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Inter-decadal transition of the leading mode of inter-annual variability of summer rainfall in East China and its associated atmospheric water vapor transport

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Abstract This study investigated the inter-decadal variations of the leading empirical orthogonal function mode of the inter-annual variability of summer precipitation in East China from 1951 to 2012. From the 1950s to the 1980s, the main rain belt in the positive-phase years was centered along the middle and lower Yangtze River Valleys, with negative rainfall anomalies in South China and North China. Since the 1990s, the main rain belt of the positive-phase years has been shifted northward. During the period 2001–2012, the center of the main rain belt in the positive-phase years has shifted to the regions between the Yangtze and Yellow Rivers. This shift could be attributed to the inter-decadal variations of the anomalous atmospheric water vapor transport (AWVT) associated with the leading mode, which changed from a previously "anticyclone–cyclone" dipole structure to an anticyclonic monopole structure. The underlying physical mechanisms concerning the exertions from sea surface temperatures (SSTs) have also been preliminarily explored. The results indicate that the significant inter-decadal transition in the leading mode of summer precipitation in East China and the causative anomalous AWVT from 2001 to 2012 may be related to an inter-decadal change of inter-annual variability of the tropical SSTs in both the Indian and Pacific Oceans, which has been below normal from 2001 to 2012. Therefore, the influence of the tropical SSTs on the inter-annual variability of the East Asian climate may be diminished from 2001 to 2012, whereby a strongly coupled "anticyclone–cyclone" dipole-structured anomalous AWVT cannot be induced.

Keywords Inter-decadal variation · Inter-annual variability · Leading mode · Summer precipitation · East China

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1 Introduction

In recent decades, summer precipitation in East China has undergone significant inter-decadal variations. Ding et al. (2008, 2009) revealed evidence of an inter-decadal variation of summer precipitation in East China from 1951 to 2004, and further investigated the causes of the weakening Asian monsoon since the end of the 1970s (Wang 2001). The inter-decadal variability of summer precipitation in East China is mainly characterized by increased precipitation in North and Northeast China from 1951 to 1978, a rapid southward shift to the middle and lower Yangtze River Valleys (YRV) from 1978 to 1992 and further extension to South China from 1993 to 2004 (Ding et al. 2008). It is suggested that the weakening of the Asian summer monsoon, which is the primary cause of the inter-decadal variation of summer precipitation in East China, should be the result of reduced land–sea thermal contrasts caused by the increasing winter and spring snow over the Tibetan Plateau and the warming sea surface temperature (SST) in the tropical central-eastern Pacific (Ding et al. 2009). The inter-decadal changes of summer precipitation in East China at the end of 1970s and the early 1990s have also been detected by Hu (1997), Gong and Ho (2002), Zhang et al. (2008), and Wu et al. (2010), etc. Both the two inter-decadal changes in precipitation are associated with inter-decadal changes in atmospheric water vapor transport (AWVT) over East Asia (Li et al. 2012). In addition, Zhu et al. (2011) found that summer precipitation significantly increased in the Yellow River–Huaihe River region and decreased in YRV from 2000 to 2008 compared with the period 1979–1999, indicating a recent inter-decadal change. Sun et al. (2011) analyzed the inter-decadal and inter-annual variations of AWVT over East Asia and found that the inter-decadal change uncovered by Zhu et al. (2011) was primarily attributed to the cyclonic anomalies of AWVT over South China and a weakening of the westerly AWVT by mid-latitude westerlies. Besides inter-decadal variations, the AWVT over East Asia has also been experiencing a long-term change in recent decades (Li et al. 2011). Recently, Fan et al. (2013) found that the inter-annual variability of summer rainfall over South China has been intensified since 1990s, implying an inter-decadal change of the rainfall regime over East Asia.

Ding et al. (2008) indicated that there is an inter-decadal transition of summer precipitation pattern in East China from a meridional structure of a positive–negative–positive (+−+) pattern to a dipole pattern in past decades, corresponding to the first two empirical orthogonal function (EOF) components of summer precipitation from 1951 to 2004. Although the weakening of the Asian monsoon can explain the southward shift of the rain belt in recent decades, the transition from a triple pattern to a dipole pattern is still not well understood. Moreover, the studies by Ding et al. (2008, 2009) focus on inter-decadal time scale in which the EOF analyses are based on a 9-year running mean time series. Thus, the leading mode of the inter-annual variability of summer precipitation was not discussed in the aforementioned studies. Essentially, the leading EOF mode of precipitation represents the dominating pattern of the inter-annual variability of precipitation and could explain a significant portion of its temporal variances, which generally reflects the influence on precipitation in different areas that are exerted by significant climate modulators, such as the El Nino-Southern Oscillation (ENSO) and Arctic Oscillation (Thompson and Wallace 1998). For instance, the plum-rain over the YRV is modulated by La Nina Events and their relationship has undergone significant changes in the late 1970s (Wang et al. 2012). The anomalous anticyclonic AWVT over the Philippinne Sea, which is teleconnected with ENSO, plays a key role in modulating the winter and spring precipitation in Southeast China (Li et al. 2013). Thus, in some way, it is quite important to obtain a comprehensive understanding of the leading mode of inter-annual variability of precipitation and its underlying mechanisms, which will be potentially conducive to the prediction of precipitation (Sun and Wang 2013a).

The inter-annual variability of summer precipitation in East Asia is dominated by the East Asian summer monsoon, which is closely associated with the western Pacific subtropical high. Many studies have been performed to investigate the influencing factors of the inter-annual variability of the East Asian summer monsoon and western Pacific subtropical high, which include ENSO and SST anomalies in the tropical Indian Ocean, western tropical Pacific, and central-eastern tropical Pacific (e.g., Huang and Lu 1989; Huang and Wu 1989; Huang 1992; Simmonds et al. 1996; Chang et al. 2000a, b; Lau and Weng 2001; Wang et al. 2001; Wang 2002; Wu and Wang 2002; Jiang et al. 2004; Sui et al. 2007; Yang et al. 2007; Wu et al. 2009; Fan et al. 2012). Huang and Wu (1989) proposed that in the developing stage of ENSO, the SST in the western tropical Pacific is colder in the summer and the convective activities are weak around the South China Sea, which led to a southward shifted subtropical high that could further cause drought in South China and floods in the YRV. However, in the decaying stage of ENSO, the convective activities were strong around the Philippines, and the subtropical high shifted northward, which could result in drought in the YRV. Wu et al. (2009) investigated the season-reliant EOF modes of precipitation over East Asia from 1979 to 2004 and found that the first mode indicates that in an El-Nino decaying summer, an anomalous anticyclone appears over the western North Pacific that brings strong positive precipitation anomalies to central East China and the second mode indicates that in an El-Nino developing summer, the anomalous heating over the equatorial central Pacific forces a cyclonic vorticity over the western North Pacific, which strengthens the western North Pacific monsoon. In addition, it was also suggested by Wu et al. (2009) that the warming in the tropical Indian Ocean plays an active role in impacting the anomalous anticyclone over the western North Pacific during the ENSO decaying summer. The results obtained by Huang and Wu (1989) and Wu et al. (2009) are not quite consistent with each other, which may be partly attributable to the two studies focusing on two different periods, 1950–1980 and 1979–2004, respectively, especially considering that there was an inter-decadal variation of the relationship between the East Asian summer monsoon and tropical SSTs, or ENSO, at the end of 1970s (Chang et al. 2000a; Wang 2001, 2002; Wu et al. 2002). The inter-decadal variation of this relationship is reflected in several respects, such as its oscillation period. Chang et al. (2000a) found that the SST anomalies in the equatorial eastern Pacific resembled a tropospheric biennial oscillation pattern from 1951 to 1977, whereas in 1978–1996, its oscillation period changed to a longer timescale.

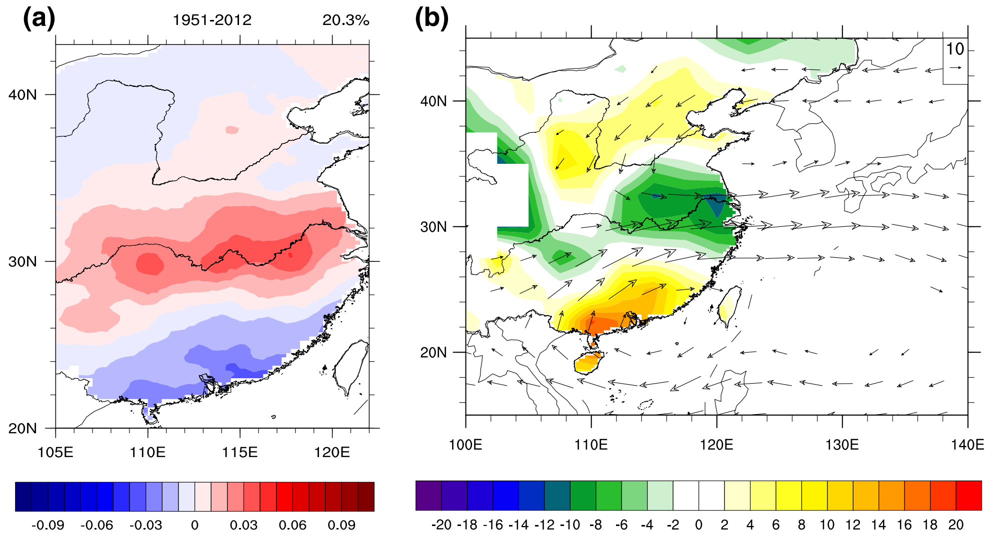

Fig. 1 **a** The leading EOF mode of summer precipitation in East China (except Taiwan, the same below) from 1951 to 2012. *Top-right* corner is the corresponding percentage of explained variance to the total variance (the same below). **b** The vertically integrated water vapor flux (vectors, unit: kg m^{-1} s^{-1}) regressed upon the PC1 and its divergences (colored shading, unit: 10^{-6} kg m^{-2} s^{-1}). Only the vectors that passed the 90 % significance level of the Student's *t* test are shown

Moreover, Sui et al. (2007) proposed that the western North Pacific subtropical high in summer exhibits significant 2–3 and 3–5 years oscillations with inter-decadal variability. The 3–5-year oscillation was most pronounced during the 1980s, whereas the 2–3-year oscillation was more evident after the 1990s.

In spite of all the above mentioned meaningful research works, there are still a few questions worthy of further explorations:

1. In recent decades, has there been any significant inter-decadal variation of the leading mode of inter-annual variability of summer precipitation in East China? An EOF analysis is a pure mathematical operation, but the physical mechanisms underlying the dominating EOF mode could be crucial for determining the inter-annual variability of precipitation. An inter-decadal variation of the leading mode should be associated with a change of the underlying physical mechanism, which is important for understanding climate change. Thus, although the leading mode is only a mathematical production, its underlying meaning can be far more complex.
2. If the answer to question (1) is affirmative, then what are the inter-decadal variations of the associated AWVT over East Asia? The AWVT is directly related to the precipitation in East Asia at synoptic, seasonal, inter-annual, and inter-decadal scales (Zhou et al. 2009; Sun et al. 2011, Sun and Jiang 2012; Wei et al. 2012; Sun and Wang 2013b), which can be regarded as a bridge between the influencing factors and precipitation.
3. Further, what are the inter-decadal variations of the influencing mechanisms? The inter-annual variability of summer precipitation in China is modulated by many factors, such as the western Pacific subtropical high, ENSO, and the SST anomalies in the Indian Ocean. The inter-decadal variations of the leading mode of inter-annual variability of summer precipitation in East China may be caused by inter-decadal changes of mechanisms involving one or more of the aforementioned factors or unmentioned factors.

The present study attempts to provide insight into the inter-decadal variation of the leading mode of inter-annual variability of summer precipitation in East China from 1951 to 2012, with the goal of providing preliminary answers to the three questions listed above.

The outline of this paper is as follows. The data and methods employed in this study are described in Sect. 2. In Sect. 3, the inter-decadal transitions of the leading mode of inter-annual variability of summer precipitation in East China and associated AWVT are discussed. Section 4 investigates the potential inter-decadal variations in underlying mechanisms through composite contrasts between positive-phase and negative-phase years in different periods, focusing on the influences of tropical SSTs. The conclusion and discussions are given in Sect. 5.

2 Data and method

In this study, an advanced gridded daily precipitation observation dataset over China, CN05.1 (Wu and Gao 2013), was used for the EOF analysis. This dataset was constructed based on an interpolation from over 2,400 observation stations in China, and has a relative high resolution of 0.25° × 0.25°. The EOF analysis was performed using the June–July–August (JJA) monthly mean precipitation over East China (20–43°N, 105–122°E in this study, see Fig. 1a). Considering that the CN05.1 dataset currently has a temporal coverage from 1961 to 2012, whereas this study focuses on a longer period from 1951 to 2012, the monthly gauged precipitation data of 160 stations in China was employed to complement the period 1951–1960, which is derived from the National Climate Center of China. Among the 160 stations, there are total 98 stations within the range of (20–43°N, 105–122°E), interpolated to the same grids of CN05.1 data. Before conducting the EOF and composite analyses, the linear trends of precipitation and SSTs, which have had notable linear trends in China in recent decades, were removed to better capture the inter-annual variability signals (Cane et al. 1997; Deser et al. 2010; Gemmer et al. 2004; Zhai et al. 2005).

The National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) supplied gridded data for the specific humidity, surface pressure, zonal and meridional winds, omega, etc. at multiple vertical levels. Monthly SST data were derived from the National Oceanic and Atmospheric Administration (NOAA) (Smith et al. 2008).

3 Inter-decadal transition of the leading mode

Figure 1a shows the leading EOF mode (EOF1) of the summer (JJA mean) precipitation in East China from 1951 to 2012. The main rain belt is centered along YRV (approximately 30°N) in the positive phase of the leading mode, with negative precipitation anomalies over South China and North China. The AWVT regressed upon the temporal principle component (PC) of the leading mode is shown in Fig. 1b and is characterized by a remarkable "anticyclone–cyclone" dipole structure over East Asia. The coupling of the anomalous anticyclonic AWVT in the south and the anomalous cyclonic AWVT in the north leads to anomalous moisture convergences over YRV and anomalous moisture divergences over South China and North China, which would cause more precipitation over YRV and less precipitation over South China and North China. The agreement between the AWVT divergence pattern shown in Fig. 1b and the leading mode shown in Fig. 1a implies that the inter-annual variability of AWVT is a causal factor for the inter-annual variability of summer precipitation in East China. Ding et al. (2009) noted that a strong Asian summer monsoon results in more precipitation in North China and South China and less precipitation in YRV, which corresponds to the negative phase of the leading mode shown in Fig. 1a, and vice versa. Thus, it appears that the leading mode of summer precipitation in East China principally reflects the inter-annual variability of the East Asian summer monsoon. It has been widely recognized that the East Asian summer monsoon has experienced significant inter-decadal variations in past decades (Xue 2001; Wang 2001, 2002; Ding et al. 2008, 2009). Therefore, the leading mode of summer precipitation in East China may have undergone noticeable inter-decadal variations, speculatively. Furthermore, the causes of the distinct "anticyclone–cyclone" dipole structure of the anomalous AWVT, which play a key role in causing the "−+−" pattern of the leading mode, are still unknown; the underlying mechanisms will be discussed in details in Sect. 4.

To provide a detailed view on the inter-decadal variations of the leading mode of inter-annual variability of summer precipitation in East China, a running EOF analysis with a 17-year window was conducted for summer precipitation in East China from 1951 to 2012, and the results are depicted in Fig. 2. It shows a transition from a relatively less consistent and less steady leading mode in the 1950s and 1960s (Fig. 2a–c) to a relatively more consistent and steadier leading mode with a "−+−" pattern in the 1970s and 1980s (Fig. 2d–f), and a further transition to a more "+−"-like pattern in the 1990s and 2000s (Fig. 2h, i). Specifically, the running EOF1s in the 1950s and 1960s have a main rain belt centered near YRV in their positive phases but not quite consistent. In the 1970s and 1980s, the patterns of the running EOF1s become more consistent and steady, with the main rain belt centered along YRV in their positive-phases and negative precipitation anomalies over South China and North China. This steady "−+−"-pattern leading mode can explain approximately 30 % variances of summer precipitation for this period (Fig. 2d, e), indicating that the physical mechanism underlying this leading mode had a significant dominating influence over the inter-annual variability of summer precipitation in East China during this period. Moreover, in view that the running EOF1s in the 1970s and 1980s resemble the leading mode for the entire period from 1951 to 2012, the 1970s and 1980s may be key periods that could largely explain the total leading mode shown in Fig. 1. Afterwards, the pattern of the running EOF1s gradually shifted, with the center of the main rain belt in their positive-phases moving northward to the regions between Yellow and Yangtze Rivers. This leading mode further developed into a "+−" pattern after entering the twenty first century, with positive anomalies over most areas north of the Yangtze River and negative anomalies over most areas south of it (Fig. 2i).

The corresponding AWVT regressed upon the PC1s are shown in Fig. 3. It is evident that the regressed AWVT assumes a significant "anticyclone–cyclone" dipole structure over East Asia in the 1970s and 1980s (Fig. 3d–f), which is essentially the same as that for the entire period from 1951 to 2012 (Fig. 1b). In contrast, the regressed AWVT structures in other periods seem to be less significant and less consistent. Particularly, a single anticyclonic structure characterizes the period from 1996 to 2012 (Fig. 3i), implying an inter-decadal transition from the

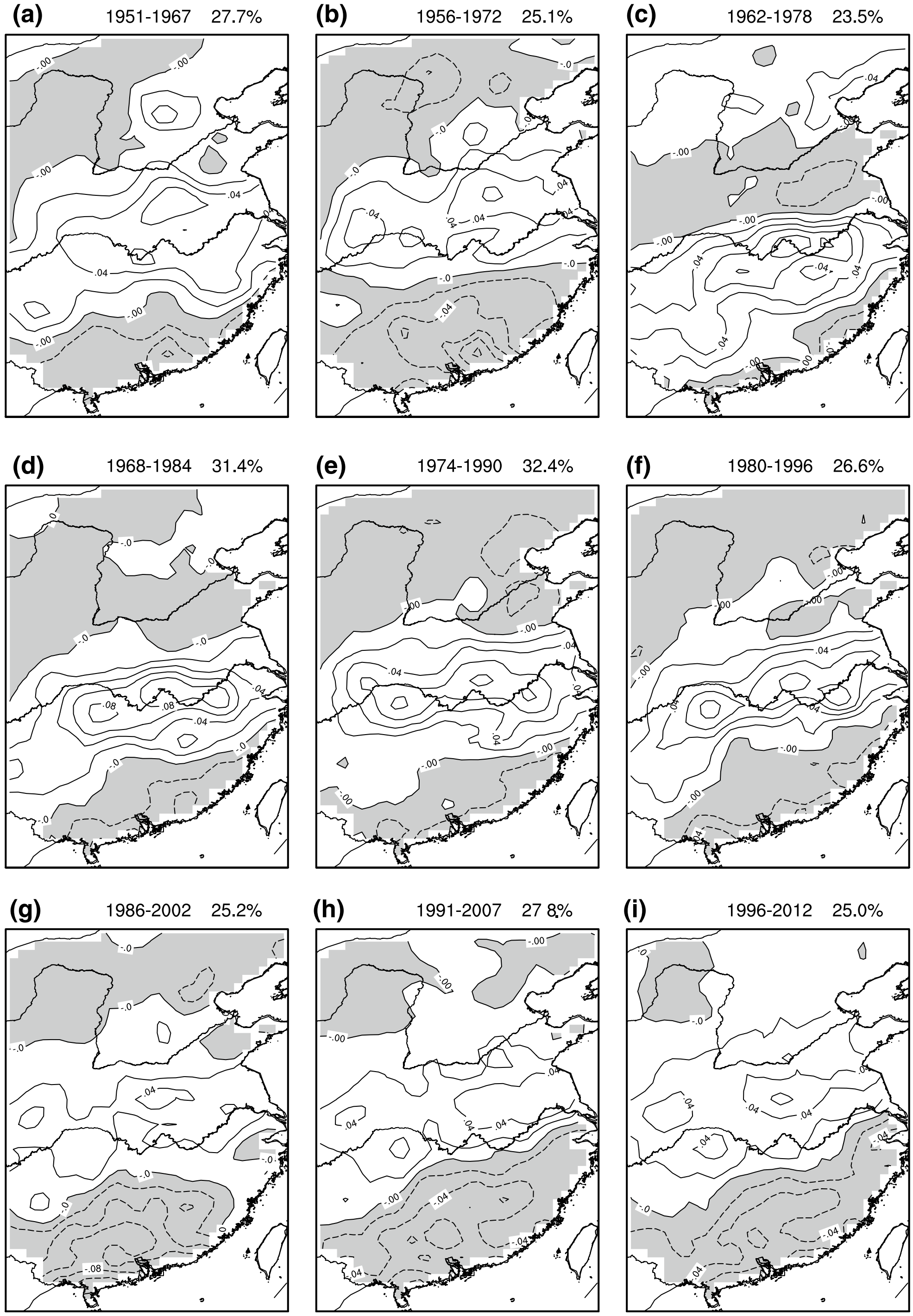

Fig. 2 Running EOF1 of summer precipitation in East China from 1951 to 2012, with a 17-year window. The subplots are shown at a 6-year interval. Areas of positive values are contoured by *solid lines*; areas of negative values are contoured by *dashed lines* and shaded in *gray*

"anticyclone–cyclone" dipole structure in the 1970s and 1980s.

Therefore, it can be inferred that the "−+−"-pattern leading mode for the entire period 1951–2012 may be principally explained by the strong leading mode in the 1970s and 1980s, which is associated with a "anticyclone–cyclone" dipole-structured anomalous AWVT. On the other hand, the leading mode and its associated anomalous AWVT in the most recent decade are quite different from those in the 1970s and 1980s, implying a significant inter-decadal transition of its underlying physical mechanism.

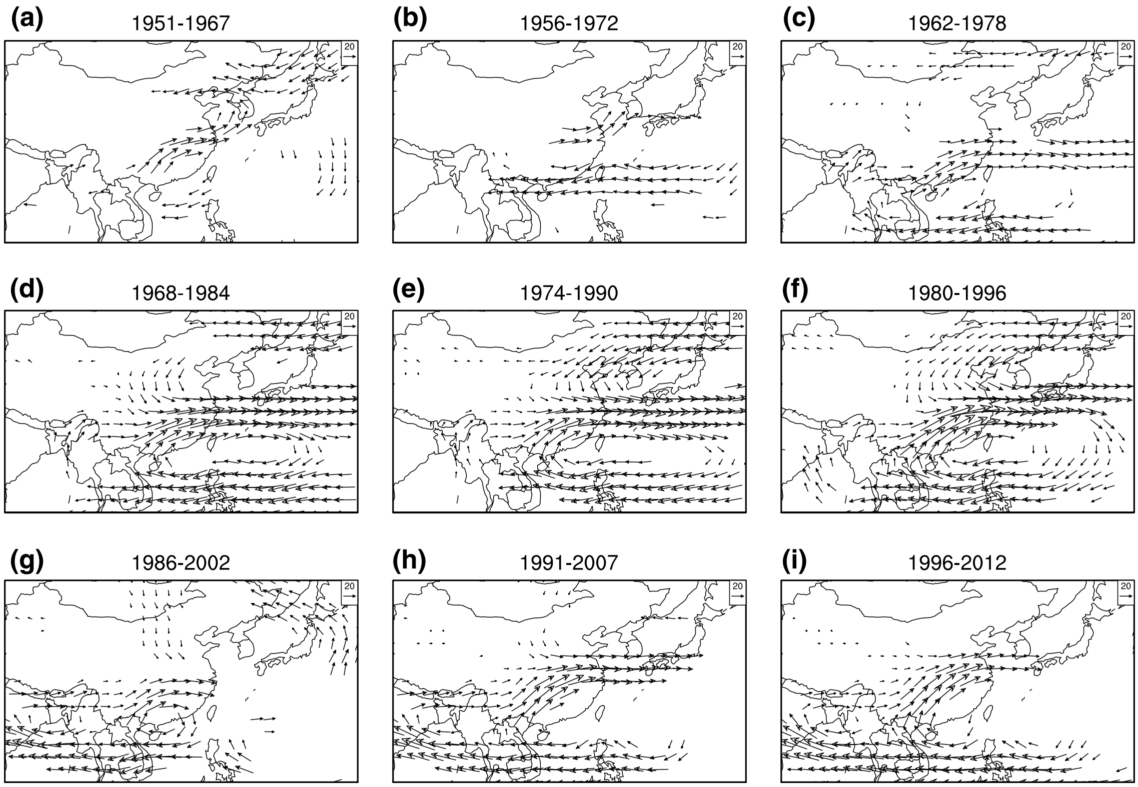

Fig. 3 The AWVT regressed upon the corresponding temporal PCs of the running EOF1s shown in Fig. 2. Unit: kg m^{-1} s^{-1}. Only vectors that passed the 90 % significance level of the Student's *t* test are shown

Because the current study focuses on the potential influences of tropical SSTs on the anomalous AWVT associated with the leading mode of summer precipitation in East China, a comparison of the leading mode and its associated AWVT and SSTs was conducted for three periods: 1950s–1960s, 1970s–1980s, and 1990s–2000s. The leading modes for the three periods are depicted in Fig. 4. It shows that the leading modes of the periods 1951–1970 and 1970–1990 have the main rain belt centered along YRV in their positive phases, with negative precipitation anomalies over South China and most parts of North China, especially for the period 1970–1990 (Fig. 4a, b). In contrast, the leading mode for the period 1990–2012 has a northward shifted main rain belt centered over the region between the Yangtze and Yellow Rivers, with negative precipitation anomalies over areas south of the Yangtze River (Fig. 4c). The anomalous AWVT and SSTs associated with the leading mode in different periods were computed through a composite analysis that calculated the differences in AWVT and SSTs between positive-phase years and negative-phase years. Considering that the representativeness of each year for the leading mode is different, the composite analysis was weighted by the corresponding temporal PC value for each year. For instance, the weighted composited SST field for positive-phase years is given by

$$SST_w(i,j) = \frac{\sum_{k=1}^{n} SST(i,j,k) \cdot PC_k}{\sum_{k=1}^{n} PC_k} \quad (1)$$

where i and j are the longitudinal and latitudinal coordinates, respectively. k represents the positive-phase years, and n is the number of positive-phase years. PC_k is the PC value of the kth positive-phase year, and thus SST_w is the weighted composite average SST for the positive-phase years. In a special case that each positive PC value has the same weight with each other, the weighted composited SST field has a normal expression that

$$SST_w(i,j) = \frac{1}{n} \sum_{k=1}^{n} SST(i,j,k). \quad (2)$$

Figure 5 shows the composite differences in AWVT and SSTs between the positive-phase and negative-phase years for the three periods. Positive SST anomalies in the tropical western Pacific characterize the period from 1951 to 1970, with "anticyclone–cyclone" dipole-structured anomalous AWVT over East Asia (Fig. 5a). This dipole structure tilts in accordance with the orientation of the positive SST anomalies in western Pacific, implying a connection between anomalous SSTs and the "anticyclone–cyclone" pattern of anomalous AWVT over East

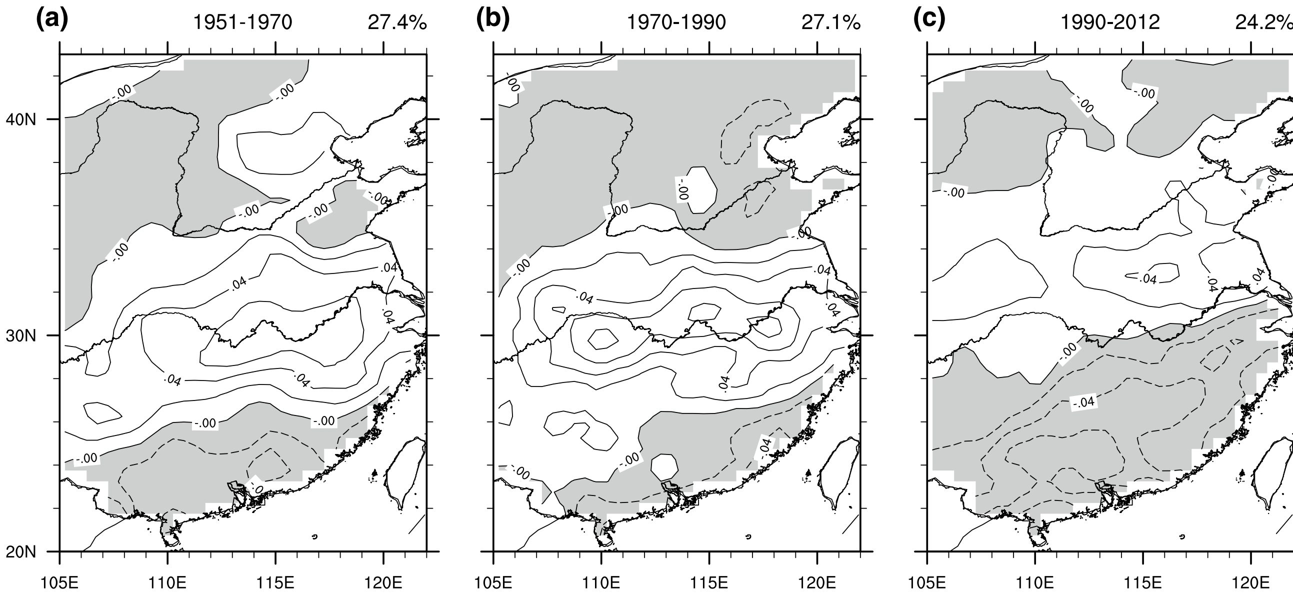

Fig. 4 The leading EOF mode of summer precipitation in East China for the periods **a** 1951–1970, **b** 1970–1990, and **c** 1990–2012. Areas of positive values are contoured by *solid lines*; areas of negative values are contoured by *dashed lines* and shaded in *gray*

Asia. For period 1970–1990 (Fig. 5b), there is even more remarkable "anticyclone–cyclone" dipole-structured anomalous AWVT over East Asia in the positive-phase years, with positive SST anomalies widely occupying the tropical and northern Indian Ocean. Whereas, with respect to period 1990–2012 (Fig. 5c), the differences in SST between positive-phase and negative-phase years are not as significant as the former two periods, and the differences in AWVT over East Asia are more characterized by an anticyclonic monopole structure than an "anticyclone–cyclone" dipole structure. The tropical SST anomalies could dramatically impact the climate in East Asia through a teleconnection. Huang (1992) suggested that the convective activities in the western Pacific warm pool largely influence the inter-annual variation of climate in East Asia through the "East Asia–Pacific" teleconnection, which is characterized by the propagation of quasi-stationary planetary waves forced by heat sources around the Philippines. Nitta (1987) referred to the teleconnection as the "Pacific–Japan pattern" because of the association between the above and/or below normal convective activity over the western tropical Pacific with the anticyclonic and/or cyclonic anomalies near Japan. The "East Asia–Pacific" teleconnection and the "Pacific–Japan pattern" describe essentially the same phenomenon wherein the climate in East Asia responds to the forcing in low-latitudes through a meridional propagation of wave trains (Hoskins and Karoly 1981; Huang 1984). Considering the above mentioned, in the current study, the attribution of the inter-decadal variation of the leading mode of summer precipitation in East China to the forcing of the tropical SST anomalies is investigated mainly from a teleconnection or wave train perspective. In addition, the positive SST anomalies in the Indian Ocean also impact the anomalous anticyclone over the western North Pacific (Wu et al. 2009). The results shown in Fig. 5 imply that the leading mode of the period from 1951 to 1970 may be mainly related to positive SST anomalies in the tropical western Pacific, whereas the significant "anticyclone–cyclone" dipole-structured anomalous AWVT associated with the leading mode of the period from 1970 to 1990 may be closely related to the expansive positive SST anomalies in the Indian Ocean. The possible relationship between the leading mode of period from 1990 to 2012 and SST anomalies needs deeper insights.

4 Possible inter-decadal variations in the underlying mechanisms

Because of the potential importance of tropical SST anomalies, it is necessary to investigate the inter-decadal variations of the inter-annual tropical SST variability. In consideration of this point, the 9-year running variances from 1951 to 2012 were computed for the boreal summer (JJA) SSTs in three areas: the tropical Indian Ocean, tropical oceanic areas around the Maritime Continent, and central-eastern tropical Pacific. Figure 6a–c show the normalized anomalies of the running SST variances in the three areas, and Fig. 6d shows the ranges of the three areas. Notably, it can be seen that the inter-annual variability of SSTs in the tropical Indian Ocean is remarkably

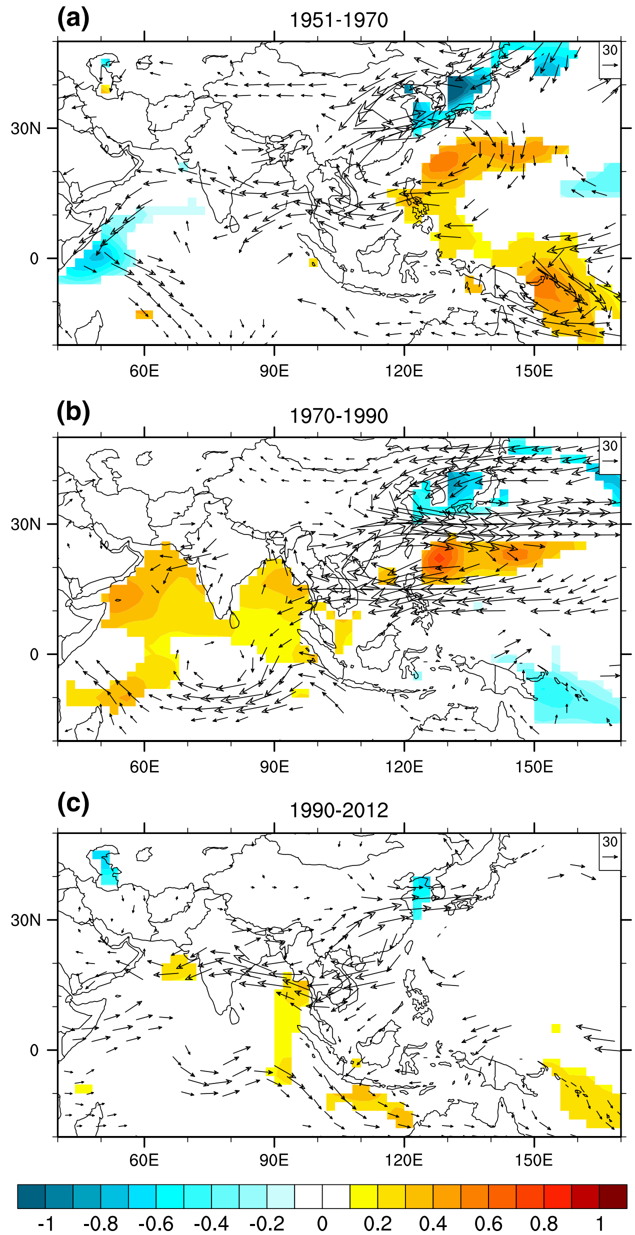

Fig. 5 The composite differences of AWVT (vectors, unit: kg m^{-1} s^{-1}) and SST (colored shading, unit: °C) between positive-phase and negative-phase years for the periods **a** 1951–1970, **b** 1970–1990, and **c** 1990–2012. Only differences in AWVT and SST that passed the 90 % significance level of the Student's *t* test are shown

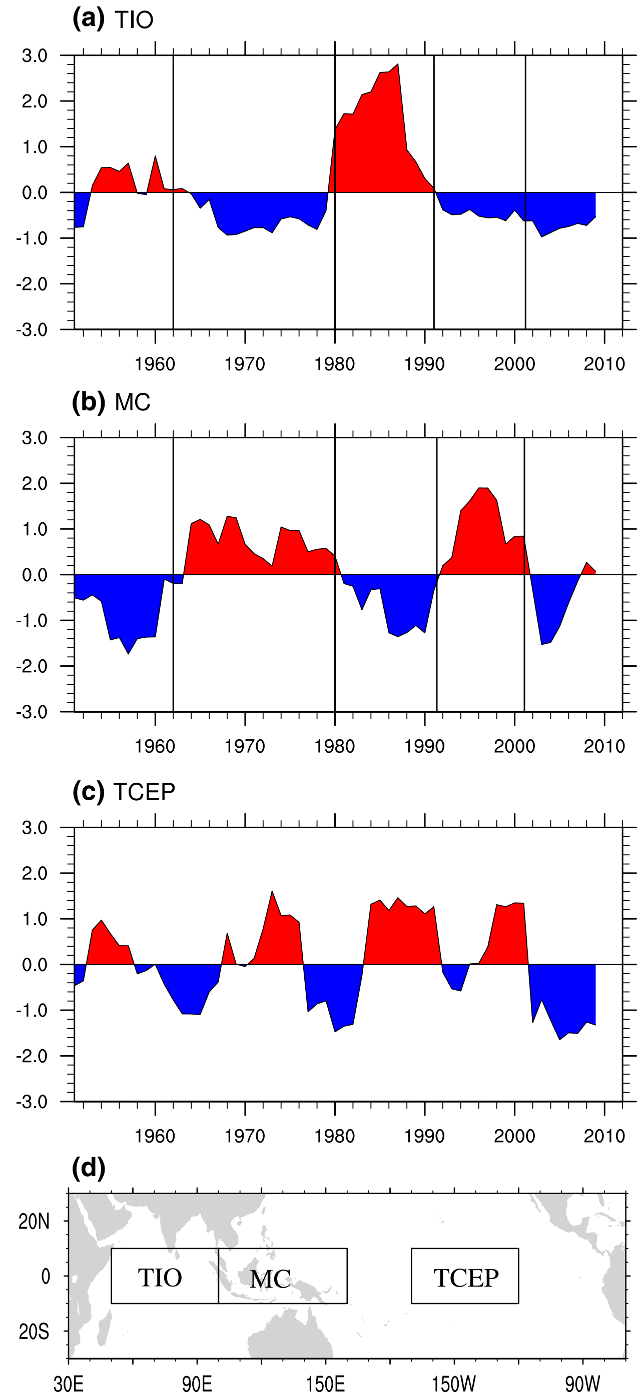

Fig. 6 Normalized anomalies of 9-year running variances of SSTs **a** in the tropical Indian Ocean (TIO), **b** around the Maritime Continents (MC), and **c** the central-eastern tropical Pacific (CETP) from 1951 to 2012. The *vertical lines* in (**a**) and (**b**) denote the demarcation of five periods in relation to the inter-decadal variations of the inter-annual variability of SSTs in tropical Indian Ocean and around the Maritime Continent. The ranges of TIO, MC, and TCEP are shown in (**d**)

high in the 1980s (Fig. 6a), whereas the variability of the SSTs around the Maritime Continent is below normal (Fig. 6b), implying that the SSTs in the Indian Ocean may have played an important role in modulating the inter-annual variability of the AWVT over East Asia in the 1980s, which is consistent with the inference from Fig. 5b. In contrast, during the 1960s–1970s and 1990s, the inter-annual variability of SSTs in the tropical Indian Ocean appears to be below normal, whereas the SST variability around the Maritime Continent is above normal and notably high in the 1990s. This implies that during the 1960s–1970s and 1990s, the inter-annual variability of the SSTs around the Maritime Continent may have had more of an impact to the inter-annual variability of the AWVT over East Asia. The running variance anomalies of SSTs in the central-eastern tropical Pacific (Fig. 6c) show more regular inter-decadal oscillations and do not exhibit an evident in-phase or out-of-phase relationship with the former two areas. During the decade after 2000, the inter-annual variability of SSTs in the three areas appears to be all below normal, implying reduced exertions from the tropical SSTs in modulating the inter-annual variability of the climate in East Asia. This circumstance did not occur from 1951 to 2000. The distinct anticyclonic monopole-structured anomalous AWVT associated with the "+−"-pattern leading mode from 1996 to 2012 (Fig. 3i) may be related to the inactive inter-annual variability of the tropical SSTs since 2000.

Therefore, the three-period partition, i.e., the 1950s–1960s, 1970s–1980s, and 1990s–2000s, may be not quite appropriate. A more reasonable partition would be five periods: 1951–1962, 1962–1980, 1980–1991, 1991–2001, and 2001–2012, which are demarcated in Fig. 6. This partition is mainly based on the inter-decadal variations of the inter-annual variability of SSTs in the tropical Indian Ocean and around the Maritime Continent, which have an evident out-of-phase relationship from 1951 to 2012.

Figure 7 shows the leading EOF modes of summer precipitation in East China during the five periods. The first period 1951–1962 is characterized by a leading mode that has its main rain belt of positive phase centered along YRV, with negative rainfall anomalies over South China (Fig. 7a). The leading modes of the periods 1962–1980 and 1980–1991 resemble that of the period 1951–1962, featured by the main rain belt of positive phase centered along YRV and negative rainfall anomalies over South China, but with more expansive negative rainfall anomalies in North China (Fig. 7b, c), presenting a significant "−+−" pattern. In the latest two periods, 1991–2001 and 2001–2012 (Fig. 7d, e), the main rain belt of positive phase appears to be shifted gradually northward to the areas between the Yangtze and Yellow Rivers, with negative rainfall anomalies over the southern part of China. There was a northward shift of the main rain belt of approximately three degrees of latitude from the period 1980–1991 to the period 2001–2012. Thus, the leading EOF mode of the inter-annual variability of summer precipitation in East China has been perceivably altered in the early twenty first century. To determine the underlying physical mechanism involving the AWVT and the exertion from tropical SSTs, a composite analysis was performed to compare the positive-phase years and negative-phase years during the five periods.

The relevant variables such as precipitation, AWVT, and SST in the positive-phase and negative-phase years were composited and weighted by their corresponding temporal PC values for each year (shown in Fig. 8). The patterns of the differences in summer precipitation between positive-phase and negative-phase years for the five periods (figure omitted) are essentially identical to the corresponding leading modes for the five periods, indicating a prominent representativeness of the weighted composite analysis method for the leading mode. Figure 9 shows the associated anomalous AWVT and its divergences. During the periods 1962–1980 and 1980–1991, anomalous AWVT in a strong "anticyclone–cyclone" dipole structure over East Asia characterized the positive-phase years, with the border between the anticyclonic anomalies and the cyclonic anomalies along YRV, as shown in Fig. 9b, c. Such anomalous AWVT could cause anomalous moisture convergences over YRV and anomalous moisture divergences over South China and North China, resulting in increased rainfall over YRV and decreased rainfall over South China and North China. Except for these two periods, relatively weak and asymmetric "cyclone–anticyclone" dipole-structured anomalous AWVT also featured the positive-phase years of the periods 1951–1962 and 1991–2001. Whereas, from 2001 to 2012 (Fig. 9e), the positive-phase years are characterized by southwesterly AWVT over East China, which is more related to an "anticyclone" monopole-structured anomalous AWVT. Without a coupled cyclonic anomalous AWVT, the anticyclonic anomalous AWVT causes moisture convergence anomalies over the northern part of China and divergence anomalies over the southern part, which can result in increased rainfall over the northern part of China and decreased rainfall over the southern part. Therefore, it appears that a strong symmetric "anticyclone–cyclone" dipole-structured anomalous AWVT over East Asia is closely related to the typical "−+−"-pattern leading mode of summer rainfall in East China, which was significant during the periods 1962–1980 and 1980–1991, whereas the "+−"-pattern leading mode from 2001 to 2012 tends to be associated with anticyclonic monopole-structured anomalous AWVT over East China. Hypothetically, the monopole-structured anomalous AWVT from 2001 to 2012 might result from a relatively weak forcing in the tropical oceans that cannot induce such a strong meridional wave train as occurred in the periods 1962–1980 and 1980–1991. Considering that the SSTs in the tropical western Pacific and tropical Indian Ocean have high inter-annual variability during the periods 1962–1980 and 1980–1991, respectively, but both have low inter-annual variability from 2001 to 2012, the inter-decadal variation of the forcing from the tropical SSTs may be one of the most important influencing factors of the varied anomalous AWVT structures associated with the leading mode.

To investigate the possible roles of tropical SSTs in generating the anomalous AWVT, Fig. 10 shows the differences in SSTs between positive-phase and negative-phase

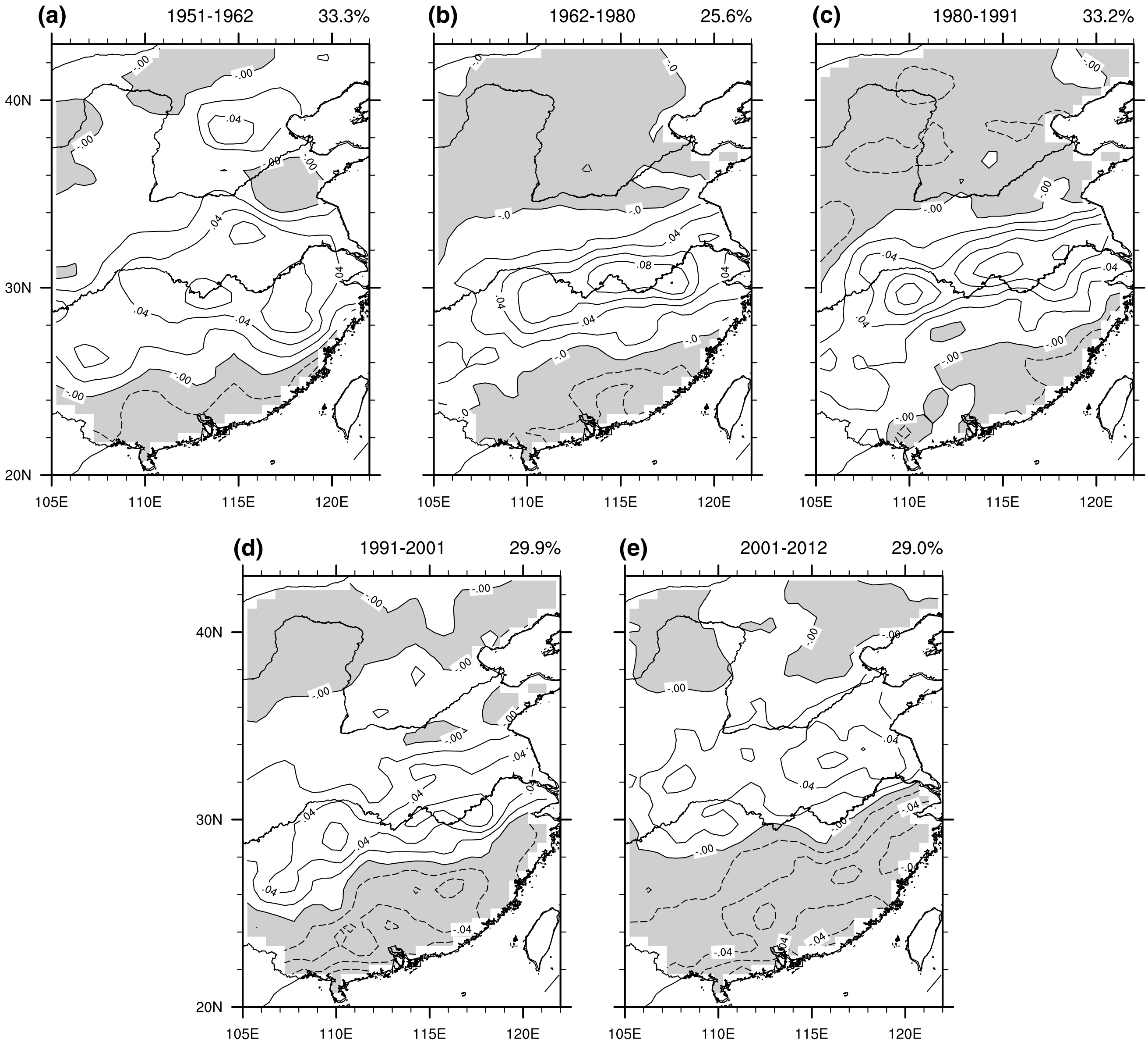

Fig. 7 The leading EOF modes of summer precipitation in East China for the periods **a** 1951–1962, **b** 1962–1980, **c** 1980–1991, **d** 1991–2001, and **e** 2001–2012. Areas of positive values are contoured by *solid lines*; areas of negative values are contoured by *dashed lines* and shaded in *gray*

years, as well as the average vertical velocity (omega) from 1,000 to 200 hPa. The circumstances for the five periods under discussion are different from each other. During the periods 1951–1962 (Fig. 10a), 1962–1980 (Fig. 10b), and 1991–2001 (Fig. 10d), the SSTs around the Maritime Continent were anomalously high in their positive-phase years. Correspondingly, ascending anomalies occurred over the Maritime Continent or its adjacent oceanic areas, indicating anomalous convective activities. Many studies have documented that an above-normal convective activity over the western tropical Pacific tends to induce anticyclonic and descending anomalies over the subtropical regions to its north (e.g., Nitta 1987; Huang 1992; Kosaka and Nakamura 2006), which would result in above-normal SSTs in the western subtropical Pacific (see the thick blue contour lines in Fig. 10). This teleconnection is the so-called "Pacific–Japan pattern" (Nitta 1987) or the "East Asia–Pacific pattern" (Huang 1992), as mentioned previously. Thus, during the aforementioned three periods, the "anticyclone–cyclone" dipole-structured anomalous AWVT shown in Fig. 9a, b, d is most likely caused by a wave train forced by the convective activity over the Maritime Continent and its adjacent oceanic areas. During the period 1980–1991, the positive-phase years were characterized

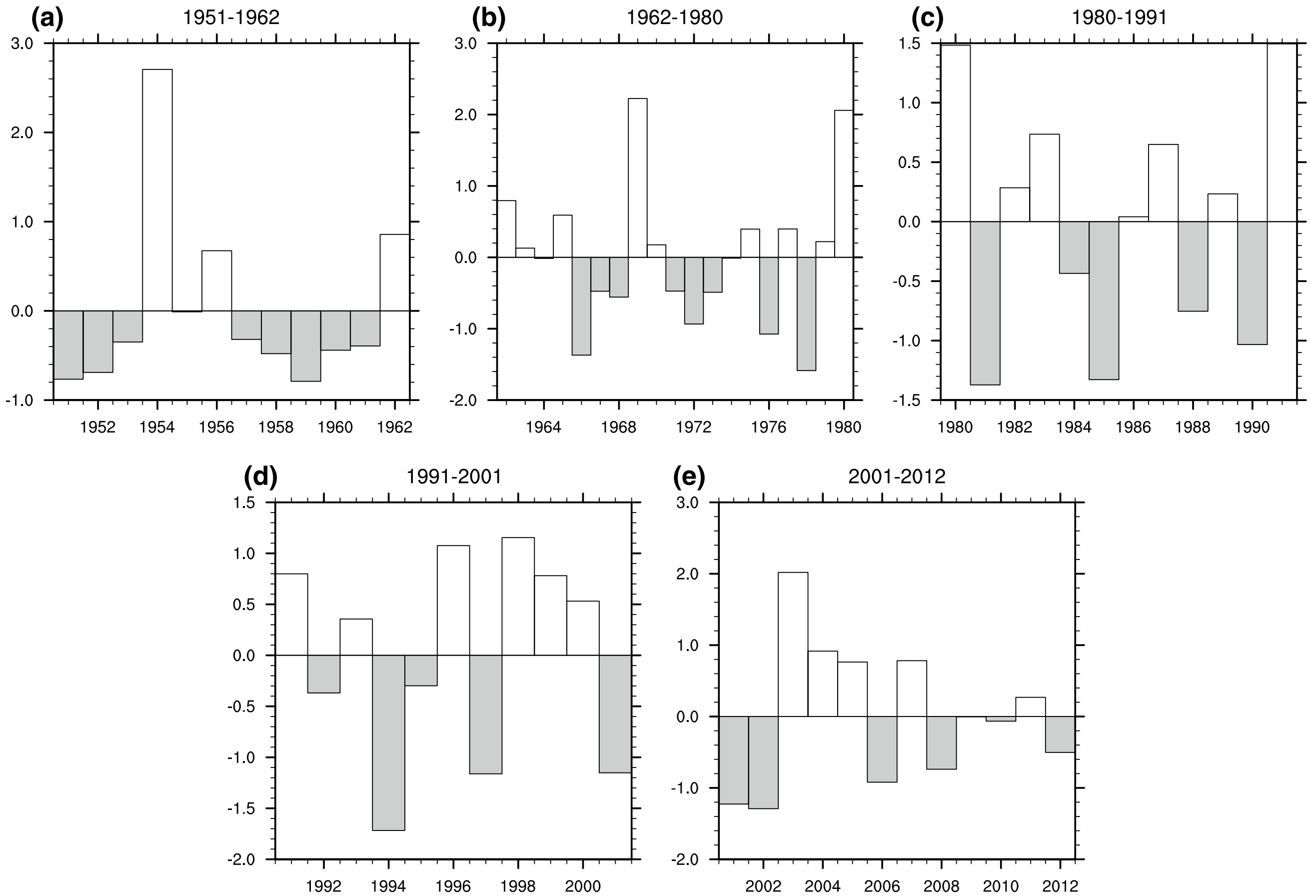

Fig. 8 The normalized temporal PCs corresponding to the leading EOF modes of summer precipitation in East China for the periods **a** 1951–1962, **b** 1962–1980, **c** 1980–1991, **d** 1991–2001, and **e** 2001–2012

by noticeable positive SST anomalies in the tropical and northern Indian Ocean and central-eastern tropical Pacific, with strong ascending anomalies over the western Indian Ocean and central-eastern tropical Pacific (Fig. 10c). On the other hand, the SSTs around the Maritime Continent are anomalously low and accompanied by descending anomalies over this region, which is on the contrary to the periods 1951–1962, 1962–1980, and 1991–2001. However, the circumstance over the western subtropical Pacific is similar to the aforementioned three periods—occupied by positive SST anomalies and descending anomalies associated with anticyclonic anomalous AWVT. Therefore, it can be inferred that the strong anomalous ascending motions over the western Indian Ocean and central-eastern tropical Pacific may have played important roles in inducing the anomalous descending motion over the western subtropical Pacific, which is closely associated with the "anticyclone–cyclone" dipole structure of the anomalous AWVT in the positive-phase years of period 1980–1991. For the period 2001–2012 (Fig. 10e), the differences in tropical SSTs between the positive-phase and negative-phase years were not as evident as in the former four periods, which could be attributed to a below normal inter-annual variability of tropical SSTs in the Indian Ocean, western Pacific, and central-eastern Pacific (Fig. 6). Positive SST anomalies and ascending anomalies over western Indian Ocean characterize the positive phase years of this period.

The sources of potential forcing in the positive-phase years are identified for each period and illustrated by thick red contour lines in Fig. 10. Correspondingly, the response regions in the western subtropical Pacific covered by potentially induced descending anomalies and positive SST anomalies are also identified for each period (the thick blue contour lines in Fig. 10). A relatively weak response in the western subtropical Pacific to the forcing source during the period 2001–2012 is indicated, which may be the result of weakened forcing source strength or changes in the location of the forcing source. However, it should be noted that the SST anomalies in the western subtropical Pacific could be partly or substantially caused by the postponement of the SSTs in preceding seasons, i.e., spring and winter. Thus, the strength of response in the western subtropical Pacific to the forcing source should not be principally inferred from the SST anomalies. Because this study

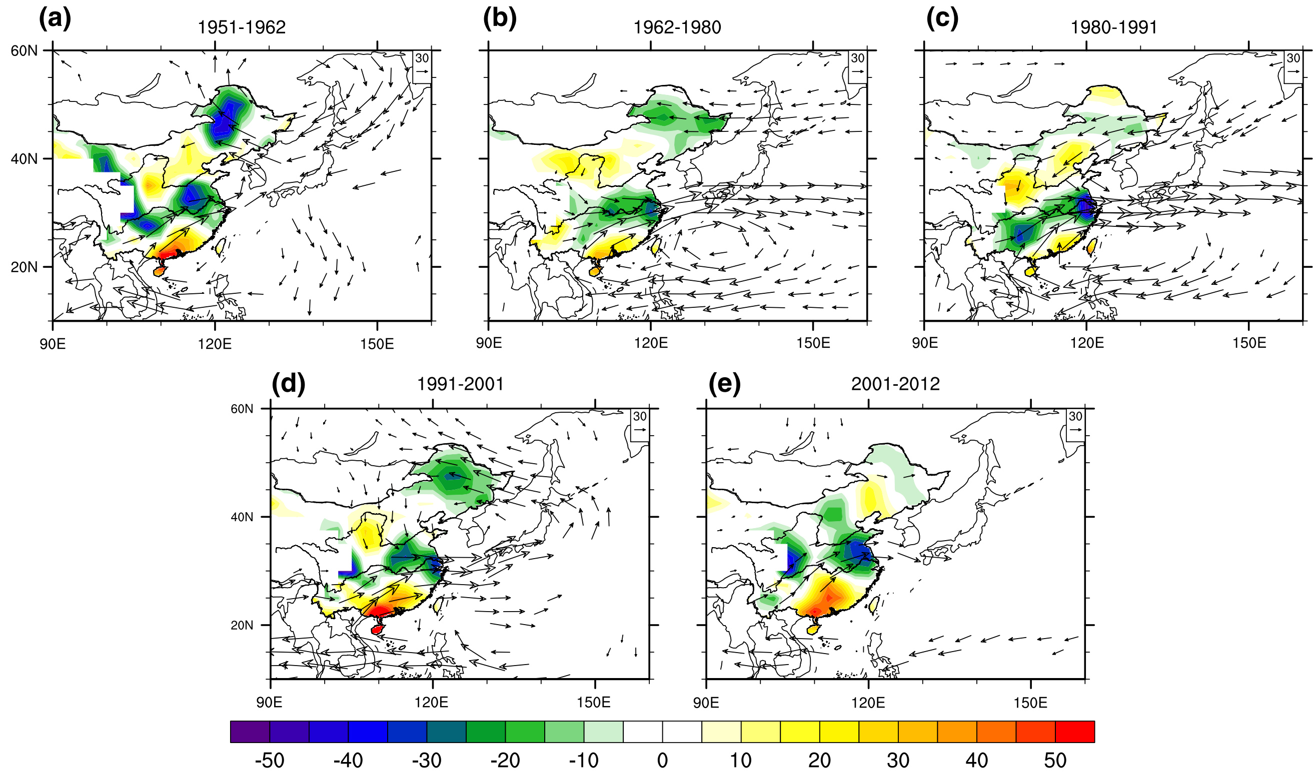

Fig. 9 The composite differences in AWVT (vectors, unit: kg m^{-1} s^{-1}) and its divergences (colored shading, unit: 10^{-6} kg m^{-2} s^{-1}) between the positive-phase years and negative-phase years for the periods **a** 1951–1962, **b** 1962–1980, **c** 1980–1991, **d** 1991–2001, and **e** 2001–2012. Only vectors that passed the 90 % significance level of the Student's *t* test are shown

is focused on the anomalous AWVT, the relevant anomalous atmospheric motions must be determined for a better understanding of the potential propagation of wave trains that induce the anomalous AWVT.

The zonal and meridional cross-section profiles of omega and winds are depicted in Figs. 11 and 12, respectively, to gain a better understanding of the origin of the anomalous dipole- or monopole-structured AWVT associated with the leading modes of the five periods. The zonal longitude-pressure profiles show the average omega and winds from 10 to 25°N (Fig. 11) to illustrate the possible zonal propagation of wave trains forced by convective activity over the northern Indian Ocean, which may play important roles from 1980 to 1991 (Figs. 10c, 11c) and 2001–2012 (Figs. 10e, 11e). The meridional latitude-pressure profiles show the average omega and winds from 110 to 150°E (Fig. 12) to illustrate the possible meridional propagation of wave trains forced by convective activity over the Maritime Continent and its adjacent oceanic areas, which may be important for periods 1951–1962 (Figs. 10a, 12a), 1962–1980 (Figs. 10b, 12b), and 1991–2001 (Figs. 10d, 12d).

For the zonal cross-section profiles, in the positive-phase years of the periods 1980–1991 (Fig. 11c) and 2001–2012 (Fig. 11e), there tends to be significant ascending anomalies over the northern Indian Ocean (50–110°E) with easterly anomalies at lower levels and westerly anomalies at upper levels. These tend to cause descending anomalies over the western subtropical Pacific (110–150°E), which is closely associated with the anomalous anticyclonic AWVT over Southeast China, with divergent wind anomalies at lower levels and convergent wind anomalies at upper levels. Specifically, in the positive-phase years of 2001–2012, there are descending anomalies over areas proximal to 90°E (the Bay of Bengal), as shown in Fig. 11e. This does not terminate the propagation of the zonal wave train forced by heating in the Arabian Sea, but it may indirectly weaken the descending anomalies over the South China Sea. During the other three periods, there is no evidence indicating an influence on the descending anomalies over western subtropical Pacific through a zonal wave train (Fig. 11a, b, d). Particularly, there is an anomalous ascending belt from 135 to 150°E in Fig. 11a that appears to be related to the descending anomalies over the western subtropical Pacific. However, based on the corresponding insignificant SST anomalies in this zonal belt (Fig. 10a), this belt could not be a strong heating source.

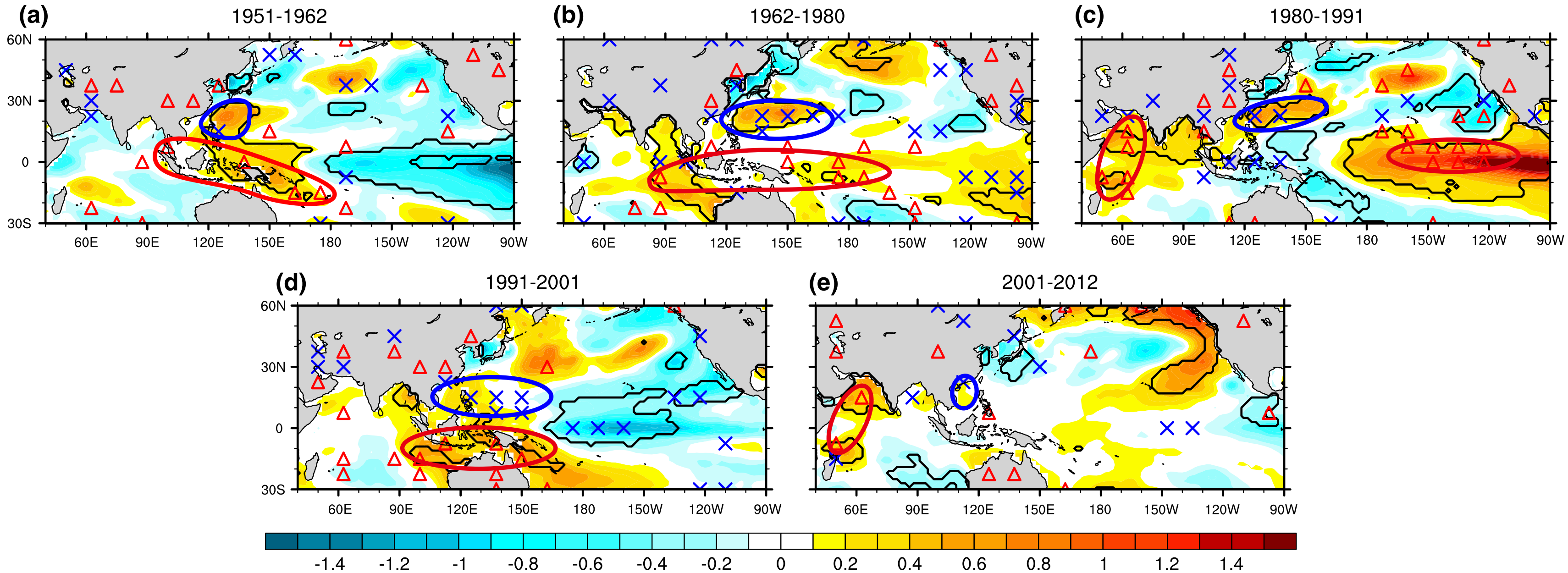

Fig. 10 The composite differences of SSTs (colored shading, unit: °C) between positive-phase years and negative-phase years, wherein those passed the 90 % significance level of the Student's *t* test are encircled by *thick black contours*. *Red triangles* and *blue furcations* denote the locations where there is significant differences (passed the 90 % significance level of the Student's *t* test) in vertically averaged (1000–200 hPa) omega (unit: Pa s^{-1}) between positive-phase years and negative-phase years. *Red triangles* denote negative omega anomalies (ascending anomalies), and blue furcations denote positive omega anomalies (descending anomalies). *Thick contours* in *red* represent potential forcing sources of positive SST anomalies and ascending anomalies; *thick contours* in *blue* represent the areas covered by descending anomalies and positive SST anomalies in the western subtropical Pacific

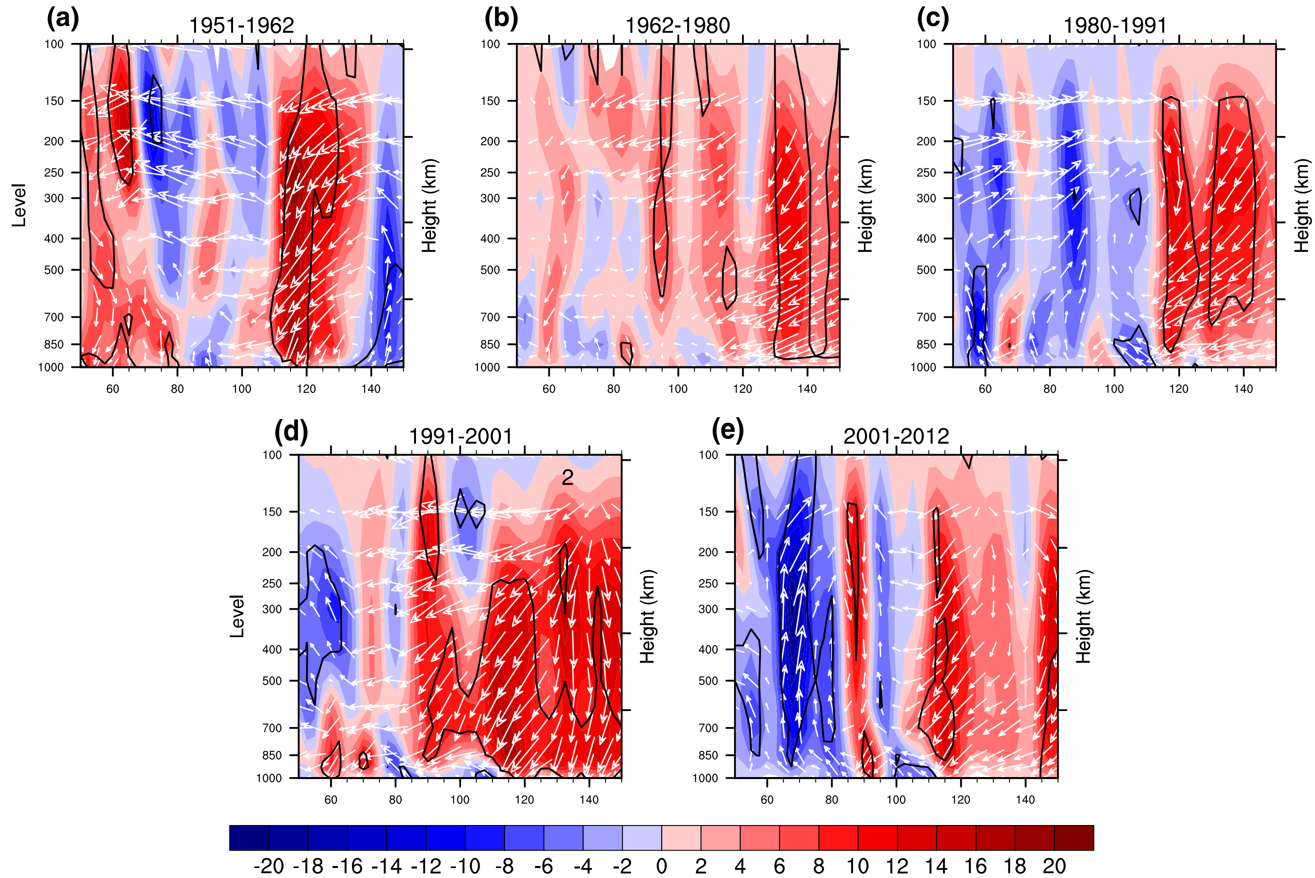

Fig. 11 The longitude-pressure cross section of differences in omega (colored shading, unit: 10^{-3} Pa s^{-1}) and winds (vectors) between positive-phase years and negative-phase years, averaged from 10 to 25°N. The differences of omega that passed the 90 % significance level of the Student's *t* test are encircled by *thick black contours*

From the meridional cross-section profiles shown in Fig. 12, there appears to be meridional wave trains in the positive-phase years of periods 1951–1962 (Fig. 12a), 1962–1980 (Fig. 12b), and 1991–2001 (Fig. 12d) that are forced by strong ascending anomalies over the Maritime Continent and its adjacent oceanic areas, whereas during the periods 1980–1991 (Fig. 12c) and 2001–2012 (Fig. 12e), descending anomalies over the tropics characterize the positive-phase years and there is no evidence indicating a meridional wave train. This evidence agrees well with the previous inferences from Fig. 10. It should be noted that the coupled descending and ascending anomalies proximal to 30°N in all the subplots of Fig. 12 correspond to the coupled "anticyclone–cyclone" dipole-structured anomalous AWVT associated with the leading modes of each period. In particular, from 2001 to 2012, because of relative weaker descending and anticyclonic anomalies over the western subtropical Pacific, the coupled ascending and cyclonic anomalies to the north are perceivably weaker than the former four periods, which makes the anomalous AWVT associated with the leading mode during this period more resemble a monopole structure.

The roles of the anomalous ascending motions over the northern Indian Ocean and the Maritime Continent as well as its adjacent oceanic areas have been discussed, but the impact of the tropical Indian Ocean and central-eastern tropical Pacific has not been determined because these two regions are not in the same latitudinal or longitudinal zone with the western subtropical Pacific. To have a deeper insight, the divergent components of the wind differences between the positive-phase and negative-phase years are shown in Fig. 13 for the lower (850 hPa) and upper (200 hPa) levels, respectively. The locations of strong convective anomalies are different in the positive-phase years of different periods, which are denoted by convergent anomalies at the lower level and divergent anomalies at the upper level. In the positive-phase years of period 1951–1962, convergent anomalies at the lower level and divergent anomalies at the upper level reside over the tropical eastern Indian Ocean and the Maritime Continent (Fig. 13a, b). Similarly, for the period 1962–1980 (Fig. 13c,

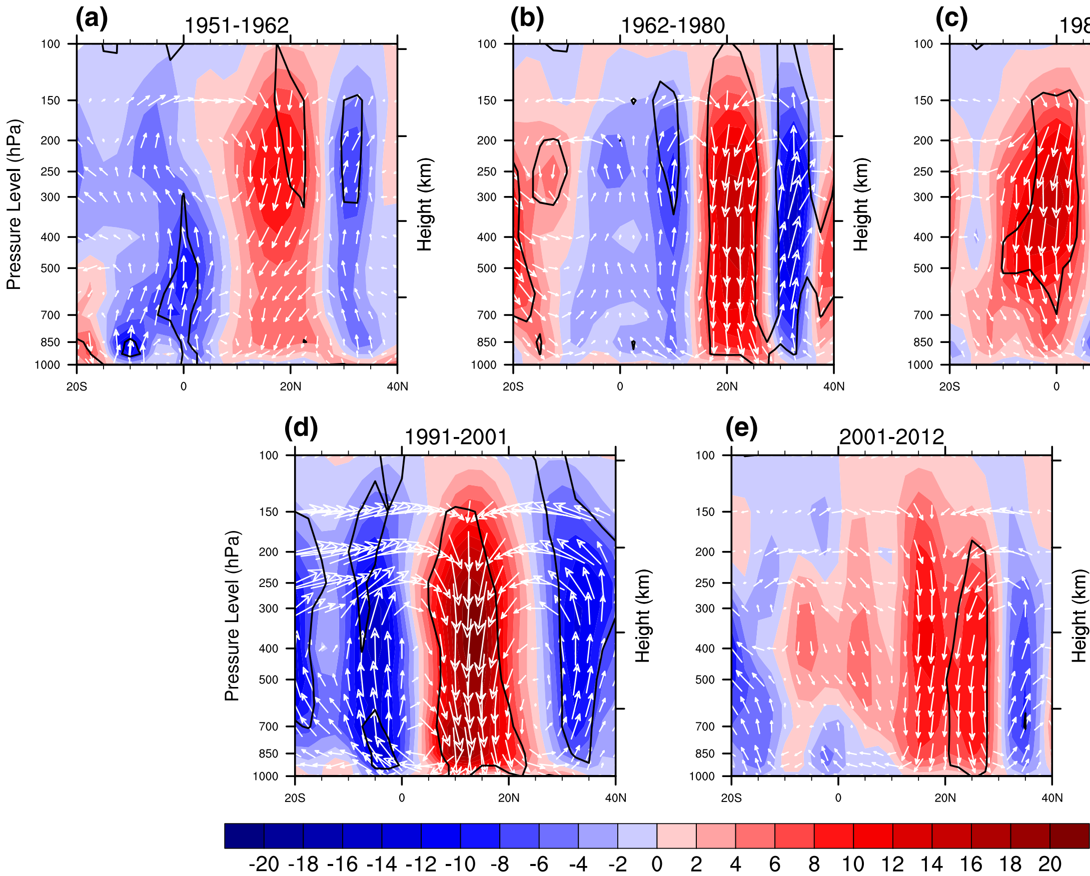

Fig. 12 The latitude-pressure cross section of differences in omega (colored shading, unit: 10^{-3} Pa s^{-1}) and winds (vectors) between positive-phase years and negative-phase years, averaged from 110 to 150°E. The differences of omega that passed the 90 % significance level of the Student's *t* test are encircled by *thick black contours*

d), the low-level convergent anomalies over the Maritime Continent and the upper-level divergent anomalies over the western tropical Pacific indicate an anomalous convective activity over this region that is related to the anomalous descending motion over the western subtropical Pacific. However, in the period from 1980 to 1991, convergent anomalies at the lower level and divergent anomalies at the upper level are situated over the western Indian Ocean and central-eastern tropical Pacific, whereas remarkable divergent anomalies at the lower level and convergent anomalies at the upper level reside over the Maritime Continent, indicating a double forcing from the western Indian Ocean and central-eastern tropical Pacific (Fig. 13e, f). From 1991 to 2001, the oceanic area to the southwest of the Maritime Continent appears to be the key region over which strong anomalous convective activity occurs in the positive-phase years, whereas a significantly anomalous descending motion occurs over the central-eastern tropical Pacific (Fig. 13g, h). For the positive-phase years of the period 2001–2012, low-level convergent anomalies and upper-level divergent anomalies can be seen over the western Indian Ocean that partly resemble the pattern from the period 1980–1991, but without significant convergent or divergent anomalies over the tropical Pacific, indicating that the Walker circulation is not significantly anomalous and has not played an important role (Fig. 13i, j).

It is important to point out that in the aforementioned figures relevant to composite differences or regression, the Student's *t* test has been performed for each computation and analysis. In most figures, those vectors or contours through the 90 % significance level are highlighted. Particularly, Fig. 13 shows the vectors through the 80 % significance level. The composite differences in AWVT, SST, and omega shown in certain figures may be not as significant as expected. However, in view that the lengths of the five periods are relatively short, it is understandable that some of the composite differences have not passed a high significance level. In addition, what is also of note is that although the periods 1951–1962, 1962–1980, and 1991–2001 are regarded as similar periods in the above discussions because they all have anomalous warmer SSTs around the Maritime continent and ascending anomalies

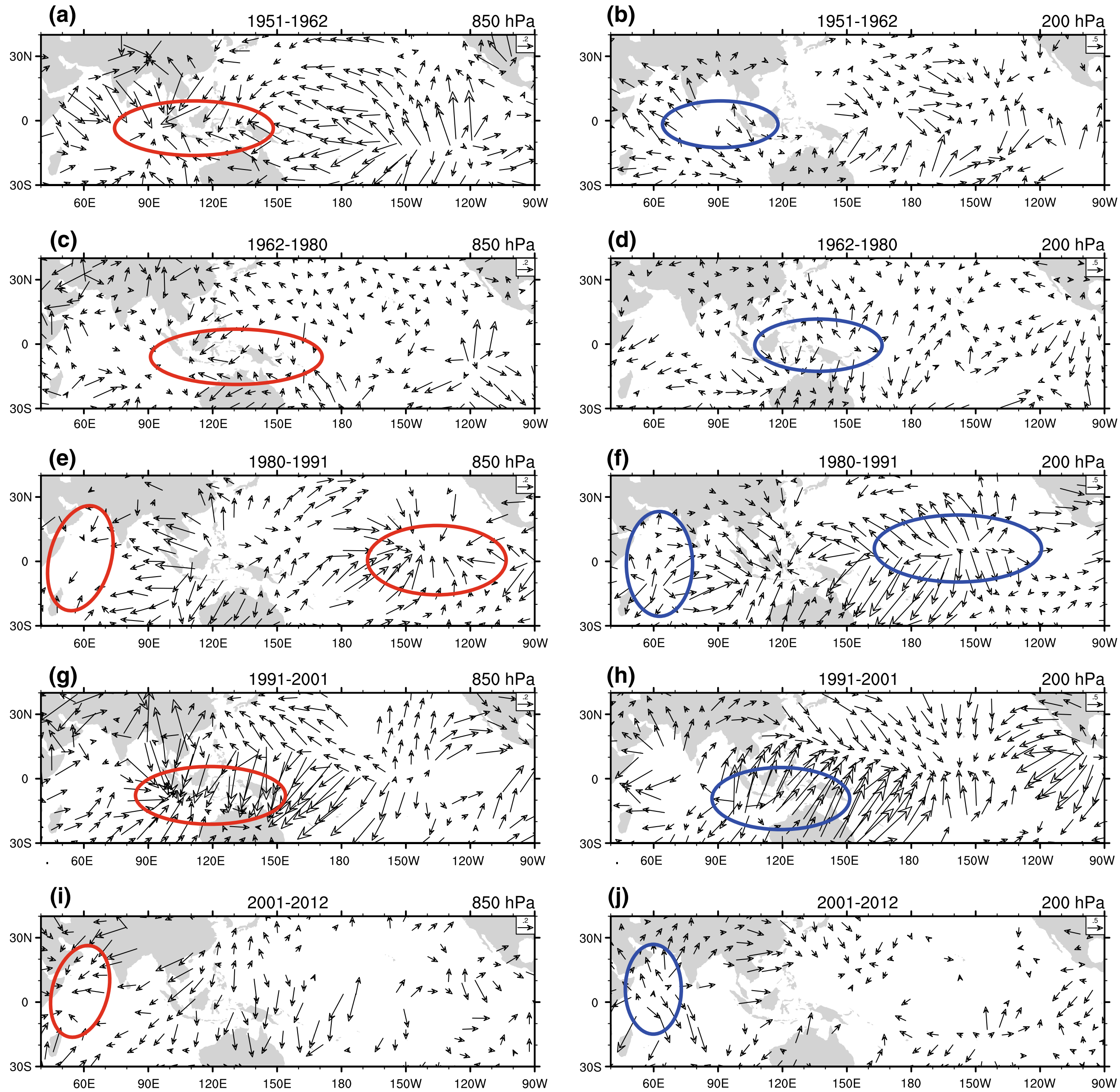

Fig. 13 Divergent components of the wind differences at 850 hPa (*left panel*) and 200 hPa (*right panel*) between the positive-phase years and negative-phase years (unit: m s^{-1}). All the vectors passed the 80 % significance level of the Student's *t* test. Convergent anomalies at 850 hPa and divergent anomalies at 200 hPa over tropical or low-latitudinal Indian Ocean or Pacific, which imply anomalous convective activity, are enclosed by *red* and *blue ellipses*, respectively

over the Maritime Continent and its adjacent oceanic areas in their positive-phase years, these three periods are still different at several aspects. For instance, significant cooler SST anomalies in central-eastern tropical Pacific characterize the positive-phase years of period 1951–1962 (Fig. 10a), while warmer SST anomalies in central-eastern tropical Pacific feature the positive-phase years of period 1962–1980 (Fig. 10b), and negative SST anomalies and descending anomalies in the central tropical Pacific characterize the positive-phase years of period 1991–2001 (Fig. 10d). Thus, the five periods under discussion are distinctive from each other with respect to the tropical SST and vertical motion anomalies associated with the leading mode of summer rainfall in East China.

In consideration of all the above discussions, a schematic diagram was drawn to illustrate the underlying mechanisms

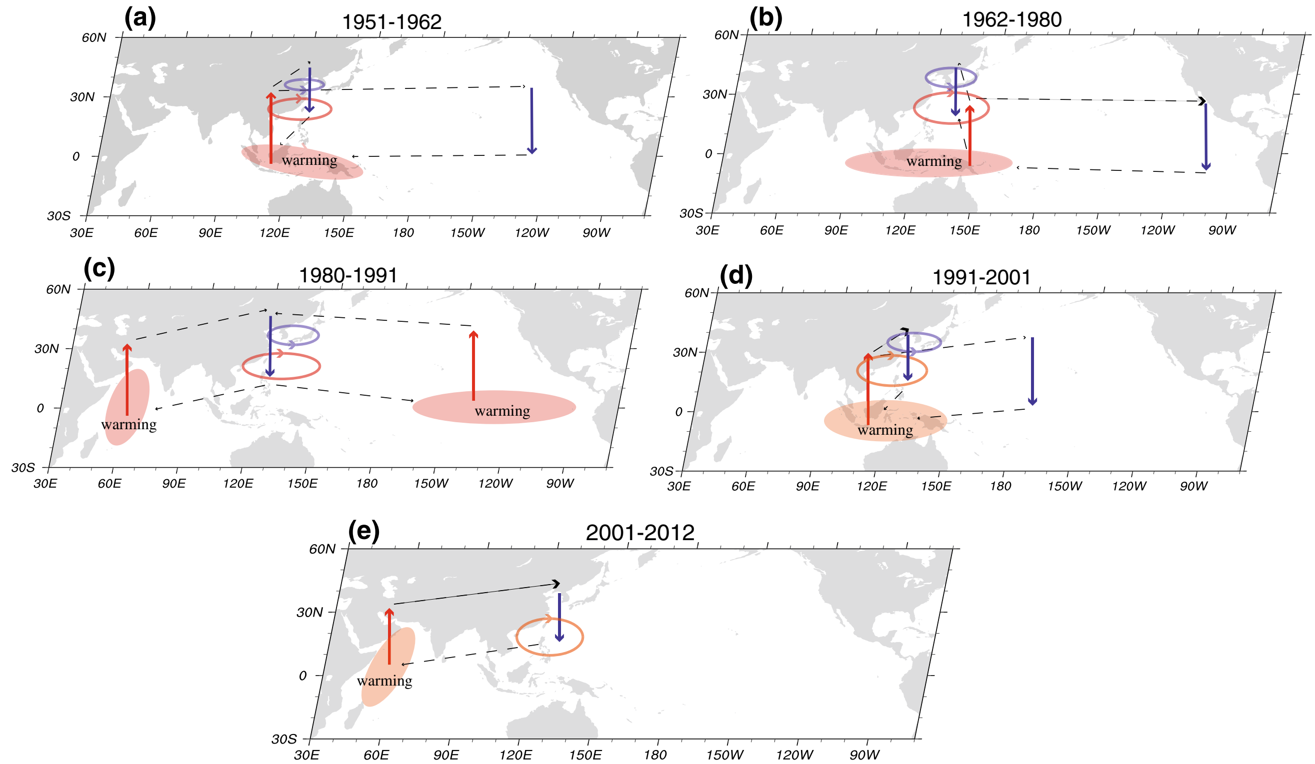

Fig. 14 Schematic diagrams of the underlying mechanisms inducing the anomalous AWVT structures associated with the leading mode of summer precipitation in East China for the five periods. *Upward arrows* denote ascending anomalies, and *downward arrows* denote descending anomalies

inducing the anomalous AWVT structures associated with the leading mode of summer precipitation in East China during the five periods for the positive-phase years, which is shown in Fig. 14. The potential mechanisms during the periods 1951–1962, 1962–1980, and 1991–2001 are similar (Fig. 14a, b, d): warming in the SSTs around the Maritime Continent would strengthen the convective activity over the Maritime continent and its adjacent oceanic areas, which may further induce a meridional wave train that causes descending and anticyclonic anomalies over the western north Pacific and South China and ascending and cyclonic anomalies over the Japan Sea and North China. This coupled "anticyclone–cyclone" dipole-structured anomalous AWVT would result in "−+−"-pattern rainfall anomalies over East China. In the meantime, the anomalous ascending motions over the Maritime Continent and its adjacent oceanic areas are associated with anomalous descending motions over central-eastern tropical Pacific, with easterly wind anomalies at low levels and westerly wind anomalies at upper levels over western-central Pacific (see Fig. 13), indicating a strengthened Walker circulation. Particularly, there seems to be two forcing sources during the period 1980–1991 (Fig. 14c): the warming of the SSTs in the western Indian Ocean and the central-eastern tropical Pacific induced two anomalous ascending branches over the two regions, which would cause easterly (westerly) wind anomalies at lower (upper) levels over the eastern Indian Ocean and westerly (easterly) wind anomalies at lower (upper) levels over the western Pacific (Fig. 13e, f). The divergent (convergent) wind anomalies at lower (upper) levels over the Maritime Continent and western subtropical Pacific resulted in descending anomalies over the Maritime Continent and western subtropical Pacific, accompanied with anticyclonic anomalies over the western subtropical Pacific and South China and further induced cyclonic anomalies over the Japan Sea and North China. During the period 2001–2012, the inter-annual variability of SSTs in the tropical Indian Ocean, western Pacific, and central-eastern Pacific was all below normal (Fig. 6), whereby the inter-annual variability of tropical air-sea interactions would have weakened impacts on the climate variability over East Asia. For this period (Fig. 14e), the single remote forcing over the western Indian Ocean may explain the absence of a strongly coupled meridional "anticyclone–cyclone" anomalous AWVT structure over East Asia in the positive-phase years: the warming of SSTs in the western Indian Ocean induced anomalous ascending motions over this region, which would cause easterly (westerly) anomalies at lower (upper) levels over eastern tropical Indian Ocean and the Maritime Continent. The easterly wind anomalies at lower (upper) levels over tropics brought about an anticyclonic shear over the western subtropical Pacific and South China, accompanied with descending anomalies. The exertion of the remote forcing of warming in the western Pacific on the anomalous anticyclonic AWVT over South China may have a relatively weak strength that a coupled anomalous cyclonic AWVT could not be further induced. In addition, no significant anomalous descending or ascending branch exists over the tropical Pacific in the positive-phase years of this period, implying less exertion from ENSO. Thus, the shift of the leading mode during the period 2001–2012 is likely to be caused by reduced influences from the tropical oceans, since the inter-annual variability of the tropical SSTs in Indian Ocean and Pacific was notably below normal during 2001–2012.

5 Conclusion and discussions

The current study investigated the inter-decadal variations of the leading mode of inter-annual variability of summer precipitation in East China from 1951 to 2012. From the 1950s to the 1980s, the main rain belt in the positive-phase years is centered along YRV, with negative rainfall anomalies in South China and North China. Since the 1990s, the main rain belt of the positive-phase years appears to be northward shifted. During the period 2001–2012, the center of the main rain belt in the positive-phase years has been shifted to the regions between the Yangtze and Yellow Rivers. This shift was mainly caused by the inter-decadal variations of the anomalous AWVT associated with the leading mode, which changed from a previously "anticyclone–cyclone" dipole structure to an anticyclonic monopole structure. The underlying physical mechanisms involving exertions from SSTs have also been investigated. In the positive-phase years of the periods 1951–1962, 1962–1980, and 1991–2001, anomalous warmer SSTs around the Maritime Continent and its oceanic areas forced anomalous convective activities in the atmosphere above, which may induce a meridional wave train that causes the "anticyclone–cyclone" dipole-structured anomalous AWVT over East Asia. In particular, there appears to be two anomalous ascending branches in the positive-phase years of the period 1980–1991 forced by the warming of SSTs in the western Indian Ocean and central-eastern tropical Pacific, respectively. During this period, the inter-annual variability of SSTs in the tropical Indian Ocean is remarkably high, implying an important role of the SSTs in the Indian Ocean in modulating the inter-annual variability of summer precipitation in East China. In the period from 2001 to 2012, a single anomalous ascending branch over the western Indian Ocean characterizes the positive-phase years, which may have failed to induce a strongly coupled "anticyclone–cyclone" dipole-structured anomalous AWVT over East Asia, resulting in a northward shift of the main rain belt and a change of the leading mode from a "−+−" pattern to a "+−" pattern. The significant inter-decadal change in the leading mode and its anomalous AWVT from 2001 to 2012 may be closely related to the below-normal inter-annual variability of the tropical SSTs in both the Indian Ocean and Pacific, whereby the influence of the tropical SSTs on the inter-annual variability of the East Asian climate could have been diminished.

Since the variability of tropical SSTs is principally characterized by the cycle of ENSO, the relationship between the leading mode of summer precipitation in East China and tropical SSTs revealed by this study implies that the inter-decadal variability of ENSO may have impacts on the inter-decadal transition of this leading mode. Although the results of an additional analysis does not show direct evidences of a significant correlation relationship between the positive/negative phase years of the leading mode and the El Nino/La Nina developing or decaying summers (figure omitted), the potential impacts of ENSO should not be neglected. Li and Zhou (2012) examined the first two modes of the AWVT over the western north Pacific and East Asia, which have similar spatial patterns with the AWVT associated with the leading mode of summer precipitation in East China, and found that they have a coupling relationship with ENSO in a quasi-4-year period. Hence, the potential exertions of ENSO on the leading mode of summer precipitation in East China deserve deeper insights.

It should be noted that this study mainly focuses on the inter-decadal variation of the leading mode of summer precipitation in East China and its associated anomalous AWVT. Although we have made efforts to explore the underlying physical mechanisms based on teleconnections, with meaningful results having been obtained, the discussions did not delve into the details of the internal mechanisms of the inter-decadal variability of SST and climate in East Asia and how the potential forcing sources have induced the anomalous AWVT over East Asia. It has been argued that the inter-decadal variations of East Asian summer monsoon in the late twentieth century are natural processes rather than consequences of anthropogenic global warming (Jiang and Wang 2005), and there exists large uncertainties in model projections of monsoon precipitation over China due to internal model physical processes (Gao et al. 2012). The inter-decadal transition of the leading mode of summer precipitation revealed in this study could be primarily an internal variability of climate system, but whether it is related to external forcing needs further research. Many studies have focused on how the climate in East Asia is influenced by tropical SSTs, which has been shown to be a complicated issue (e.g., Wang et al. 2000; Wu et al. 2009). In addition, the inter-decadal variation of the relationship between the climate in East Asia and ENSO and the internal instability of the climate system make this problem even more complex (Chang et al. 2000a, b; Wang 2002; Wu and Wang 2002; He and Wang 2013; Wang et al. 2013). Thus, it is out of the question for the current study to completely make it clear. However, the suppositions proposed in this study are expected to give rise to further more valuable thoughts on this issue.

Another limitation of this study is that the current paper only considers the potential exertions from tropical and low-latitude SSTs in concurrent summers when investigating the underlying mechanism associated with the inter-decadal variation of the leading mode of summer precipitation in East China. Nevertheless, there are other important factors that could significantly influence the inter-annual and inter-decadal variability of summer precipitation in East China, such as the snow cover and heating over the Tibetan Plateau (Hsu and Liu 2003; Zhang et al. 2004; Zhao et al. 2007), the Arctic Oscillation (Gong and Ho 2003), the boreal spring Hadley circulation (Zhou and Wang 2006), the North Atlantic SSTs (Gu et al. 2009), the Pacific Decadal Oscillation (Zhou et al. 2006; Zhu et al. 2011), and the winter SSTs east of Australia (Zhou 2011). Thus, the anomalous AWVT over East Asia may be partly caused by other factors in addition to the tropical SST anomalies and their connected anomalous vertical motions. A more comprehensive understanding on this issue calls for further studies.

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