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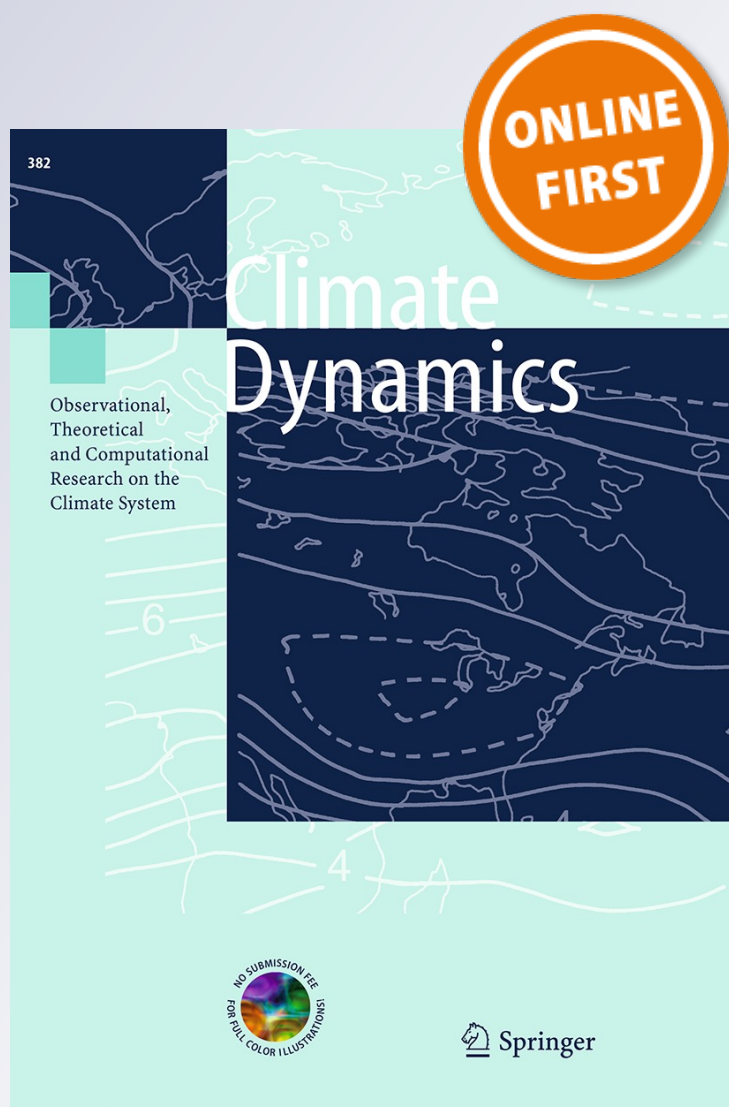
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# Interdecadal change of the controlling mechanisms for East Asian early summer rainfall variation around the mid-1990s

So-Young Yim · Bin Wang · MinHo Kwon

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**Abstract** East Asian (EA) summer monsoon shows considerable differences in the mean state and principal modes of interannual variation between early summer (May–June, MJ) and late summer (July–August, JA). The present study focuses on the early summer (MJ) precipitation variability. We find that the interannual variation of the MJ precipitation and the processes controlling the variation have been changed abruptly around the mid-1990s. The rainfall anomaly represented by the leading empirical orthogonal function has changed from a dipole-like pattern in pre-95 epoch (1979–1994) to a tripole-like pattern in post-95 epoch (1995–2010); the prevailing period of the corresponding principal component has also changed from 3–5 to 2–3 years. These changes are concurrent with the changes of the corresponding El Niño–Southern Oscillation (ENSO) evolutions. During the pre-95 epoch, the MJ EA rainfall anomaly is coupled to a slow decay of canonical ENSO events signified by an eastern Pacific warming, which induces a dipole rainfall feature over EA. On the other hand, during the post-95 epoch the anomalous MJ EA rainfall is significantly linked to a rapid decay of a central Pacific warming and a distinct tripolar sea surface temperature (SST) in North Atlantic. The

central Pacific warming-induced Philippine Sea anticyclone induces an increased rainfall in southern China and decreased rainfall in central eastern China. The North Atlantic Oscillation-related tripolar North Atlantic SST anomaly induces a wave train that is responsible for the increase northern EA rainfall. Those two impacts form the tripole-like rainfall pattern over EA. Understanding such changes is important for improving seasonal to decadal predictions and long-term climate change in EA.

**Keywords** East Asian summer monsoon · El Niño–Southern Oscillation (ENSO) · North Atlantic Oscillation (NAO) · Philippine Sea anticyclone · Prediction

## 1 Introduction

The seasonal prediction of the East Asian (EA) summer monsoon (EASM) is a challenging issue in climate studies. Wang et al. (2009) (hereafter as WL2009) suggested that separate prediction of bi-monthly anomalies for May–June (MJ) and July–August (JA) may help improve seasonal prediction of summer rainfall over EA. The reasons are (a) there are prominent differences in the mean state of precipitation and atmospheric circulation between MJ and JA, and (b) there are distinct principal modes of interannual precipitation variation. The predictability of these modes was investigated by analyzing the outputs of the Atmospheric Model Intercomparison Project Phases II (AMIP II) (Li and Zhou 2011). There are unexplained features and characteristics of the EA MJ rainfall which need to be better understood for improving EA summer monsoon prediction. Thus our study focuses on the MJ precipitation in EA.

Previous studies have shown interdecadal shifts of precipitation and large-scale circulation patterns over EA in

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the late-1970s (Wu and Wang 2002; Yu et al. 2004; Li et al. 2005; Yu and Zhou 2007; Wang et al. 2008; Zhou et al. 2008, 2009) and the mid-1990s (Kwon et al. 2005; Yim et al. 2008; Kajikawa and Wang 2012). The mid-1990s shift is prominent in spring and summer seasons. Here, our study aims to detect whether EA MJ rainfall anomalies have an interdecadal change in the mid-1990s. We examine differences in spatial and temporal structures between the leading modes of EA MJ rainfall variability before and after the mid-1990s. In addition, we are trying to determine possible factors that are responsible for such an interdecadal change.

The data and methods are briefly described in Sect. 2. We document the interdecadal changes in the EA MJ rainfall variability around the mid-1990s and explore the possible mechanisms responsible for the changes in Sect. 3. The last section presents a summary and discussion.

## 2 Data and methods

There are two global precipitation datasets available: Global Precipitation Climatology Project (GPCP) Version 2.2 (Huffman et al. 2011) and Climate Prediction Center merged analysis of precipitation (CMAP) (Xie and Arkin 1997). We use the GPCP data to derive the leading mode of MJ rainfall variability because the GPCP data is more reliable in revealing long-term variability (Zhou et al. 2008; Wang et al. 2012). However, we compared the leading modes of MJ precipitation derived from CMAP and GPCP dataset. The results show that their leading modes have extremely similar spatial ( $r = 0.94$ ) and temporal ( $r = 0.95$ ) structures. Only the higher modes show differences.

The atmospheric circulation and sea surface temperature (SST) data used were derived from the newly released ERA interim (Dee et al. 2011) and the National Oceanic and Atmospheric Administration extended reconstructed SST version 3 (Smith et al. 2008), respectively. The data periods are from 1979 to 2010. The principal modes of EA MJ rainfall were identified by applying empirical orthogonal function (EOF) analysis. The maximum covariance analysis (MCA) (Wallace et al. 1992) was used to identify important coupled modes of variability between EA rainfall and SST.

## 3 Interdecadal change of EASM in the mid-1990s

### 3.1 Changes of the temporal-spatial structure of MJ precipitation in East Asia

WL2009 presented the first three EOF modes of interannual precipitation variability (2–8 years only) in the

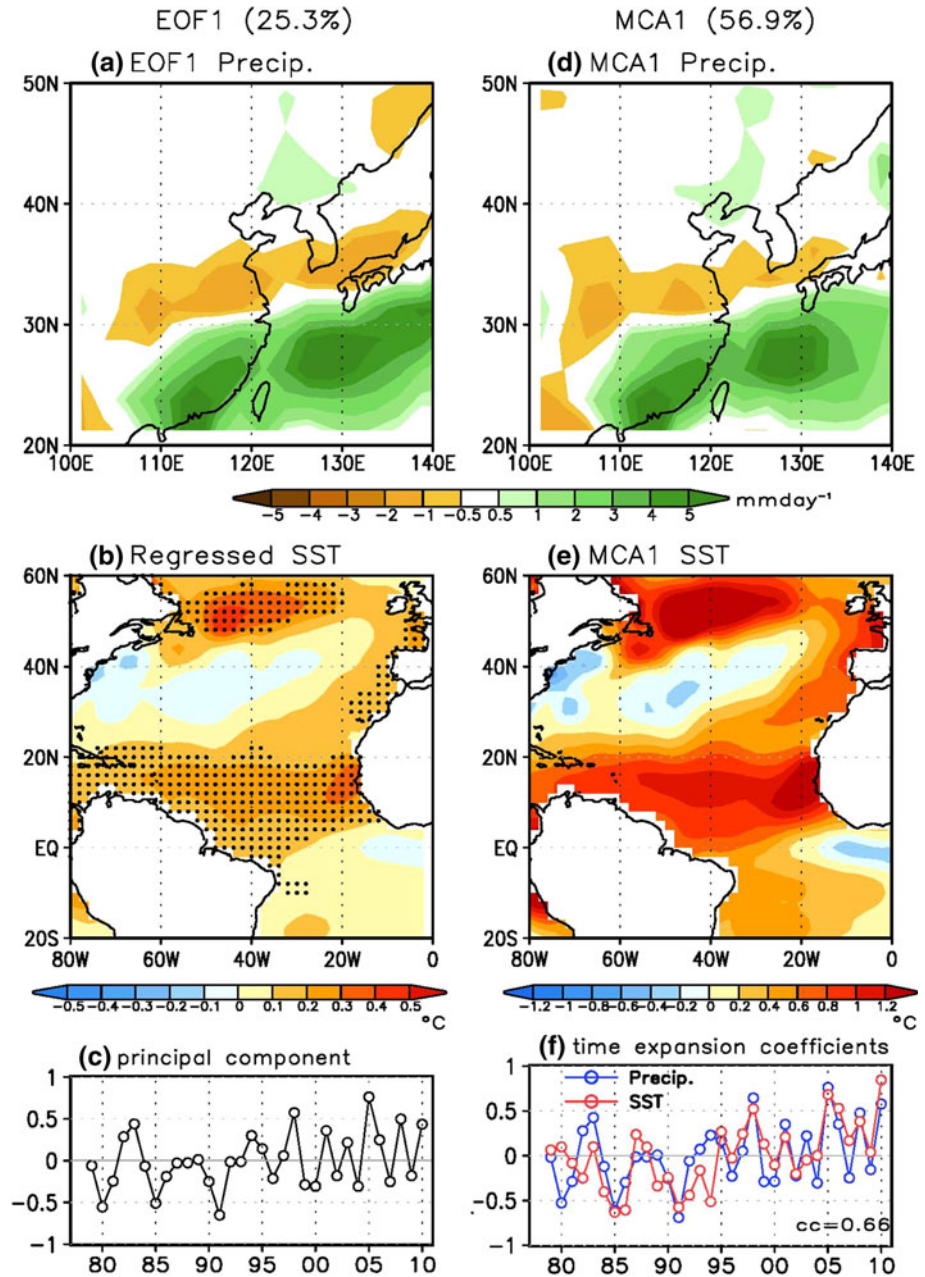
subtropical and midlatitude EA monsoon domain during MJ, which are associated with the north-eastward movement of rain-band. Here, an EOF analysis was performed over the region ( $20^{\circ}\text{N}$ – $50^{\circ}\text{N}$ ,  $100^{\circ}\text{E}$ – $140^{\circ}\text{E}$ ) to detect the interdecadal change but using total MJ rainfall which includes both interannual and decadal variations.

The leading EOF mode (EOF1) for the entire period (1979–2010) accounts for 25.3 % of the total precipitation variance, which is clearly separated from the rest of the modes according to the criterion of North et al. (1982). The spatial pattern of EOF1 shows large positive rainfall anomalies along a belt between  $20^{\circ}\text{N}$  and  $30^{\circ}\text{N}$  and localized positive precipitation anomalies in the northern Korean peninsula with negative precipitation anomalies between these two wet regions (Fig. 1a). The corresponding principal component (PC1) shows moderate amplitude before the mid-1990s but increased variability after the mid-1990s, indicating a decadal shift of the variability around mid-1990s (Fig. 1c). The regressed MJ SST anomalies associated with PC1 exhibit a significant tripole-like structure in North Atlantic (Fig. 1b).

To confirm the EA MJ rainfall–North Atlantic SST relationship, we applied the MCA analysis to identify the coupled patterns of variability between EA MJ rainfall and North Atlantic SST for the entire period. The leading coupled pattern (i.e., MCA1 precipitation and MCA1 SST) explains about 57 % of the total covariance. Note that MCA1 precipitation pattern corresponds to EOF1 of precipitation extremely well with a spatial correlation coefficient of 0.93 (Fig. 1d) and a temporal correlation coefficient of 0.99 (Fig. 1c, f), indicating the robustness of this coupled mode. The MCA1 SST features a positive–negative–positive SST anomaly pattern in the meridional direction of North Atlantic (Fig. 1e). The cooling occurs in the subtropical Atlantic with a center located at the east coast of the United States; and the warming appears in the northern North Atlantic and the tropical North Atlantic. The corresponding time expansion coefficients of MCA1 precipitation and SST are significantly correlated each other ( $r = 0.66$ ) for the entire period. However, the time series during post-95 (1995–2010) seem to go together better than during pre-95 (1979–1994) period. Indeed, the correlation coefficient between the two time expansion coefficients abruptly changes from 0.35 during pre-95 to 0.84 during post-95 (Fig. 1f). The above results indicate that the relationship between EA MJ precipitation and North Atlantic SST has apparently strengthened in a recent epoch and the tripolar North Atlantic SST might be one of the possible factors causing an interdecadal change of EA MJ precipitation in the mid-1990s.

To test the aforementioned hypothesis, we compare the EOF1s of MJ precipitation anomalies derived for two epochs in Fig. 2. The pre-95 EOF1 and the post-95 EOF1

**Fig. 1** The leading EOF mode of **a** MJ precipitation over East Asia, **b** regressed SST anomalies over Atlantic Ocean, and **c** its corresponding principal component for the period 1979–2010. The leading MCA mode of **d** East Asian MJ precipitation and **e** North Atlantic SST, and **f** the corresponding time expansion coefficients. The EOF1 and MCA1 explain 25.3 and 56.9 % of the total precipitation variance and co-variance, respectively



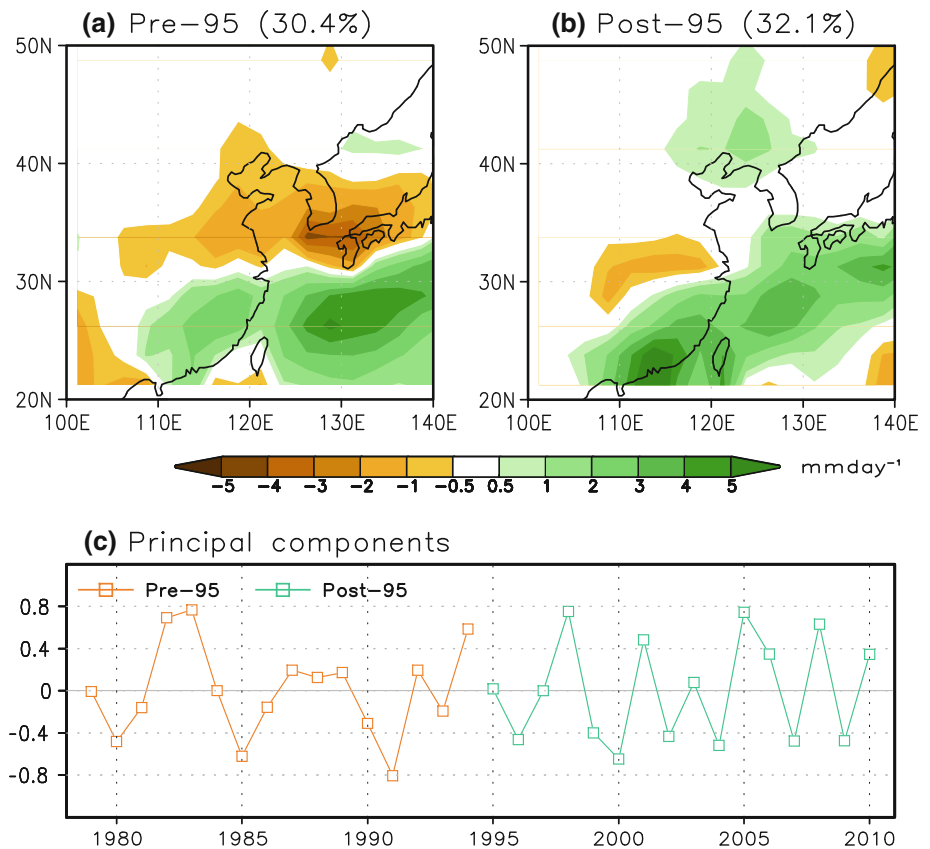
explain 30 and 32 % of the total precipitation variance, respectively. Of interest is that significant differences between two epochs are seen in their spatial patterns. The pre-95 EOF1 features a north–south dipole pattern with the positive center located south of 30°N and the negative center north of 30°N (Fig. 2a). On the other hand, the post-95 EOF1 features a tripolar rainfall pattern that is almost the same as that during the entire period (Figs. 2b, 1a). In addition, the prevailing period of the corresponding principal component has also changed from 3–5-years to 2–3 years (Fig. 2c). The PC1s in pre-95 and post-95 correspond well to the time series of PC1 in the entire period (Fig. 2c).

### 3.2 The evolution of SST and atmospheric circulation during the post-95 epoch

As mentioned above, the relationship between EA MJ rainfall and North Atlantic SST has obviously changed in the mid-1990s and its relationship has also been enhanced since the mid-1990s. The EA MJ rainfall is coupled well with the triple-like SST in North Atlantic in post-95 epoch (Fig. 3). The SST evolution and large-scale circulation anomalies associated with MCA1 SST during post-95 are investigated in this subsection.

The regressed SST patterns associated with MCA1 SST during post-95 show a central Pacific warming that

**Fig. 2** The leading EOF mode of MJ precipitation in East Asia: Spatial patterns for **a** the pre-95 epoch and **b** the post-95, and **c** their corresponding principal components

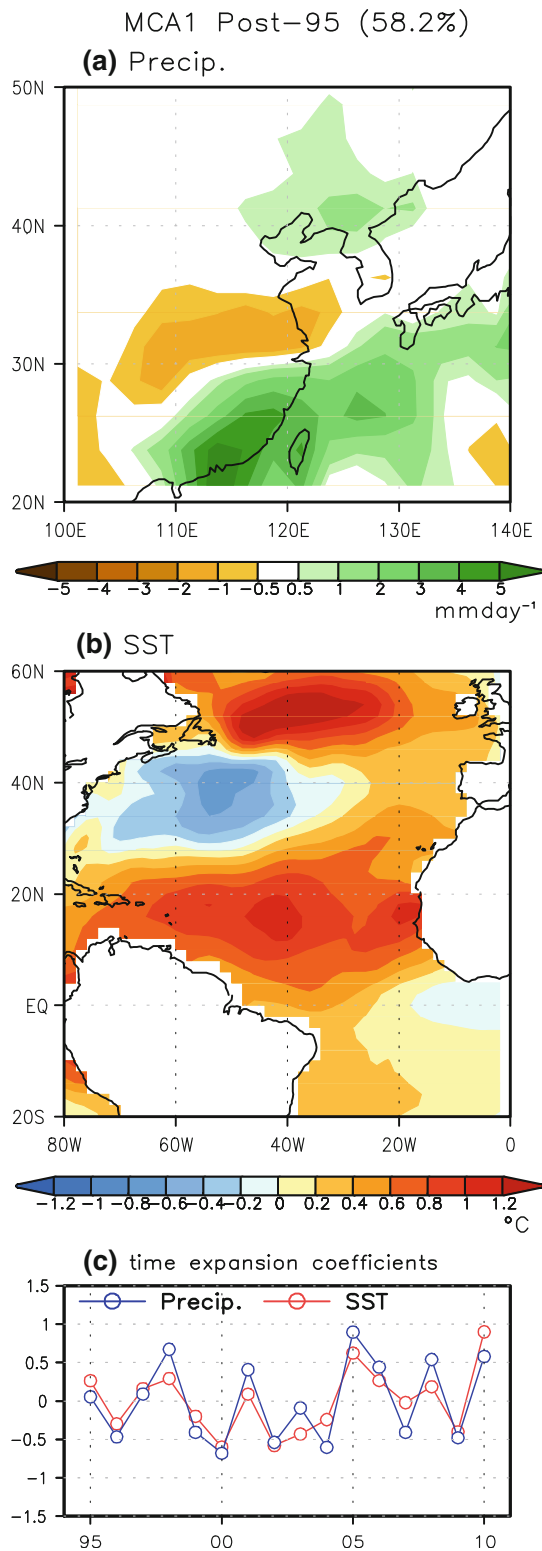


resembles the El Nino Modoki or warm pool El Nino (Weng et al. 2007; Kug et al. 2009) in the previous January–February (JF) and March–April (MA) (Fig. 4a, c), which rapidly changes to a La Nina phase in the following late summer (not shown). An interesting feature is that the distinct tripole-like SST anomalies in North Atlantic, which occur in the previous MA, tend to strengthen in MJ and last until the following autumn even though their amplitudes weaken. Additionally, we have repeated the MCA analysis by using MJ global SST anomalies and the SST result shows almost the same as the regressed MJ SST pattern, which indicate a weak correlation between EA MJ rainfall and ENSO simultaneously (not shown).

Some studies demonstrated that the tripole-like SST anomalies in North Atlantic is driven by the North Atlantic Oscillation (NAO) (e.g., Deser and Blackmon 1993). The NAO is the dominant mode of natural climate variability in the North Atlantic and surrounding continents (Hurrell and Harry 1997) and features a large-scale seesaw in atmospheric mass between the subtropical high and the polar low. It has been reported that the summer NAO has some different characteristics compared to winter NAO and can exert a strong influence on the summer climate variability although its amplitude is smaller than the winter NAO (Folland et al. 2009). However, most studies of the associations between the NAO and regional to hemispheric

climate have focused on boreal winter and only a few studies focusing on the East Asian climate and summer NAO's influence (Wu et al. 2009; Sun et al. 2008, Gong et al. 2011).

Here, we examine simultaneous atmospheric patterns during post-95 to see whether the teleconnection associated with MCA1 SST shows the NAO pattern or not. The regressed sea level pressure (SLP) anomalies show a meridional seesaw pattern, with high SLP anomalies in the high latitudes and low SLP anomalies south of about 55°N (Fig. 4f). To some degree, this pattern is quite similar to a negative NAO pattern that has two nodes in the North Atlantic region, one centered near 35°N and the other around 65°N. Another striking feature is a notable wave train from North Atlantic via Eurasia to northeastern Asia, which is apparent in both the regressed SLP and 500 hPa geopotential height anomalies (Figs. 4f, 5). This extratropical teleconnection is characterized by three positive height anomalies over the North Atlantic, the Ural Mountain and the Okhotsk Sea, and two negative ones over Western Europe and Mongolia. The wave train corresponds to the regressed surface air temperature very well with high pressure being accompanied by warming (Fig. 5). The cyclone over Mongolia might relate to increased rainfall over the northern EA. The regressed 925-hPa wind field shows prominent southwesterly anomalies along the



**Fig. 3** The same as Fig. 1d, e, and f except for the post-95 epoch

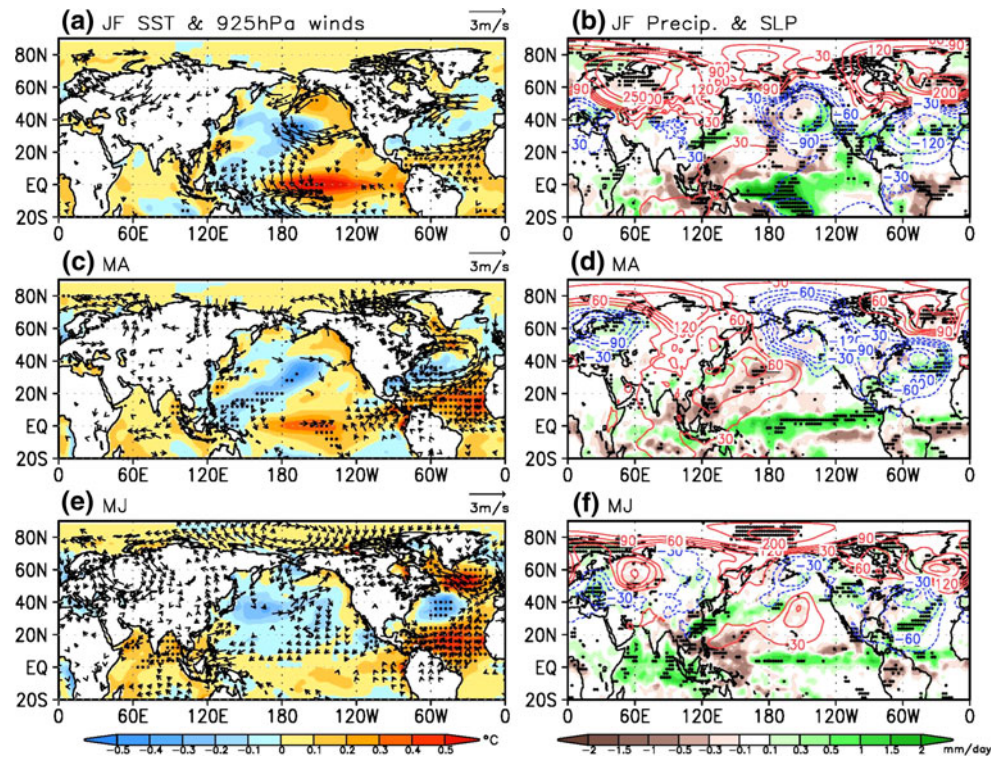
northwestern flank of anomalous Philippine Sea anticyclone, which leads to enhanced (decreased) rainfall over the southeastern China (central eastern China) (Fig. 4f). The results indicate that MJ EA rainfall anomaly can be

affected by both tropical and midlatitude circulations: One is from the anomalous Philippine Sea anticyclone and the other is from the NAO.

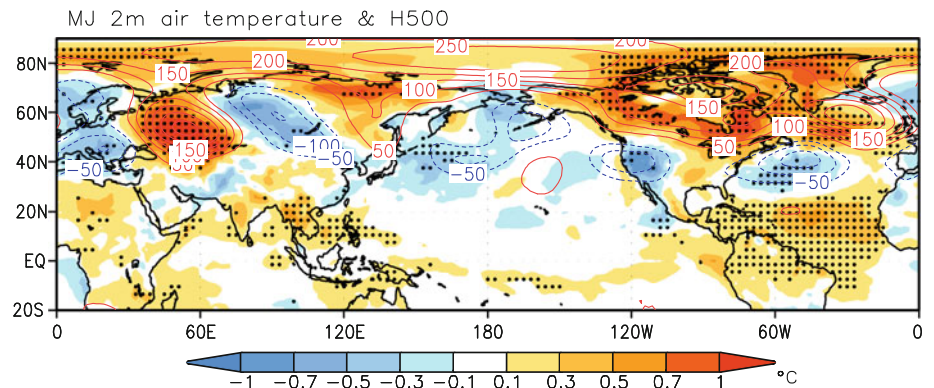
How are the MJ atmospheric circulation anomalies established? To shed light on this question, we investigated the atmospheric circulations and precipitation anomalies with a bi-monthly interval extending from MJ back to the previous JF and MA. During JF, there is a central Pacific warming (Fig. 4a) and the corresponding rising motion leads to enhanced precipitation anomalies near the dateline. At the same time, significant suppressed precipitation is seen in the western Pacific and maritime continent, while enhanced precipitation is seen over the EA polar frontal zone from southern China coast to south of Japan. A prominent anticyclone titled along southwest to northeast direction occupies the southeast Indian Ocean and the Philippine Sea (Fig. 4b). In MA, this anomalous anticyclone intensifies over the Philippine Sea (Fig. 4d) along with sea surface cooling to its southeast side (Fig. 4c), indicating a positive thermodynamic feedback between the Philippine Sea anticyclone and underneath ocean proposed by Wang et al. (2000) amplifies both the atmospheric and oceanic anomalies. The development of the Philippine Sea anticyclone also extends its ridge into the northern Indian Ocean, which enhances downward solar radiation and results in strong warming in the northern Indian Ocean in MJ (Fig. 4e). The northern Indian Ocean warming during MJ in turn increases precipitation heating which maintains the anomalous Philippine Sea anticyclone (Fig. 4f). This evolution process supports the positive feedback theory between the anomalous western Pacific anticyclone and Indo-Pacific ocean warm pool elaborated by Wang et al. (2013). The anomalous Philippine Sea anticyclone enhances southwesterly winds along the northwest flank of the anticyclone, transporting abundant moisture toward the southeastern China, and increasing (decreasing) rainfall over the same region (central eastern China).

The tripole-like SST pattern in North Atlantic is linked to strong westerly wind anomalies in the subtropical North Atlantic during MA (Fig. 4c). The southwesterly wind anomalies weaken the climatological northeasterly trade wind. This favors a positive feedback of the wind speed-evaporation-SST (WES) mechanism (Xie and Philander 1994; Chang et al. 1997), which develops the meridional gradient among the SST anomalies (Fig. 4e). Here, we can see the persistence of the triple-like North Atlantic SST from MA to MJ. Indeed, during post-1995 epoch the MA tripolar North Atlantic SST index (TSSTI) is highly correlated with the MJ TSSTI at  $r = 0.75$ . The TSSTI is defined as the difference between the sum of averaged SST in two positive regions ( $0^{\circ}\text{--}20^{\circ}\text{N}$ ,  $50^{\circ}\text{W--}25^{\circ}\text{W}$  and  $45^{\circ}\text{N--}55^{\circ}\text{N}$ ,  $40^{\circ}\text{W--}25^{\circ}\text{W}$ ) and averaged SST in the negative region ( $35^{\circ}\text{N--}45^{\circ}\text{N}$ ,  $70^{\circ}\text{W--}60^{\circ}\text{W}$ ) (Wu et al. 2009). The

**Fig. 4** The regressed SST, 925 hPa winds, precipitation, and SLP anomalies during **a**, **b** JF, **c**, **d** MA, and **e**, **f** MJ with respect to the time series of MCA1 SST in the post-95 epoch. The areas exceeding 95 % confidence level for SST and precipitation are dotted and shown are wind vectors that are significant above the 90 % confidence level by Student's  $t$  test



**Fig. 5** The regressed field of MJ 2 m air temperature (shading) and 500 hPa geopotential height (contour) with respect to the time series of MCA1 SST in the post-95 epoch. The areas exceeding 95 % confidence level were dotted



signal of the tripole-like SST in North Atlantic in earlier season prior to the summer may be important as a precursor for better prediction of the EA MJ rainfall ( $r = 0.54$ ) even though their simultaneous correlation coefficient is higher ( $r = 0.66$ ). The persistent tripolar North Atlantic SST anomaly induces an extratropical wave train in MJ that is supported by Wu et al. (2009).

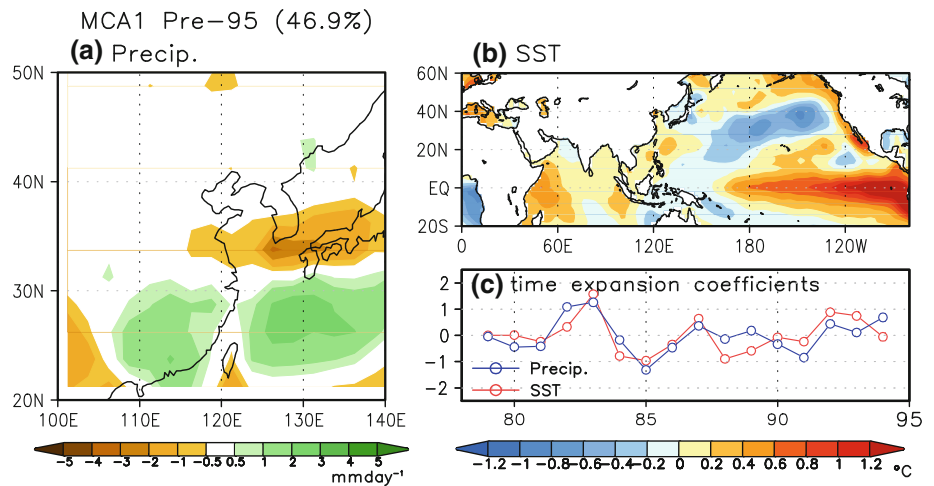
### 3.3 What is the mechanism for pre-95 scenario?

To investigate the SST pattern associated with EA MJ precipitation anomalies during pre-95, the MCA analysis is performed using the EA MJ precipitation and the Indo-Pacific SST. The spatial and temporal patterns of MCA1 precipitation in pre-95 epoch are similar to those of the pre-95 EOF1 with

spatial and temporal correlation coefficients of 0.86 and 0.92, respectively (Fig. 6a). Unlike post-95 epoch the associated SST distribution shows a canonical eastern Pacific El Niño pattern (Fig. 6b). There are no significant tripole-like structures over the North Atlantic in MJ (Fig. 7e).

In the lead-lag SST relationship, the evolution of SST anomalies features the slow decay of canonical ENSO events that has a clear warming over the tropical central-eastern Pacific and a cooling over the western Pacific from JF to MJ (Fig. 7a, c, e). The associated rising motion and sinking motion dominate in the tropical eastern Pacific and western Pacific, respectively. Meanwhile the anomalous anticyclone appears in the western North Pacific and this is maintained from JF to MJ (Fig. 7b, d, f) through a positive feedback between the anticyclone and underlying cold SST

**Fig. 6** The leading MCA mode of **a** East Asian MJ precipitation and **b** Indo-Pacific SST, and **c** their corresponding time expansion coefficients during the pre-95 epoch



anomaly (Wang et al. 2000). In MJ, the prominent feature is an anomalous low-level anticyclone in the western North Pacific, which leads the increasing (decreasing) rainfall anomalies along  $20^{\circ}\text{N}$ – $30^{\circ}\text{N}$  ( $30^{\circ}\text{N}$ – $40^{\circ}\text{N}$ ). As expected, no significant patterns exist in the mid-latitude (Fig. 7). As a result, the MJ rainfall anomaly features a dipole rainfall pattern over EA.

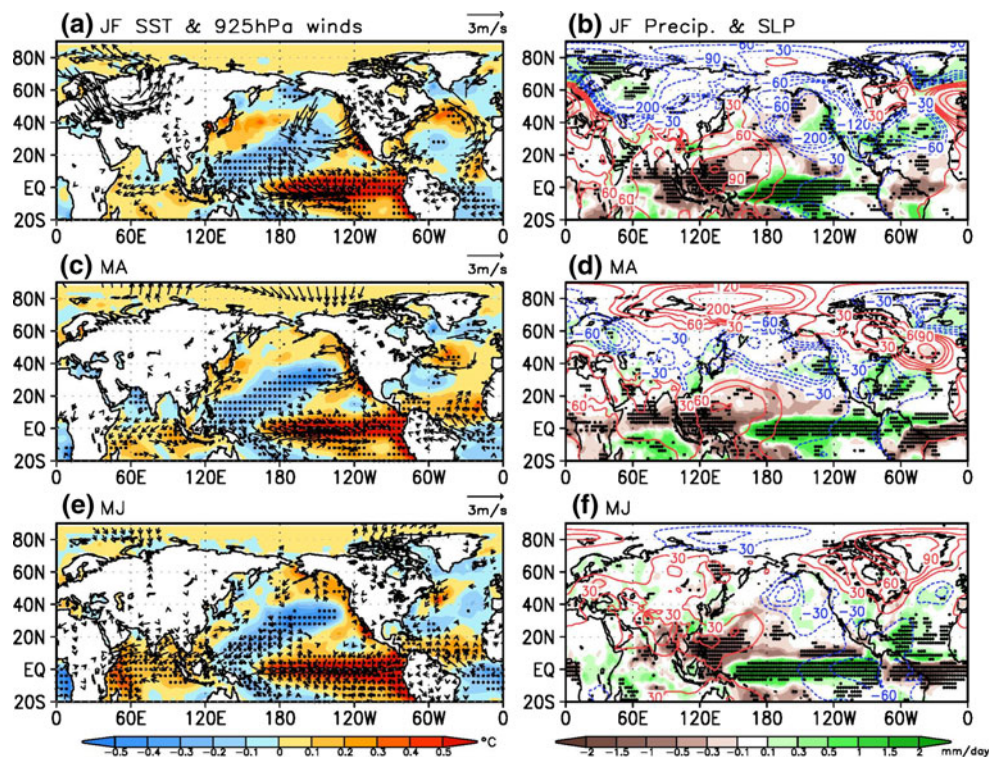
#### 4 Summary and discussions

We detected that anomalous EA MJ rainfall has experienced a remarkable interdecadal change around the mid-

1990s. The spatial structure of the rainfall anomalies associated with the EOF1 has changed from a dipole-like pattern in pre-95 epoch (1979–1994) to a tripole-like pattern in post-95 epoch (1995–2010). The prevailing period of the corresponding principal component has also changed from 3–5 years to 2–3 years. Understanding such changes is important for improving seasonal to decadal predictions and long-term climate change in EA.

What causes the differences between two epochs? Firstly, the corresponding ENSO evolutions have been changed. The pre-95 EOF1 is associated with a slow decay of canonical ENSO as evidenced by a significant SST anomaly in the central-eastern Pacific that persists from JF to MJ (Fig. 7).

**Fig. 7** The same as Fig. 4 except for the pre-95 epoch



The anomalous Philippine Sea anticyclone in MJ is primarily maintained by the positive thermodynamics feedback between an anomalous Philippine Sea anticyclone and the local sea surface cooling (Wang et al. 2000). On the other hand, the post-95 EOF1 is associated with a rapid decay of a central Pacific warming (Fig. 4). Here, we need to clarify the difference between our EOF1 and the EOF1 in WL2009. Their EOF1 has no lead-lag relationship with ENSO. The difference might come from a different time scale because they focused on the rainfall variability with interannual component (2–8 years) only by filtering. Second, the MA tripole-like SST anomaly in North Atlantic during post-95 epoch is much stronger than during pre-95 epoch and it lasts until MJ unlike pre-95 epoch. As a result, the principal pattern of MJ rainfall variability over EA is dominantly associated with the slow decay of canonical ENSO events in the pre-95 epoch, whereas it is closely associated with the rapid decay of central Pacific warming and the tripole-like North Atlantic SST in the post-95 epoch.

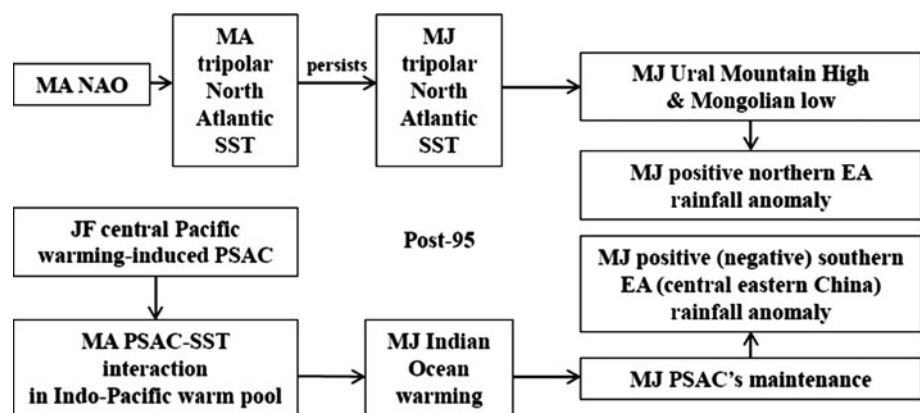
During the post-1995 epoch, the NAO-related tripolar North Atlantic SST persists from MA to MJ and induces a wave train that has a prominent Ural mountain High and Mongolian low which is responsible for the northern EA increased rainfall. On the other hand, the central Pacific warming–induced Philippine Sea anticyclone in the winter interacts with the underlying warm ocean and the Philippine Sea anticyclone is maintained by the air-sea interaction in Indo-Pacific warm pool (Indian Ocean warming and western Pacific cooling) in MA and MJ, which leads to the enhanced southern China rainfall and suppressed central china rainfall. Together with the impact of the North Atlantic SST anomaly form the tripolar rainfall pattern over EA during the post 1995 epoch. The rapid decay of the central Pacific warming also paces the biennial tendency of the EA MJ rainfall variability during the post-1995 epoch. The associated process is summarized in a schematic diagram (Fig. 8).

In summary, we proposed two mechanisms that affect EA MJ rainfall anomaly. One is the western North Pacific

(WNP) anomalous anticyclone-warm ocean interaction originally advanced by Wang et al. (2000). This mechanism works for both the pre- and post-1995 epochs but with notable differences. For pre-1995 epoch the WNP anticyclone is excited by canonical ENSO signified by an eastern Pacific warming. The anticyclone is strong and associated with the slow decay of ENSO, which induces a dipole rainfall anomaly over EA: increased rainfall over Southern China and decreased rainfall over Japan and South Korea. On the other hand, during post-95 epoch, the WNP anticyclone is associated rapid decay of a central Pacific warming, which induces an increased rainfall in southern China and decreased rainfall in central eastern China. The second mechanism is the North Atlantic NAO-related tripolar SST anomaly, which is only significant in the post-95 epoch and induces an extratropical wave train that affects northern EA rainfall in MJ.

The previous studies have discussed how the NAO can affect EASM rainfall (Wu et al. 2009; Gong et al. 2011; Wu et al. 2012). The extratropical wave train mechanism discussed here is essentially the same as that elaborated by Wu et al. (2009). However, different from Gong et al. (2011) and Wu et al. (2012), in which they attribute the anomalous WNP anticyclone to the NAO, we think that the evidence for NAO impacts on the WNP anomalous anticyclone is not evident in our analysis of MJ precipitation variability. Rather the WNP anticyclonic anomaly is seen existing in previous winter and persists through local atmosphere–ocean interaction. In a recent study of the WNP subtropical High dynamics, Wang et al. (2013) proposed another mechanism by which tropical Atlantic warming could affect WNP subtropical High, i.e., a warm northern tropical Atlantic in spring can excite a Rossby wave response and generates a cyclonic anomaly to the west of the SST warming, which weakens trade wind and induces a central Pacific warming in ensuing summer. The central Pacific warming during summer can have a forced response in the western Pacific that changes the Subtropical High strength. This issue remains open and calls for further investigation.

**Fig. 8** A schematic diagram to summarize the controlling mechanism for MJ EA rainfall anomaly in post-95 epoch. The PSAC indicates anomalous Philippine Sea anticyclone



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