaying El Niño is strengthened (Xie et al. 2010; Huang et al. 2010).

Overall, the ENSO–EASM relationship has experienced a decadal shift since the late 1970s, which has substantially changed the impact of ENSO on ECSR. However, due to the limited data temporal coverage in previous studies, the ENSO-related ECSR anomaly pattern after the late 1970s is not clear enough. With the accumulation of updating observations, it is worth exploring whether new changes have occurred in ENSO’s impact on ECSR. Moreover, the enhanced anomalous WNPAC seems to be contradictory to the weakening predictive significance of ENSO on ECSR after the late 1970s, since, as mentioned above, ECSR is closely related to the WNPAC.

Ye and Lu (2011) tried to understand it from the view of subseasonal variations in the ENSO-related rainfall, but logically we should be able to explain it in seasonal time scale. Actually, as the typical monsoonal precipitation, ECSR is affected by both tropical and midlatitude signatures (Ding 1992; Simmonds et al. 1999; Chen et al. 2004; Huang et al. 2012), while the previous studies mainly examined the changes in ENSO-related tropical circulation (e.g., the intensified anomalous WNPAC since the late 1970s), the concurrent part in midlatitudes should also be investigated in different decadal backgrounds. Wu (2002) pointed out that ENSO can exert influences on the northern China rainfall via a midlatitude Asian wave train which arises from the ENSO-induced Indian monsoon heating anomalies, and this pathway also varies on interdecadal time scale (Wu and Wang 2002; Feng and Hu 2004). Thus, it needs to jointly consider the ENSO-related tropical and midlatitude circulation anomalies for fully understanding the changing impact of ENSO on ECSR.

This paper aims to systematically investigate the changing impact of ENSO on ECSR since the 1950s by identifying different ENSO-related ECSR anomaly patterns and associated tropical and midlatitude circulation anomalies in different decadal backgrounds, and by revealing the mechanisms behind the changes of circulation anomalies. The rest of this paper is organized as follows. Section 2 describes the data and methods used. Section 3 identifies the decadal shifts in the ENSO–ECSR relationship and presents three distinct ENSO-related ECSR anomaly patterns. Section 4 examines the associated tropical and midlatitude circulation anomalies over East Asia. Section 5 further explores the causes for the decadal shifts of ENSO-related circulation anomalies. The final section is devoted to a summary and discussion.

2. Data and methods

a. Data

The observed monthly precipitation dataset is obtained from the Chinese Meteorological Administration, including 160 stations in mainland China and covering nearly 70-yr temporal range from January 1951 to December 2018. We extract the data of 120 stations distributed east of 105°E and calculate the seasonal [June–August (JJA)] average to represent the eastern China summer rainfall (ECSR). The ENSO variability is measured by the oceanic Niño index (ONI), which is the most commonly used index to define El Niño and La Niña events, defined as the 3-month running mean of SST anomalies (SSTAs) in the Niño-3.4 region (5°N–5°S, 120°–170°W), based on centered 30-yr periods updated every 5 years to remove the warming trend (L’Heureux et al. 2013; available at https://www.cpc.ncep.noaa.gov/data/indices/oni.ascii.txt).

The reanalysis dataset mainly used in this paper is the Japanese 55-yr Reanalysis (JRA-55), the second global atmospheric
reanalysis conducted by the Japan Meteorological Agency (Kobayashi et al. 2015). The JRA-55 dataset covers a long time range (extending back to 1958) with a finer spatial resolution (1.25° latitude–longitude grids) and is more suitable for studying the interannual variability in East Asia (Harada et al. 2016). The monthly and daily mean variables used include geopotential height, wind, vertical velocity, precipitation, and air temperature. In particular, we process the 6-hourly data (horizontal wind, specific humidity, and surface pressure) to calculate the vertically integrated moisture flux for considering the synoptic-scale transport (Simmonds et al. 1999). We also utilize other reanalysis datasets to compare with JRA-55 for ensuring the robustness of results. They are the NCEP–NCAR Reanalysis 1 (hereafter simply NCEP) dataset at 2.5° spatial resolution covering from 1951 to 2018 (Kalmay et al. 1996) and the latest generation of ECMWF atmospheric reanalysis (ERA5) at 0.25° spatial resolution covering from 1951 to 2018 (Hersbach et al. 2020).

The monthly sea surface temperature is derived from the Hadley Centre Sea Ice and Sea Surface Temperature dataset version 1 (HadISST1) (Rayner et al. 2003), on a global 1° spatial resolution from January 1951 to December 2018. Additionally, the NOAA interpolated monthly-mean outgoing longwave radiation (OLR) dataset at 2.5° spatial resolution from January 1951 to December 2018. Generally, as pointed out by Wu et al. (2003), the pattern originally revealed by Huang and Wu (1989) becomes characterized by the warm-peak phase locked in boreal winter (DJF(0/1)) (Figs. 1a–c; Rasmusson and Carpenter 1982). It on and following summer ECSR is made to reveal the decadal shifts in ENSO–ECSR relationship. The main analysis method is regression, and the statistical significance is calculated with a two-tailed Student’s t test. Accounting for the autocorrelation of time-filtered series, the effective sample size \((T_{XY}^s)\) of the \(T\) observations is measured by the formula

\[
T_{XY}^s = T \frac{1 - r_X r_Y^p}{1 + r_X r_Y^p},
\]

where \(r_X\) is the lag-one autocorrelation of the series \(X_i\), and similarly for \(r_Y\) (Bretherton et al. 1999).

The wave activity flux (WAF) is used to illustrate the energy propagation of Rossby wave train associated with a particular teleconnection pattern. Here we use the wave activity flux \(W\) derived by Takaya and Nakamura (2001), which is phase-independent and applicable for stationary quasigeostrophic eddies on a zonally varying basic flow. The horizontal component of \(W\) is defined by the formula

\[
W = \frac{1}{2 \mathbf{U}} \left[ \mathbf{U} (\mathbf{\psi}_x^c - \mathbf{\psi}_x^s) + \mathbf{V} (\mathbf{\psi}_y^c - \mathbf{\psi}_y^s) \right],
\]

where \(\mathbf{U} = (\mathbf{U}, \mathbf{V})\) is the steady zonally varying basic flow and \(\mathbf{\psi}\) is the streamfunction anomaly calculated from regressed geopotential height anomalies through quasigeostrophic approximation.

For the midlatitude climate dynamics, the quasigeostrophic geopotential tendency equation, which is derived from the quasigeostrophic potential vorticity (QGPV) equation, is a powerful tool for diagnosing the seasonal-mean atmospheric response to the thermal and dynamical forcing (Fang and Yang 2016). Considering the leading role of transient eddy vorticity forcing \(F_{\text{eddy}}\) in maintaining the equivalent-barotropic geopotential height anomalies over the midlatitudes (Ting and Lau 1993; Fang and Yang 2016; Tao et al. 2020), the feedbacks of \(F_{\text{eddy}}\) anomalies are only discussed in this paper and can be demonstrated by the derivation relation following Fang and Yang (2016):

\[
\left[ f \nabla^2 + f \frac{\partial}{\partial p} \left( \frac{1}{\rho_0} \frac{\partial}{\partial \rho} \right) \right] \left( \frac{\partial \mathbf{\Delta \Theta}}{\partial t} \right) = \mathbf{\Delta F}_{\text{eddy}},
\]

where the overbar denotes the seasonal mean and \(\Delta\) denotes anomaly from its climatology; \(\theta\) is the geopotential, \(\sigma_\tau\) the static stability parameter \((\sigma_\tau = -\alpha \delta m \delta \partial p)\), and \(f\) the Coriolis parameter. The transient eddy vorticity forcing \(F_{\text{eddy}}\), which is determined by the convergence of vorticity flux transported by transient eddies, is expressed as \(F_{\text{eddy}} = -\nabla \cdot (\mathbf{V}_h \zeta)\), where \(\mathbf{V}_h\) is the horizontal wind, \(\zeta\) is the relative vorticity, and a prime denotes the 2–8-day filtering with Lanczos filter (Duchon 1979). Based on above relation, the tendency of geopotential anomaly \((\partial \mathbf{\Delta \Theta}/\partial t)\) induced by \(F_{\text{eddy}}\) anomalies can be numerically solved by the successive overrelaxation (SOR) method [see Tao et al. (2020) for more details]. Since the midlatitude synoptic-scale transient eddy is closely related to low-level atmospheric baroclinicity (Simmons and Hoskins 1978), we examine the atmospheric baroclinicity with Eady growth rate \((\sigma_{\text{Eady}})\) at 850 hPa, which is measured by \(\sigma_{\text{Eady}} = 0.31 f / \theta / \zeta / N\) (Lindzen and Farrell 1980).

3. Decadal shifts in the impact of ENSO on ECSR

El Niño features seasonal phase-locking behavior characterized by the warm-peak phase locked in boreal winter \([\text{DJF}(0/1)]\), decaying from the following spring, defined as March–May \([\text{MAM}(+1)]\), and dissipating in following summer \([\text{JJA}(+1)]\) (Fig. 1a–c; Rasmusson and Carpenter 1982). It determines the predictive significance of ENSO to the ECSR in \(\text{JJA}(+1)\). Here we first reexamine the correlation of seasonal-mean \([\text{DJF}(0/1)], \text{MAM}(+1), \text{and JJA}(+1)\) rainfall anomalies in eastern China with the \(\text{DJF}(0/1)\) ONI during 1951–2018. Generally, as pointed out by Wu et al. (2003), the robust positive correlation occurs in southeastern China in \(\text{DJF}(0/1)\) and expands to almost all of eastern China in \(\text{MAM}(+1)\) (Figs. 1d,e). But in \(\text{JJA}(+1)\), the tripole correlation pattern originally revealed by Huang and Wu (1989) becomes less significant in the prolonged data (Fig. 1f), which suggests that the impact of ENSO on ECSR is not changeable on interdecadal time scale, and decadal shifts may exist in the ENSO–ECSR relationship.

To reveal possible decadal shifts in the ENSO–ECSR relationship, we calculate the 21-yr running correlation between
ECSR anomalies and the DJF(0/+1) ONI from 1951 to 2018. As shown in Fig. 2, the running correlation patterns are gradually changing with time. The correlation patterns exhibit conspicuous changes north of the Yangtze River, whereas they are relatively robust in the Yangtze River and south of it. Specifically, in Northeast China, the correlations are dominantly positive in the early epochs, then turn to be negative since the 1970s, but appear to be positive again in southern Northeast China after the 1990s. During the first epoch, positive and negative correlations are observed in North China and the Huaihe River basin, respectively. But over time, the positive correlation in North China decreases and negative correlation even occurs in the western and northern North China during recent epochs. The negative correlation in the Huaihe River basin has weakened since the 1970s, and has changed to positive in the Huanghe–Huaihe area in recent 30 years. By contrast, the correlation in the Yangtze River basin is relatively robust with positive correlations occurring in all epochs, and the correlation in South China is basically negative and presents an overall strengthening trend. Thus, different from previous studies that pointed out that a decadal shift only occurred in the 1970s (Wu and Wang 2002; Zhu et al. 2007), we find that the ENSO–ECSR relationship has actually undergone two decadal shifts, in the late 1970s and again in the late 1990s.

To clearly identify the timing of decadal shifts and further determine the representative epochs for different typical ENSO–ECSR relationships, we divide mainland China into six subregions and then calculate 21-yr running correlations of each region-averaged JJA(+1) rainfall anomalies with the DJF(0/+1) ONI (Fig. 3). According to the regional features of the changing ENSO–ECSR relationship shown in Fig. 2, the six subregions are northern Northeast China, southern Northeast China, North China, the Huanghe–Huaihe area, the Yangtze River basin, and South China (station distribution for each region shown in left panel of Fig. 3). Consistent with Fig. 2, North and Northeast China present significant positive
correlations before the 1970s, followed by an obvious weakening after the mid-1970s and negative correlations in the 1980s (Figs. 3a–c). Until 30 years ago, northern Northeast China and North China mainly sustained weak negative correlations (Figs. 3a,c), whereas southern Northeast China recovered to positive correlations after the late 1990s (Fig. 3b). The Huanghe–Huaihe area exhibits a remarkable shift from significant negative correlations before the 1980s to positive correlations after the late 1990s (Fig. 3d). The correlations are robust in the Yangtze River basin, characterized by positive correlations for the whole period (Fig. 3e), and South China primarily presents negative correlations with an overall strengthening trend (Fig. 3f). It is confirmed again that decadal changes of the ENSO–ECSR relationship are mostly confined to the north of the Yangtze River, with two shifts in the late 1970s and late 1990s. Thus, considering the data temporal coverage, it is reasonable to contrast the ENSO-related ECSR anomalies for three epochs: 1958–77 (epoch I), 1978–97 (epoch II), and 1998–2017 (epoch III), all of which span 20 years with the same sample size for comparison.

For summarizing the changing impact of ENSO on ECSR, the ECSR anomalies are regressed onto the DJF(0/1) ONI for the three epochs, respectively (Fig. 4). It is clearly shown that the ENSO-related ECSR exhibits three different typical anomaly patterns since the 1950s. Specifically, in epoch I (Fig. 4a), just as previous studies revealed (Huang and Wu 1989; Wu et al. 2003),
the El Niño–induced ECSR anomalies feature a typical tripole pattern with less precipitation in the Huaihe River basin and more precipitation in both the Yangtze River basin and northern China, whereas in epoch II (Fig. 4b) the rainfall anomalies in northern China are changed to be negative, and the negative rainfall anomalies in South China are intensified. In epoch III (Fig. 4c), the El Niño–induced more precipitation extends northeastward from the Yangtze River basin to southern Northeast China, and the negative rainfall anomalies in South China remain intensified. A dipole rainfall anomaly pattern occurs in this epoch: less rainfall in South China and the southeast coast and more in the Yangtze/Huaihe River basin–eastern North China–southern Northeast China sector. We also slightly change the chosen epoch to check the robustness of the result, and confirm that similar regression patterns can be obtained under slight adjustment of periods (figure not shown).

4. Decadal shifts in the ENSO-related circulation anomalies

Associated with the three distinct ENSO-related ECSR anomaly patterns, the ENSO-related circulation anomalies over East Asia in JJA(+1) also display remarkable decadal shifts. Here the moisture transport, wind, and geopotential height anomalies are regressed onto the DJF(0/+1) ONI for three epochs (Figs. 5 and 6). Since rainfall anomaly is directly caused by the anomalous moisture transport, we first show the regression patterns of vertically integrated moisture flux and its divergence in eastern China (Fig. 5), in which the moisture flux convergence is well coherent with positive rainfall anomalies.

a. Moisture transport anomalies

In epoch I (Fig. 5a), the anomalous anticyclonic moisture circulation over the east of Northeast China and cyclonic moisture circulation over Mongolia play a crucial role in the tripole rainfall anomaly pattern. This pair of zonal cyclonic–anticyclonic moisture circulation makes the southwesterly moisture flux converge over northern China to cause positive rainfall anomalies, whereas the moisture flux divergence controls the Huaihe River basin to cause negative rainfall anomalies there. Meanwhile, the anomalous anticyclonic moisture circulation over the western North Pacific is weak and mainly located to the east, but there still exists some anomalous moisture flux convergence from the tropics, favoring positive rainfall anomalies in the Yangtze River basin.

In epoch II (Fig. 5b), the tropical anticyclonic moisture circulation is strengthened and extended westward, intensifying the moisture flux divergence and negative rainfall anomalies in South China. Basically opposite to epoch I, the anomalous moisture circulation over the east of Northeast China is changed to be cyclonic. Correspondingly, anomalous northeasterly-induced moisture flux occurs over northern China and reduces moisture supply, causing negative rainfall anomalies there. Jointly affected by the strengthened tropical anticyclonic moisture circulation and midlatitude northeasterly moisture flux, the moisture flux convergence and positive
rainfall anomalies during this epoch in the Yangtze River basin.

In epoch III (Fig. 5c), anomalous moisture circulation is characterized by a meridional cyclone–anticyclone dipole pattern, in which the midlatitude cyclonic part is just centered over Northeast China and the tropical anticyclonic moisture circulation exhibits a larger meridional expansion (e.g., Li et al. 2019). The latter promotes northeastward extension of the moisture flux convergence zone, also enhancing the moisture flux divergence and negative rainfall anomalies in South China. The midlatitude cyclonic moisture circulation causes southwesterly moisture flux over southern Northeast China, favoring positive rainfall anomalies there. Such tropical and midlatitude moisture circulation anomalies together make the positive rainfall anomalies extend northeastward, causing the dipole ECSR anomaly pattern during this epoch.

b. Tropical and midlatitude circulation anomalies

The changes in ENSO’s impact on ECSR can be directly explained by different moisture transport anomalies in three epochs, but fundamentally they are caused by the decadal shifts in ENSO-related tropical and midlatitude circulation anomalies. Here we further present the regression patterns of wind and geopotential height anomalies over East Asia in JJA(+1) for three epochs (Fig. 6).

In the tropics, the anomalous western North Pacific anticyclone (WNPAC) is a robust signal appearing in all three epochs (Figs. 6d–f), which causes a relatively robust positive correlation between summer rainfall in the Yangtze River basin and the preceding winter El Niño (see Fig. 3e). But it also features changes in intensity and location, responsible for the decadal shifts of ENSO-related tropical moisture circulation as mentioned above. Specifically, in epoch I (Figs. 6a,d), the anomalous WNPAC is weak and mainly located over the east of the Philippines, and the anomalous southwesterlies to its western flank are confined over the Philippine Sea, which limits its impact on the ECSR. By contrast, in epoch II (Figs. 6b,e), the anomalous WNPAC is intensified and extended westward to southern China, and exhibits a zonally elongated shape with controlling vast seas from the South China Sea (SCS) to the date line (e.g., Wu and Wang 2002). The strengthening anomalous southwesterlies reach the Yangtze River basin (Fig. 6e) and thus convey a stronger impact on the rainfall anomalies there. In epoch III (Figs. 6c,f), the main body of the anomalous WNPAC shifts to the SCS and exhibits a large meridional expansion compared with its zonally elongated shape during epoch II (e.g., Li et al. 2019). With significant positive geopotential height anomalies over the SCS (Fig. 6c), such an anomalous WNPAC indicates a strengthened western Pacific subtropical high that directly controls South China and dramatically decreases rainfall there. Meanwhile, the accompanied anomalous southwesterlies can further reach the far north in eastern China, favoring the northeastward extension of ENSO-related rainfall anomalies (see Figs. 4c, 5c, and 6f).
However, the ENSO-related midlatitude circulation anomalies feature larger variabilities than the tropical signals (e.g., the anomalous WNPAC), which cause more changeable impact of ENSO on rainfall north of the Yangtze River. In epoch I, an anomalous low-level anticyclone affects the north in eastern China (Fig. 6d), linked to a midlatitude zonal wave-like pattern with an anomalous low pressure over Mongolia and an anomalous high pressure over the Sea of Japan (Fig. 6a; Wu and Wang 2002), which explains the cyclonic–anticyclonic pair observed in moisture transport fields (see Fig. 5a). In epoch II, the zonal wave-like pattern disappears, and a strong anomalous equivalent-barotropic cyclone dominates the midlatitude North Pacific (Figs. 6b,e). Accompanied by the concurrent enhanced anomalous WNPAC, this meridional pattern along the East Asian coast (Fig. 6b) appears to be reminiscent of positive PJ/EAP teleconnection (Nitta 1987; Huang and Li 1987), which causes northeasterly wind anomalies over Northeast Asia (Fig. 6e) and decreases rainfall in northern China. In epoch III, the East Asian midlatitude circulation is mainly characterized by positive geopotential height anomalies, and the PJ/EAP-like pattern is no longer clear (Fig. 6c), which is consistent with structural changes of the summertime PJ pattern in the late 1990s (Xu et al. 2019; Li and Lu 2020). But between the strong anomalous high pressure over the Urals and western midlatitude North Pacific, an anomalous cyclone occurs locally over Northeast China (Figs. 6c,f). Such an anomaly pattern may indicate the frequent occurrence of the Urals–Okhotsk double-blocking pattern and Northeast China cold vortex (Liu et al. 2017), favoring more rainfall in southern Northeast China (see Figs. 4c and 5c).

Therefore, in both the tropics and the midlatitudes, the ENSO-related East Asian circulation anomalies have also experienced remarkable decadal shifts, which are closely associated with the changing impact of ENSO on ECSR. The above results of the regressed circulation anomalies from JRA-55 can be confirmed by NCEP and ERA5 reanalysis (figure not shown). Based on the regression analysis, we summarize the configuration between the ENSO-related ECSR and circulation anomaly patterns for three epochs in a schematic diagram, as shown in Figs. 14a–c.

5. Causes for the changes of ENSO-related circulation anomalies

As for the cause of changing impact of ENSO on ECSR, it needs to be answered why the East Asian summer circulation anomalies respond differently to the preceding winter El Niño among three epochs. In this section, we address this issue by illustrating causes for the changes in ENSO-related tropical and midlatitude circulation anomalies, respectively.

a. Tropical circulation anomalies: The role of zonal SST teleconnection

The tropical SSTAs (e.g., SSTAs in the tropical Indian Ocean, western North Pacific, and central Pacific; Xie et al. 2009; Wu et al. 2010; Fan et al. 2013) play a crucial role in the maintenance of the anomalous WNPAC during the El Niño decaying phase. We speculate that the changes of the anomalous WNPAC arise from the different ENSO-related tropical SST’s zonal teleconnections in three epochs.
To verify this hypothesis, the SSTAs (Fig. 7) and tropical circulation anomalies (Fig. 8; 500-hPa vertical velocity and 850-hPa wind) from El Niño mature winter [DJF(0/1)] to decaying summer [JJA(+1)] (shown from top to bottom) regressed onto the DJF(0/1) ONI. The white dots represent the 95% significance level. The regressed results for three epochs are shown chronologically in the left-to-right direction.

The different tropical SSTAs in JJA(+1) are closely related to different seasonal evolutions of ENSO-related SST teleconnections. In epoch I (Figs. 7a,d,g), the warm SSTAs in the equatorial eastern Pacific (EP) decay rapidly in MAM(+1) and exhibit an EP La Niña–like pattern in JJA(+1). Meanwhile, the Indian Ocean basinwide warming (IOBW) is dissipated (Fig. 7g). Accompanied by such an SSTA evolution, the anomalous WN PAC and associated suppressed convection over the tropical western North Pacific are obviously weakened and withdrawn eastward (Figs. 8a,d,g). In epoch II (Figs. 7b,e,h), El Niño decays slowly, and there remain warm SSTAs in the equatorial eastern Pacific in JJA(+1). The prolonged El Niño helps the tropical Indian Ocean to keep basinwide warming (Fig. 7h), which can sustain the anomalous WN PAC via the so-called Indian Ocean capacitor effect (Fig. 8h; Xie et al. 2009). In epoch III (Figs. 7c,f,i), El Niño decays a little faster, the SSTAs in the equatorial central Pacific (Figs. 8a,c,e) and a pair of cyclonic anomalies over the equatorial central Pacific (Figs. 8a–c). But in contrast to the similarity in DJF(0/1), the JJA(+1) tropical SSTAs show conspicuous differences among three epochs (Figs. 7g–i), which actually determines the changes of the anomalous WN PAC (Figs. 8g–i).

Therefore, due to the different seasonal evolutions of ENSO-related SST anomalies, the tropical zonal SST teleconnections in JJA(+1) show obvious differences among three epochs, in which the persistent IOBW after the late 1970s, the EIO-MC warming during epoch III, and different zonal SSTA gradient in the tropical Pacific among three epochs are keys to the changes of the anomalous WN PAC. To further clarify the detailed mechanism, we focus on the JJA(+1) ENSO-related SSTAs in the tropical Indo-Pacific Ocean and the overlying atmospheric response (Fig. 9).

Previous studies revealed that the persistent IOBW and strengthened Indian Ocean capacitor effect contribute to the enhancement of anomalous WN PAC after the late 1970s (e.g., Xie et al. 2010; Huang et al. 2010; Chowdary et al. 2012). Consistent with their results, we can see that the dissipated IOBW fails to stimulate the Indian Ocean capacitor effect in epoch I (Figs. 9a,b). However, as mentioned before, the
anomalous WNPAC still exists in JJA(+1), but is just confined over the east of the Philippines (Figs. 6d and 9b). According to the previous study (Wang et al. 2000), this may be explained by the atmospheric Rossby wave response to the suppressed convective heating induced by localized cooling SSTA in the tropical western North Pacific (precipitation anomalies and SSTA in 10°N–20°N near the date line; Figs. 9a,b). In epoch II (Figs. 9c,d), responding to the persistent IOBW, the heating over the tropical Indian Ocean induces a tropospheric warming that features a Kelvin wave–like wedge (temperature...
anomalies in Fig. 9d). It acts to suppress the convection over the tropical western North Pacific (OLR and precipitation anomalies in Figs. 9c and 9d) via the Kelvin wave–induced divergence mechanism (Xie et al. 2009) and then favors the amplification and westward extension of the anomalous WNPAC.

However, the Kelvin wave–like warm temperature anomalies are also observed in epoch III, and thus the Indian Ocean capacitor effect cannot explain the discrepancy of the anomalous WNPAC between epochs II and III (Figs. 9d,f). Interestingly, associated with the different zonal SSTA gradient in the tropical Pacific, the anomalous convection shows obvious difference in the latter two epochs (Figs. 9c,e). In epoch II, the enhanced convection occurs in the equatorial central Pacific as a response to the remaining El Niño–like SSTA, and it forms a meridional dipole pattern with the positive OLR anomalies over the tropical western North Pacific (Fig. 9c). But as the JJA(+1) zonal SST teleconnection changes into the CP La Niña–like SSTA pattern in epoch III, the associated anomalous convection shows a zonal dipole pattern which is characterized by convective enhancement over the EIO-MC region and suppression over the tropical western Pacific (Fig. 9e). This zonal dipole anomalous convection can affect the anomalous WNPAC in epoch III via the following two ways. First, the suppressed convective heating around the tropical western Pacific (OLR and rainfall anomalies in Figs. 9e and 9f) can induce an anticyclonic Rossby wave response to maintain the anomalous WNPAC directly (Terao and Kubota 2005). Second, with the coexisting warm Kelvin wave (Fig. 9f), the enhanced convective heating over the EIO-MC region can anchor the main body of the anomalous WNPAC over the SCS through stimulating an anomalous local Hadley cell (e.g., Jiang et al. 2019; Xie and Wang 2020). To verify this, we check the zonally averaged (100°–140°E; see green box in Fig. 9) anomalous meridional circulation in three epochs (Fig. 10). It is clearly shown that the large cross-equatorial local Hadley cell only occurs in epoch III, which features anomalous rising over the EIO-MC region and widely descending in the tropical western North Pacific (Fig. 10c). The wide sinking branch north of the equator facilitates to anchor the anomalous WNPAC over the SCS with a large meridional expansion (Figs. 5c, 6f, and 9f; e.g., Li et al. 2019).

Therefore, we can synthesize various mechanisms (i.e., local forcing of cooling SSTas in the tropical western North Pacific, the Indian Ocean capacitor effect, and convection anomalies induced by the zonal SSTA gradient in the tropical Pacific), some of which have been well known in previous studies, to understand the intensity and location discrepancy of the anomalous WNPAC in three epochs. But in essence, we argue that they are all in the category of ENSO-related zonal SST teleconnection.

b. Midlatitude circulation anomalies: The role of meridional SST teleconnection

In previous sections, we pointed out that the changing impact of ENSO on ECSR mainly occurs in the north of the Yangtze River and the associated circulation anomalies exhibit larger variability in the midlatitudes. Considering that the stationary Rossby wave often plays a crucial role in the formation of the midlatitude circulation anomalies (Wallace and Gutzler 1981; Hoskins and Karoly 1981), we first explore the possible connection between the East Asian midlatitude circulation anomalies and the large-scale stationary wavetrains over the Northern Hemisphere. The regressed upper-level wave train (200-hPa geopotential height anomalies and associated WAF) are shown in Fig. 11.

The ENSO-related upper-level wave activities in JJA(+1) exhibit remarkable differences among three epochs. In epoch I (Fig. 11a), the anomalous low pressure over Mongolia and high pressure over the Sea of Japan (see Fig. 6a) are part of a zonally oriented wave train, which resembles the Silk Road (SR) pattern (Lu et al. 2002; Enomoto et al. 2003) or the Asian portion of circumglobal teleconnection (Ding and Wang 2005). The WAF indicates that the SR-like pattern mainly originates from the anomalous high pressure northwest of India and propagates eastward, causing the formation of the anomalous cyclonic–anticyclonic pair from Mongolia to the Sea of Japan. This result is consistent with that in Wu and Wang (2002) and they proposed that the zonal wave train can be excited by Indian summer monsoon (ISM) heating anomalies. In epoch II (Fig. 11b), the zonal SR-like pattern disappears in the East Asian midlatitudes (e.g., Wu and Wang 2002; Feng and Hu 2004). The primary midlatitude circulation anomaly affecting ECSR during this epoch, namely the anomalous equivalent-barotropic cyclone over North Pacific (see Figs. 6b,c), is connected with a high-latitude wave train that initiates from North Atlantic and passes through northern Eurasia along a great

![Fig. 10. Latitude–altitude sections of the regressed zonally averaged JJA(+1) meridional circulation (vector) and vertical velocity anomalies (shaded; $10^{-3}$ Pa s$^{-1}$) onto the DJF(0+) ONI during (a) epoch I, (b) epoch II, and (c) epoch III. White dots denote the regressed vertical velocity anomalies at the 95% significance level.](image-url)
circle (Hoskins and Karoly 1981). But more notably, WAF is amplified over the midlatitude North Pacific (MNP), which implies that the overlying anomalous cyclone itself may be a geopotential anomaly source and maintained by some local processes. In epoch III (Fig. 11c), the stationary wave train associated with the anomalous cyclone over Northeast China (see Figs. 6c,f) can be traced back to the MNP, and further relayed over the North Atlantic–Europe sector. This wave train continuously propagates southeastward from the Urals, causing an anomalous cyclone locally over Northeast China, although it is relatively weak possibly due to wave energy dissipation.

Through WAF diagnosis, the main differences of ENSO-related midlatitude wave train in three epochs can be summarized as two key points. One is the disappearance of the zonal SR-like pattern after epoch I, which has been clarified by many previous studies; that is, the loosening ENSO–ISM relationship after the late 1970s reduces the ISM variability, and then the weakened ISM-induced heating anomalies cannot effectively excite the geopotential anomaly source northwest of India, thus leading to the disappearance of ENSO-related zonal wave train in later epochs (Wu and Wang 2002; Feng and Hu 2004). Another key point is that the wave trains affecting the ENSO-related ECSR anomalies in three epochs, to some degree, are all connected with the robust WAF over the MNP. It implies that some local processes over the MNP may play a crucial role in the formation of ENSO-related midlatitude circulation anomalies affecting the ECSR, while this point is rarely emphasized in relevant previous studies. So next we examine the details in such possible local processes and try to understand the cause for different ENSO-related midlatitude circulation anomalies based on this viewpoint.

Considering the equivalent-barotropic structure of midlatitude circulation anomalies (Figs. 6 and 11), which cannot be simply explained as the direct response to diabatic heating forcing, the midlatitude air–sea interaction theory provides a clue for understanding the ENSO-related equivalent-barotropic circulation anomalies over the MNP. In the recent decade, many observational and modeling studies have revealed that the midlatitude ocean (especially in oceanic fronts) can influence the atmospheric transient eddy activity via altering the low-level atmospheric baroclinicity and then driving the maintenance of seasonal-mean equivalent-barotropic circulation anomalies, particularly through the transient eddy vorticity forcing (Nakamura et al. 2008; Sampe et al. 2010; Fang and Yang 2016; Wang et al. 2017; Wills and Thompson 2018; Tao et al. 2020; Chen et al. 2020; Yu et al. 2020; Liu et al. 2020). Thus, the local processes over the MNP may arise from the ocean-to-atmosphere feedback in the midlatitude air–sea coupling system, which can also be linked with the ENSO-related SST teleconnection.

To test our hypothesis, we regress the JJA(+1) SST, the minus meridional SST gradient (as a measure of oceanic front), 850-hPa Eady growth rate (as a measure of low-level atmospheric baroclinicity), and 200-hPa geopotential height anomalies onto the DJF(0/1) ONI for three epochs (Fig. 12). The ENSO-related meridional SST teleconnections in the MNP show different spatial patterns among three epochs (Figs. 12j–l). Especially in epoch II (Fig. 12k), with a slower El Niño decay, the cooling SSTAs in the MNP that resulted from the “atmospheric bridge” (Alexander et al. 2002) persist to JJA(+1) and enhance in the Kuroshio–Oyashio Extension region (see Figs. 7b,e,h). Cooling SSTAs increase the meridional SST gradient south of 40°N and then strengthen the

![Fig. 11. Regression patterns of the JJA(+1) 200-hPa geopotential height anomalies (shaded; gpm) over the Northern Hemisphere regressed onto the DJF(0/1) ONI and the associated wave-activity fluxes (vector; m² s⁻²) during (a) epoch I, (b) epoch II, and (c) epoch III. The white dots represent the 95% significance level, and only the WAF values above 0.02 m² s⁻² are shown for clarity.](image-url)
subarctic front (Fig. 12h). Further, the enhanced oceanic front acts to intensify the low-level atmospheric baroclinicity through surface sensible heat flux from the ocean (Sampe et al. 2010), so that there are positive Eady growth rate anomalies along the summertime climatological baroclinicity zone (centered on 40°N; Fig. 12e), which favor more active transient eddies. According to the transient eddy–mean flow interaction (Lau and Holopainen 1984; Fang and Yang 2016), the intensified transient eddy activities tend to induce convergence of anomalous transient eddy vorticity fluxes (i.e., positive \( F_{\text{eddy}} \) anomalies), thus maintaining the negative equivalent-barotropic geopotential tendency (Fig. 13e), which substantially contributes to the observed equivalent-barotropic cycloonic anomalies over the MNP (Figs. 12b and 6b,e).

Thus, in epoch II, modulated by the meridional SST teleconnection, the anomalous equivalent-barotropic cycloone over the MNP is maintained by the above-mentioned local processes that involve the oceanic front and atmospheric transient eddy forcing, and then it extends to Northeast Asia and directly affects the rainfall in northern China. In epochs I and III, the process is basically opposite to that in epoch II. Specifically, with a rapid El Niño decay, the JJA(+1) cooling SST teleconnection dissipates in the Kuroshio–Oyashio Extension region (Figs. 12j,l). The decreased meridional SST gradient weakens the Kuroshio Extension front (Figs. 12g,i) and then reduces the atmospheric baroclinicity (Figs. 12d,f), suppressing the transient eddy vorticity forcing (Figs. 13a,c). Consequently, the anomalously negative \( F_{\text{eddy}} \) induces positive equivalent-barotropic geopotential tendency anomalies north of 40°N.

FIG. 12. Regressions of (a)–(c) JJA(+1) 200-hPa geopotential height (gpm), (d)–(f) 850-hPa Eady growth rate (day\(^{-1}\)), (g)–(i) negative SST meridional gradient [°C (1000 km)\(^{-1}\)], and (j)–(l) SST (°C) anomalies onto the DJF(0/+1) ONI for three epochs (from left to right). The green contours in (d)–(f) and the green lines in (g)–(i) represent the climatology of 850-hPa Eady growth rate and the climatological location of subarctic oceanic front zone [defined by Wang et al. (2017)] in boreal summer, respectively. The white dots represent the 95% significance level.
causing the maintenance of anomalous high pressure (green box in Figs. 12a,c). But in fact, compared with the zonal SR-like pattern (Fig. 11a), such a local process may be secondary for the maintenance of anomalous anticyclone over the Sea of Japan in epoch I. In epoch III, after forming the geopotential anomaly source over the MNP by the above process, the wave energy dispersion and the relay effect over the North Atlantic–Europe sector are required (Fig. 11c), so that the geopotential anomaly can further propagate downstream and cause the anomalous cyclone locally over Northeast China to affect ECSR.

6. Summary and discussion

a. Summary

The impact of ENSO on the following summer rainfall in eastern China is complicated and changeable with decadal background. Using nearly 70-yr observed rainfall records and JRA-55 reanalysis, this study systematically examines the changing impact of ENSO on ECSR since the 1950s. Through the 21-yr running correlation analysis, it is found that the ENSO–ECSR interannual relationship experiences two decadal shifts, one in the late 1970s and the other in the late 1990s, which cause three distinct ENSO-related circulation anomaly patterns during 1958–77 (epoch I), 1978–97 (epoch II), and 1998–2017 (epoch III). Corresponding changes in the East Asian circulation anomalies in JJA(+1) are also identified by regression analysis. On this basis, we develop our understanding in the changes of ENSO-related tropical and midlatitude circulation anomalies, from the perspective of zonal and meridional SST teleconnections. The three ENSO-related ECSR and circulation anomaly patterns and the mechanisms behind the changes of tropical and midlatitude circulation anomalies for three epochs are summarized in a comprehensive schematic diagram (Fig. 14).

We can get a clear understanding of the configuration between ENSO-related ECSR and circulation anomaly patterns in Figs. 14a–c. In epoch I (Fig. 14a), a weak anomalous WNPAC and a midlatitude anomalous cyclone–anticyclone pair contribute to the tripole rainfall anomalies with less precipitation in the Huaihe River basin and more in northern China and the Yangtze River basin. In epoch II (Fig. 14b), a stronger westward-extended anomalous WNPAC and an equivalent-barotropic anomalous cyclone over the midlatitude North Pacific jointly cause the antitripole rainfall anomalies with more precipitation in the Yangtze River basin and less in South China and north of the Yangtze River. In epoch III (Fig. 14c), a meridional expanded anomalous WNPAC and an equivalent-barotropic anomalous cyclone over the midlatitude North Pacific jointly cause the antitripole rainfall anomalies with more precipitation in the Yangtze River basin and less in South China and north of the Yangtze River. In epoch III (Fig. 14c), a meridional expanded anomalous WNPAC and an anomalous cyclone locally over Northeast China make the ENSO-related positive rainfall anomalies extend northeastward, forming a dipole rainfall anomaly pattern. Thus, ENSO’s impact on ECSR actually has both robust and changeable sides, in which the former manifests generally more precipitation in the Yangtze River basin due to robust tropical signal (i.e., anomalous WNPAC) while the latter is reflected in the more variable ENSO-related rainfall anomalies in northern...
China that arise from the large variabilities of the East Asian midlatitude circulation anomalies. Meanwhile, the anomalous WNPAC also exhibits changes in location and intensity, which features intensification and westward extension from the late 1970s and a meridional expansion since the late 1990s, causing an enhanced drying trend in South China and promoting a northeastward extension of ENSO-related more rainfall (see Figs. 4c and 5c).

FIG. 14. (a)–(c) Schematic diagram of the changing impacts of ENSO on following summer rainfall in eastern China since the 1950s and (d)–(f) corresponding mechanisms for the ENSO-related tropical and midlatitude circulation anomalies in JJA(+1). In (a)–(c), the blue (yellow) shaded area denotes the ENSO-related more (less) precipitation, and the blue (red) curved arrow denotes the associated cyclone (anticyclone) anomalies. In (d)–(f), the red (blue), green (yellow), and purple (gray) shaded areas represent the warm (cold) SSTA, enhanced (depressed) convection, and intensified (weakened) oceanic front anomalies, respectively.
The changes of the anomalous WNPAC stem from the different ENSO-related SST zonal teleconnections from tropical Pacific to Indian Ocean, which lead to different responses of the anomalous WNPAC via affecting the Indian Ocean capacitor effect and convective activities over the tropical Indo-western Pacific. Specifically, for the decadal shift in the late 1970s, the persistent IOBW in JJA(+1) during epoch II causes a stronger Indian Ocean capacitor effect to intensify anomalous WNPAC and make it extend westward (Fig. 14e). However, in epoch I (Fig. 14d), which lacks the Indian Ocean capacitor effect due to the dissipation of IOBW, the anomalous WNPAC is weak and located east. This is consistent with previous studies (Xie et al. 2010; Huang et al. 2010) that originally pointed out that the enhanced tropical Indian Ocean response to ENSO strengthens the impact of El Niño on Indo-western Pacific climate after the late 1970s. For the decadal shift after the late 1990s (Fig. 14f), associated with the zonal SSTA gradient between the EIO-MC warming and equatorial central Pacific cooling in JJA(+1), a convection anomaly dipole occurs over the tropical Indo-western Pacific. Through stimulating an anomalous local Hadley cell and causing the anticyclonic atmospheric response to negative convective heating anomalies over the tropical western North Pacific, this dipole convection makes the anomalous WNPAC anchor over the SCS and meridionally expand largely, favoring the anomalous WNPAC to exert more impacts on ECSR in epoch III.

The changes of East Asian midlatitude circulation anomalies among three epochs are closely related to the ENSO-related SST meridional teleconnections in the midlatitude North Pacific and the different stationary wave trains. In epoch I (Fig. 14d), a zonal SR-like wave train over the midlatitude Asia contributes to the formation of the anomalous cyclone–anticyclone pair covering from Mongolia to the Sea of Japan (e.g., Wu 2002; Wu and Wang 2002), favoring southwesternly wind and rainfall anomalies in northern China. However, in epoch II (Fig. 14e), the zonal SR-like wave train disappears, and the equivalent-barotropic anomalous cyclone over the MNP is primarily maintained by the local process of ocean-to-atmosphere feedback in the midlatitude air–sea coupling system, which is strengthened by the enhanced ENSO-related cooling SST teleconnection in the MNP. Intensified oceanic front and transient eddy vorticity forcing tend to generate negative geopotential anomalies, sustaining the equivalent-barotropic anomalous cyclone. In epoch III (Fig. 14f), the local process is basically opposite to that in epoch II due to the weakened SST teleconnection in the western MNP. The decreased meridional SST gradient weakens the oceanic front and then the atmospheric baroclinicity. Further, the negative transient eddy vorticity forcing anomalies cause the positive geopotential anomaly source over the MNP. Through wave energy dispersion and other relay effects over the North Atlantic–Europe sector, the stationary wave train originating from the MNP further propagates downstream and finally causes the anomalous cyclone locally over Northeast China to affect ECSR.

b. Discussion

With focus on the changing impact of ENSO on ECSR, three distinct ENSO-related ECSR and associated circulation anomaly patterns since the 1950s are identified, and possible mechanisms responsible for the changing impact are proposed to emphasize ENSO-related zonal and meridional SST teleconnections in this study. Certainly, further deeper understanding for such a changing impact of ENSO is still needed. Fundamentally, the changing impact can also be partly attributed to the changes of ENSO itself (i.e., ENSO diversity in its pattern, amplitude, and temporal evolution; Timmermann et al. 2018) and/or the changing climate background state. As the important cause emphasized in this paper, the different ENSO-related SST zonal and meridional teleconnections are mainly related to the El Niño decaying phase (see Fig. 7), consistent with the studies starting with different El Niño decay periods (e.g., Zhou et al. 2019; Jiang et al. 2019). In fact, the frequent occurrence of CP El Niño may also play a role after the 1980s (Wang et al. 2019). Especially during epoch III, two super EP and several CP El Niño events are mixed together in this study. So it needs to further distinguish and clarify the different mechanisms for their respective impact on the ECSR and associated circulation anomalies. In addition to the changes in ENSO, the ENSO-related SST teleconnection and its climate impact are modulated by the decadal climate variability (e.g., Pacific decadal oscillation; Feng et al. 2014; Dong et al. 2018). Under the global warming scenario, a recent study has confirmed that the tropical Pacific mean SST influences the ENSO-related precipitation changes in the midlatitudes (Yang et al. 2021).

Moreover, for the midlatitude circulation anomalies that affect the ENSO-related ECSR anomalies in JJA(+1), we understand their changes among three epochs based on the ocean-to-atmosphere feedback in the midlatitude air–sea coupling system. From the perspective of the tropical–extratropical connections, if we recall the absence of a PJ/EAP-like pattern from epoch II to III (Figs. 6b,c), it can be inferred that the midlatitude ocean-to-atmosphere feedback is an important mechanism for the decadal change of PJ/EAP pattern in the late 1990s (e.g., Xu et al. 2019; Li and Lu 2020). But considering that the midlatitude air–sea interaction is responsible mainly for the interdecadal climate variability (Latif and Barnett 1996; Miller and Schneider 2000), such a local process through which ENSO exerts its influence on the interannual climate anomalies over East Asia needs to be further examined by lead–lag regression analysis using daily data, and the relevant mechanism modulated by the meridional ENSO-related SST teleconnection also needs to be verified with numerical experiments.

Certainly, ENSO’s impact on the ECSR anomalies may also involve other factors that are not considered here. Especially we note that the wave train over East Asia in the last two epochs is not very typical with a lack of robust WAF continuity (Figs. 11b,c), which suggests that ENSO’s impact on the midlatitude East Asia has been capricious in recent decades. This subtle phenomenon requires us to further explore other possible midlatitude approaches (such as the Tibetan Plateau heating, Eurasian snow cover, and North Atlantic SST) in future studies to fully understanding ENSO’s impact on the East Asian summer climate.
Acknowledgments. This study is supported by the National Natural Science Foundation of China (Grants 41621005 and 41875086) and the National Key Basic Research and Development Program of China (Grant 2018YFC1505902).

REFERENCES


Huang, R.-H., and W. Li, 1987: Influence of the heat source anomaly over the western tropical Pacific on the subtropical high over East Asia. Proc. Int. Conf. on the General Circulation of East Asia, Chengdu, China, Institute of Atmospheric Physics, Chinese Academy of Sciences, 40–51.


