Out-of-Phase Relationship between Boreal Spring and Summer Decadal Rainfall Changes in Southern China*

ZHIWEI ZHU
Key Laboratory of Meteorological Disaster of Ministry of Education, and School of Atmospheric Science, Nanjing University of Information Science and Technology, Nanjing, China

TIM LI
Key Laboratory of Meteorological Disaster of Ministry of Education, and School of Atmospheric Science, Nanjing University of Information Science and Technology, Nanjing, China, and International Pacific Research Center, and Department of Meteorology, University of Hawai‘i at Mānoa, Honolulu, Hawaii

JINHAI HE
Key Laboratory of Meteorological Disaster of Ministry of Education, and School of Atmospheric Science, Nanjing University of Information Science and Technology, Nanjing, China

(Manuscript received 18 March 2013, in final form 3 September 2013)

ABSTRACT

A multivariate empirical orthogonal function (MV-EOF) analysis for 1979–2010 shows that low-level circulation and rainfall over East Asia experienced a significant decadal shift around the mid-1990s. During boreal spring (March–May), the first principal component (PC) of the MV-EOF exhibits a marked decadal change around the mid-1990s, while during boreal summer (June–August) the second PC shows a pronounced decadal shift around the same time. It is further noted that the decadal rainfall change over southern China experienced an out-of-phase relationship between boreal spring and summer; that is, from the pre-1994 to the post-1994 period, the rainfall tends to decrease in boreal spring but increase in boreal summer.

A mechanism is put forward to explain the out-of-phase decadal rainfall change over southern China between boreal spring and summer. In boreal spring, the composite differences of SST between the latter and former decadal periods indicate a La Niña–like pattern with warming in the western Pacific and cooling in the eastern Pacific. This pattern leads to enhanced convection over the Maritime Continent, which may further induce anomalous subsidence and thus negative rainfall anomalies over southern China through the local Hadley circulation. In boreal summer, dominant decadal SST warming appears in the entire tropical Indian Ocean while the negative SST anomalies in eastern Pacific are much weaker. The warm SST anomaly over the Indian Ocean leads to suppressed convection over the Maritime Continent, which, through the local Hadley cell, favors the strengthening the East Asian monsoon trough and leads to a positive rainfall anomaly over southern China.

1. Introduction

Prediction of rainfall variability over southern China is a challenging issue, largely because rainfall over southern China exhibits complex spatial (Tao and Chen 1987; Zhu et al. 1986) and temporal structures. For instance, rainfall over southern China experiences a marked intraseasonal to interannual time scale variability (Wang and Li 2004; Li 2010). The boreal summer intraseasonal oscillation (ISO) is related to the rainfall variability over southern China through it effects on summer monsoon onsets (Wang and Xie 1997), the active phases of the monsoon (Annamalai and Slingo 2001; Ding and Wang 2009), and the monsoon seasonal mean state (Krishnamurthy and Shukla 2007). Meanwhile, the interannual variation (IAV) of rainfall over southern China is mainly attributed to the remote forcing of

* School of Ocean and Earth Science and Technology Contribution Number 9014 and International Pacific Research Center Publication Contribution Number 1019.

Corresponding author address: Prof. Tim Li, International Pacific Research Center, and Department of Meteorology, University of Hawai‘i at Mānoa, Honolulu, HI 96822.
E-mail: timli@hawaii.edu

DOI: 10.1175/JCLI-D-13-00180.1

© 2014 American Meteorological Society
tropical sea surface temperature anomalies (SSTAs) including the El Niño–Southern Oscillation (ENSO). For example, during an El Niño peak winter, southern China often experiences an abnormal wet condition (Wu et al. 2009, 2010a), whereas during an El Niño decaying summer, severe floods frequently hit the Yangtze River Valley (Chang et al. 2000a; Wang et al. 2003). Besides, rainfall in southern China also experienced an interdecadal change (Chang et al. 2000b; Zhang et al. 2004; Li et al. 2010). Prior to 1979, rainfall anomalies over southern China and the Yangtze River had an in-phase relation, whereas after 1979 they have had an out-of-phase relation. The cause of the meridional pattern change has been argued to be related to the interdecadal changes of tropical SST and associated western Pacific subtropical high (Chang et al. 2000b).

In addition to the well-known climate change point in the late 1970s, a new regime interdecadal shift over East Asia was revealed in the mid-1990s. Kwon et al. (2005) first found that the dominant factor controlling the East Asian summer monsoon (EASM) has changed from an ENSO-related variation in the earlier period (1979–93) to a western North Pacific summer monsoon (WNPSM)-dominated variation in the later period (1994–2004). Numerical simulations also confirmed that the ENSO destructively interfered with the relationship between EASM and WNPSM after the mid-1990s (Yim et al. 2008). Under this context, southeastern China rainfall presents an increased shift after 1994 and the distinctive increase of landfall typhoon may be directly responsible for it (Kwon et al. 2007). The interdecadal change around the mid-1990s was also recognized in the South China Sea (SCS) monsoon (Wang et al. 2009). The advance onset date of the SCS monsoon was suggested to be primarily induced by the decadal change of the SST over the equatorial western Pacific (Kajikawa and Wang 2012). Meanwhile, after the mid-1990s, the abnormal warming SST in the western Pacific caused the diabatic cooling in the Indian summer monsoon (ISM) and in turn affected the rainfall pattern over East Asia through development of an anomalous local meridional cell and the Eurasian wave train pattern (Yun et al. 2010). In addition, the periodicity of interannual variability of western Pacific subtropical high has been subject to a decadal change after 1990. The change was accompanied by an anomalous meridional overturning circulation characterized by anomalous ascending and descending motion in the Maritime Continent (near the Philippine Sea) and a warm-to-cold transition of SSTA in the central-eastern equatorial Pacific from the preceding winter to the summer (Sui et al. 2007).

Besides the tropical SST forcing, processes from the middle and high latitudes also play a role in causing this decadal regime shift. Ding et al. (2008) showed that the cooling in the upper troposphere at midlatitudes made an important contribution to the significant weakening of East Asian summer monsoon after the mid-1990s. Zhu et al. (2011) suggested that the shift of the Pacific decadal oscillation (PDO) to a negative phase could weaken the westerly jet and induce a warming over the Lake Baikal, which further changed the summer precipitation pattern in eastern China after the mid-1990s. Besides, the decadal change of Tibetan Plateau snow cover around the mid-1990s may also significantly affect the relationship between ENSO and the EASM through the modulation of the ENSO teleconnection (Wu et al. 2011).

Most of the previous interdecadal variability studies focused only on boreal summer and little attention has been paid to other seasons. Given the fact that climatological rainfall in southern China starts from early spring, natural questions to be raised are 1) Does the interdecadal change have seasonal dependency? 2) What is the phase relationship between the interdecadal changes of rainfall in boreal spring and summer? Because of the persistence of the SST, long-term SST variability generally has a similar pattern in boreal spring and summer. Given the similar SST forcing, one would expect an in-phase relationship between the spring and summer rainfall anomalies. However, as demonstrated by the present study, such an in-phase relationship has not materialized. Rather, we observed an out-of-phase relationship. Therefore, the main objectives of the present study are to reveal the characteristics of circulation and rainfall changes associated with the interdecadal variability over East Asia in boreal spring and summer and to understand the physical mechanisms responsible for the out-of-phase interdecadal relationship of rainfall over southern China.

The rest of the paper is organized as follows. Section 2 introduces the datasets, analysis methods, and model used in this study. The interdecadal change of the East Asian circulation and rainfall in boreal spring and summer is depicted in section 3. In section 4, we examine the associated decadal changes of the dynamic and thermodynamic fields and discuss the physical mechanisms of the out-of-phase decadal rainfall change in southern China with the ECHAM model. The last section summarizes our major findings and discusses some outstanding issues.

2. Data, methods, and model

The primary dataset used for the analysis includes zonal and meridional winds ($U, V$), vertical $p$-velocity (omega), geopotential height ($Z$), and specific humidity...
fields at a 2.5° × 2.5° global grid from the National Centers for Environmental Prediction (NCEP)–Department of Energy (DOE) Reanalysis II (NCEP-2; Kanamitsu et al. 2002), pentad mean Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997), 160-gauge monthly rainfall data from the Chinese Meteorology Administration (CMA), and monthly precipitation data from the Global Precipitation Climatology Project (GPCP; Adler et al. 2003). Additional datasets are daily outgoing longwave radiation (OLR) from the National Oceanic and Atmospheric Administration (NOAA) satellite (Liebmann and Smith 1996) and Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al. 2003) at 1° horizontal resolution. All the datasets cover the period from 1979 to 2010.

To better capture the interdecadal rainfall variability and associated circulation change over East Asia, we applied a multivariate empirical orthogonal function (MV-EOF) analysis method. The MV-EOF analysis method was described in detail in Wang (1992). The analysis domain is defined as 10°–50°N, 100°–140°E since this is the major East Asian monsoon region according to previous studies (e.g., Zhu et al. 1986; Tao and Chen 1987; Wang and LinHo 2002). The variables used for the MV-EOF analysis include the seasonal mean anomalies of precipitation and zonal and meridional winds at 850 hPa. The MV-EOF analysis was conducted for boreal spring [March–May (MAM)] and summer [June–August (JJA)], respectively. In addition, the composite difference analyses between the two epochs were used and a local t test was applied to judge the statistical significance of the composite difference. The local t test formula is

\[ t = \frac{|\bar{x} - \bar{y}|}{\sqrt{\frac{1}{m_1} + \frac{1}{m_2}}} \]

where \( s^2 = \left[ \sum_{i=1}^{m_1} (x_i - \bar{x})^2 + \sum_{i=1}^{m_2} (y_i - \bar{y})^2 \right] / (m_1 + m_2 - 2) \), \( m_1 \) and \( m_2 \) are the sample numbers for each epoch, and \( \bar{x} \) and \( \bar{y} \) are the means for each sample, respectively.

An atmospheric general circulation model (AGCM), the ECHAM (v4.6) model (Roeckner et al. 1996), was used in this study to investigate physical process for the decadal rainfall change in boreal spring and summer. The model horizontal resolution is 2.8° × 2.8° (T42). Seven numerical experiments are designed and listed in Table 1. In the control experiment (CTRL), the model is integrated for 15 years using the climatological monthly mean SST. Parallel to the control experiment, three sets of sensitivity experiments are performed separately for boreal spring season and boreal summer season. The first set of the sensitivity experiments is with imposed SSTA in both the tropical Pacific Ocean (PO) and Indian Ocean (IO), the second set is with the prescribed SSTA in the tropical PO only, and the third set is with the prescribed SSTA in the tropical IO only. To enhance the atmospheric response, we doubled the amplitude of decadal SSTA (shown in Figs. 7a and 7b) as the prescribed SSTA in sensitivity experiments in both boreal spring and summer. For detailed description of the numerical experiments such as the definitions of the tropical PO and IO domains, readers are referred to Table 1.

### 3. Decadal change of East Asian circulation and rainfall in boreal spring and summer

Figure 1 shows the spatial patterns and principal components of the first and second MV-EOF modes in boreal spring. The first EOF mode explains 19.6% of the total variance, while the second EOF mode accounts for 13.2% of the total variance. According to the rule by North et al. (1982), the two leading modes are statistically distinguished from higher modes. The first MV-EOF mode shows a north–south dipole pattern with enhanced
precipitation over East China, extending westward to the Korean Peninsula and western Japan and suppressed precipitation from Indochinese Peninsula to the South China Sea and Philippine Sea (Fig. 1a). An anomalous anticyclonic circulation center appears east of Taiwan, with a ridge axis oriented southwestward. The north-easterly (south-westerly) anomalies appear to the south (north) of the ridge. The anomalous south-westerly transports moisture from the south and leads to enhanced rainfall over eastern China.

The principal component (PC) of the first MV-EOF mode shows an obvious decadal shift. According to an 11-yr smooth curve (red in Fig. 1c), the PC values change from positive to negative with the turning point around 1994. Here, we define the period from 1979 to 1992 as the pre-1994 epoch and the period from 1997 to 2010 as the post-1994 epoch. There are 10 positive years out of 14 in the pre-1994 epoch and 11 negative years out of 14 in the post-1994 epoch. We intentionally exclude the transition period from 1993 to 1996. Our sensitivity tests by including these transition years in the pre- and post-1994 epochs show that the results of the composite difference would remain the same.

The spatial pattern of the second EOF mode in boreal spring is characterized by enhanced rainfall over central China and SCS and suppressed rainfall over southeast and northeast China. There is no obvious interdecadal change associated with this mode (Fig. 1d).

Figure 2 shows results from boreal summer MV-EOF analyses. In contrast to the spring results, the first MV-EOF mode in boreal summer does not show a significant interdecadal shift, while the second mode does. According to the rule given by North et al. (1982), the first mode with a fraction variance of 19.9% is statistically distinguished from the rest of the eigenvectors. The second mode, which accounts for 10.1% of the total variance, albeit not totally separated from the higher modes, is still a large fraction of the total variance. From the spatial pattern of the first MV-EOF mode (Fig. 2a), one can find a similar north–south dipole rainfall pattern with suppressed (enhanced) rainfall anomalies south (north) of 25°N. This mode has a dominant interannual variation and has been extensively studied by many previous investigators (e.g., Chang et al. 2000a; Wang et al. 2008). It has been shown that this mode is closely related to ENSO (Wang et al. 2000).
What might have been ignored in the past is the second MV-EOF mode, which has a distinct interdecadal change in the mid-1990s. The 11-yr smooth curve (red in Fig. 2d) indicates that the PC values change from negative to positive from pre-1994 to post-1994. There are 11 negative years out of 14 in the first epoch and 11 positive years out of 14 in the more recent epoch. The spatial pattern of the second mode in boreal summer presents a south to north tripole pattern with enhanced precipitation and low-level cyclonic anomalies over southern China and suppressed rainfall and anticyclonic anomalies over the SCS/Philippine Sea and northeast Asia. This meridional wave train pattern is quite similar to the East Asian–Pacific (EAP) or Pacific–Japan (PJ) patterns (Nitta 1987; Huang and Sun 1992).

Therefore the time series of the first and second MV-EOF modes indicate that the atmospheric circulation over East Asia exhibits a remarkable interdecadal shift signal in both boreal spring and summer. Furthermore, rainfall changes over southern China associated with the decadal shift show a clear out-of-phase relationship between boreal spring and summer; that is, the spring rainfall anomaly tends to switch from a positive to negative value in the mid-1990s, whereas the summer rainfall has an opposite evolution.

The analysis above is based on the GPCP rainfall data. To double check the out-of-phase decadal rainfall change over southern China in the mid-1990s, we further conduct composite analyses using GPCP and two independent rainfall datasets (the 160-gauge data and the CMAP pentad mean data).

Figure 3 shows the composite difference (the mean of 1997–2010 minus the mean of 1979–92) using both the 160-gauge rainfall data and the GPCP rainfall data. The most significant decadal rainfall anomalies are found in southern China from both datasets. For example, the composite difference pattern from the 160-gauge rainfall data shows that spring rainfall in southern China decreased about 30 mm month$^{-1}$ (Fig. 3a) whereas summer rainfall in southern China increased by 50 mm month$^{-1}$ (Fig. 3b). A similar opposite change between boreal spring and summer can be found in the GPCP data (Figs. 3c,d). A negative (positive) precipitation anomaly appears in boreal spring (summer) composite map with the maximum amplitude about 1 mm day$^{-1}$ (1.5 mm day$^{-1}$). The composite rainfall patterns are consistent with the first MV-EOF mode in spring (Fig. 1a) and the second MV-EOF mode in boreal summer (Fig. 2b), respectively.

To demonstrate the boreal spring–summer contrast of the decadal rainfall change over southern China, the
time–latitude cross section (averaged between 105° and 130°E) of pentad mean CMAP precipitation difference between two periods was plotted (Fig. 4). Note that a sign change appears around the 30th pentad, which is a natural time separating local spring and summer. From the 8th pentad to 30th pentad, the rainfall decreases consistently between 20° and 30°N; from the 30th to the 48th pentad, the rainfall increases consistently in this region.

To sum up, during the mid-1990s the rainfall over southern China undergoes an out-of-phase decadal change in boreal spring and summer. In boreal spring, the reduced rainfall over southern China is closely associated with the decadal shift of the first MV-EOF mode while the increased rainfall in boreal summer is associated with the second MV-EOF mode.

Figure 5 depicts 850- and 200-hPa circulation anomalies associated with the interdecadal rainfall changes in boreal spring and summer, respectively. In boreal spring, the negative rainfall anomaly over southern China is associated with a low-level anticyclonic circulation in situ and a cyclonic circulation anomaly over the SCS (Fig. 5a). Low-level westerly anomalies prevail from the western Indian Ocean to western Indonesia. To the east of Indonesia, the easterly anomalies blow from the Pacific. As a result, there is convergent airflow over the Maritime Continent. At 200 hPa (Fig. 5b), convergent flows appear over southern China and equatorial India Ocean, whereas divergent flows are over Indonesia. In contrast, in boreal summer, a low-level cyclonic circulation appears over southern China (Fig. 5c) while an anomalous anticyclonic circulation dominates over the SCS. The tropical Indian Ocean (the Maritime Continent) is controlled by low-level convergent (divergent) flows. At 200 hPa (Fig. 5d), an anomalous cyclone appears over southern China and an anomalous anticyclone appears to its north.

4. The cause of the out-of-phase decadal rainfall change between boreal spring and summer

a. Observed decadal change of dynamic and thermodynamic fields

To reveal physical processes responsible for distinctive decadal precipitation changes in boreal spring and summer, we conducted a moisture budget analysis over southern China. The red (blue) arrows in Fig. 6 indicate
vertically integrated moisture fluxes during the pre-1994 (post-1994) period over southern China (dashed rectangle), whereas the black arrows show the differences between the two epochs. The total changes of moisture budget are consistent with the decadal rainfall changes in Fig. 3 and low-level wind anomalies in Fig. 5. In boreal spring, northeasterly anomalies at around 20°N reduced the moisture flux income of southern China. In boreal summer, however, southwesterly anomalies transport increased moisture from the SCS to southern China and led to increased rainfall over southern China. It is interesting to note that the change of the vertically integrated moisture flux convergence is primarily contributed by the meridional moisture transport on the south edge of southern China in both the boreal spring and summer seasons. The net income moisture flux in the meridional

![Graph](image_url)

**Fig. 4.** Composite differences (1997–2010 minus 1979–92) of time–latitude section of pentad mean precipitation (color shadings, mm day$^{-1}$) averaged over 105°–130°E.

**Fig. 5.** Composite differences (1997–2010 minus 1979–92) of (a),(c) 850- and (b),(d) 200-hPa wind fields (vectors, m s$^{-1}$) in boreal (top) spring and (bottom) summer. The vectors that exceed 0.05 confidence level are bold. Anticyclones and cyclones are denoted by letters A and C, respectively. Red contour is 1500 m isoheight.
The results above imply that the tropical SSTA forcing, which will lead to changes of local Hadley circulation through anomalous Walker circulation, may be crucial for the out-of-phase decadal rainfall change over southern China. Figure 7 illustrates the composite difference maps of the SST and OLR over the tropical PO and IO sectors. In boreal spring, the SST difference field displays a La Niña–like pattern in the Pacific: a horseshoe warming pattern appears on the western and subtropical Pacific while a cooling occurs over the eastern Pacific (Fig. 7a). Meanwhile, a warming appears in the western IO. Whereas the gross pattern remains the same as in boreal summer (Fig. 7b), two important differences in boreal summer SST difference fields are worth noting. First, the cooling in the eastern tropical PO is greatly reduced. Second, the warming in the equatorial IO is strengthening and expanding eastward and covers the entire IO basin. Because of these differences, the convection anomalies are quite different in the Maritime Continent between the two seasons. Figures 7c and 7d present the decadal change of OLR distribution in each season. Note that in boreal spring (Fig. 7c) the convection is enhanced over the Maritime Continent in response to the warming (cooling) over the western (eastern) tropical Pacific. According to the Gill (1980) solution, a Rossby wave response to the Maritime Continent heating may lead to a low-level cyclonic circulation anomaly and thus enhanced convection over the northern IO and SCS. Although the warm SSTA over the western tropical IO could promote a descent over the Maritime Continent, this forcing is weak compared to the force from the tropical PO. Therefore, the Maritime Continent heating anomaly may be mutually controlled by the western and eastern Pacific SSTA in boreal spring.

In response to the enhanced large-scale convection over the northern IO and Maritime Continent, low-level winds tend to converge into the region. So, there are low-level southward flows along approximately 20°N (Fig. 5a). The anomalous southward flows tend to suppress climatological convection over southern China (through divergence). As a result, the OLR exhibits a north–south dipole pattern over the East Asian and South Asian sectors (Fig. 7c). The OLR dipole pattern bears a great similarity to the GPCP rainfall anomalies in Fig. 3c. In addition to the north–south dipole over Asia, the OLR difference field also shows a Pacific–North American (PNA) teleconnection pattern over the eastern Pacific and North American sector, with suppressed convection over western North America.

In contrast to the boreal spring season, convection over the Maritime Continent in boreal summer is suppressed (Fig. 7d), and enhanced convection appears to the north of 10°N. The most pronounced feature in the summer OLR field is strong negative anomalies over the equatorial IO. The enhanced convection is associated with local warm SSTA. The warm SSTA over the Indian Ocean induces anomalous local Walker circulation with
anomalous ascent over the western IO (where maximum SST anomalies are located) and anomalous descent over the Maritime Continent. Over the East Asian sector, the OLR anomaly pattern is characterized by a tripole pattern, with suppressed convection over the Maritime Continent (south of 10°N) and northern China (north of 30°N), and enhanced convection in between (from 15° to 30°N). Again, this tripole OLR anomalous pattern is consistent with wind field anomalies in Fig. 5c and the GPCP anomalous rainfall pattern shown in Fig. 3d.

This season-dependent feature is to some extent analogous to the season-dependent Indian Ocean–western Pacific teleconnection on the interannual time scale (Wu et al. 2009, 2010b). The effect of the Pacific and Indian Ocean SSTA forcing on convection over the Maritime Continent may be inferred from the vertical overturning circulation along the east–west direction. Figure 8 shows the longitude/vertical circulation along with the zonal distribution of OLR, precipitation, and SST for the climatological (1979–2010) and epochal difference in boreal spring and summer respectively. In boreal spring, climatological maximum SST is located around 100°E and minimum SST is located around 140°W (Fig. 8a). The negative gradient of the SST between the western and eastern PO leads to strong easterlies from the eastern Pacific to the Maritime Continent (near 100°E) while the SST gradient over Indian Ocean is relatively weak. The convergent flow appeared at lower levels over the Maritime Continent with the dominant ascending motion in situ. On epochal difference fields, the anomalous ascents (descents) are prevalent over the Maritime Continent (central and eastern Pacific). The enhanced Pacific Walker circulation with negative (positive) zonal pressure gradient anomalies in the upper (lower) troposphere are linked to negative zonal SST gradient anomalies over the PO. Another branch of the Walker circulation with smaller zonal length appears in the equatorial IO, but the zonal pressure gradient associated with this branch is relatively weak. This implies that the enhanced convection in the Maritime Continent may be primarily forced by the warming in the western Pacific and the cooling in the eastern Pacific.

For boreal summer, climatological maximum SST is located around 150°E and two minimum SSTs are located around 50°E and 80°W (Fig. 8b). A strong westerly (easterly) over the IO (PO) at the lower level meets at the Maritime Continent where ascending motion appears. While in the epochal difference fields (Fig. 8d), there is broad-scale descent motion from 80°E to 150°W. The descent is collocated with anomalous high pressure in the lower troposphere. The warm SSTAs accompanied with strong ascent motion and negative OLR anomalies (or enhanced precipitation) appear over the western IO while suppressed rainfall and convection are observed elsewhere.

The Walker circulation will further affect southern China rainfall through the local Hadley circulation. Figure 9 illustrates the latitude–height sections of climatological (1979–2010) and epochal difference fields averaged between 105°E and 130°E for boreal spring and summer. In boreal climatological spring, two ascending flows appear at equatorial and subtropical regions that are consistent with the OLR valleys (rainfall peaks). On epochal difference fields, the pronounced ascending motion appears over the equatorial region. Significant high pressure and strong descent occurs over southern China (20°–35°N), which may suppress the climatological ascent over subtropical regions and lead to suppressed
Fig. 8. (left) Longitude-vertical sections of climate mean state and (right) the composite difference (1997–2010 minus 1979–92) of wind vector (with vertical $p$-velocity multiplied by $-100$) and geopotential height (contour, 10 gpm, areas exceeding 0.05 confidence level are shaded), along with the longitudinal distributions of rainfall (blue, left vertical axis, mm day$^{-1}$), OLR (red, right vertical axis, W m$^{-2}$) and SST (purple, second right vertical axis, °C) fields averaged at 5°S–15°N in boreal (top) spring and (bottom) summer.
Fig. 9. (left) Latitude-vertical sections of climate mean state and (right) the composite difference (1997–2010 minus 1979–92) of wind vector (with vertical $p$-velocity multiplied by $-100$) and geopotential height (contour, 10 gpm, areas exceeding 0.05 confidence level are shaded), along with the latitudinal distributions of rainfall (blue, left vertical axis, mm day$^{-1}$), OLR (red, right vertical axis, W m$^{-2}$) fields averaged at 105$^\circ$–130$^\circ$E in boreal (top) spring and (bottom) summer.
(enhanced) rainfall over the South China Sea (SCS) through local Hadley circulation. The anomalous OLR and rainfall is in general consistent with the updraft (downdraft) anomaly over Maritime Continent (southern China). Therefore, the warm (cold) SST anomaly in the west (eastern) Pacific may transform an indirect impact on rainfall anomaly over southern China through the enhanced Walker and Hadley circulations.

In boreal summer, the climatological intertropical convergence zone (ITCZ) moves northward. The ITCZ is combined with the local ascending motion over subtropical region; thus, uniform ascents with the OLR trough (rainfall peak) occur from the equator to 35°N (Fig. 9b). In epochal difference fields (Fig. 9d), anomalous descent is pronounced from the equator to the south of 20°N accompanied with a high pressure anomaly in lower troposphere. Anomalous updraft and low pressure anomalies are observed from 20° to 35°N. Again the OLR and precipitation anomalies are consistent with the anomalous vertical motion, with suppressed (enhanced) convection and precipitation to the south (north) of 15°N. The anomalous downdraft suppressed the climatological ITCZ (tropical monsoon trough) but enhanced the East Asian monsoon trough with updraft anomalies. Therefore, the warm SST in the Indian Ocean may exert a remote forcing effect on southern China rainfall through anomalous Walker and Hadley circulations.

b. Effect of the SST on anomalous circulation response: Numerical experiments

In this section, we use the ECHAM (v4.6) model to verify the hypothesis that tropical PO SST controls the interdecadal rainfall variability over southern China in boreal spring, whereas the tropical IO SST determines the interdecadal rainfall variability over southern China in boreal summer. Figure 10 shows the longitude/vertical section and latitude/vertical section of simulated climatological fields from the control run (CTRL). The model well captures the main features of climatological Walker circulation and local Hadley circulation in both boreal spring and summer.

For the sensitivity experiments, first we examine the relative roles of tropical PO and IO SSTAs in affecting convection over Maritime Continent and rainfall over southern China in boreal spring. Figure 11a shows the atmospheric OLR and rainfall response to the imposed SSTAs in both the tropical PO and IO. The OLR shows strong negative anomalies over the northern IO and Maritime Continent while positive anomalies appear over southern China. However, if the SSTAs is prescribed only over the IO (Fig. 11b), the enhanced convection is strictly confined in the IO; no significant anomalous signal appears over the Maritime Continent and in turn there is no marked rainfall anomaly over southern China. When only the SSTAs over the PO are given, the convection over the Maritime Continent is enhanced and leads to significantly suppressed rainfall over southern China (Fig. 11c). The above three simulations verified that PO SST controls the convection anomalies and southern China rainfall change through anomalous Walker cell and Hadley cell in boreal spring. To further investigate which part of the PO SST is crucial to the Maritime Continent convection change, we conducted additional sensitivity experiments in which the PO is separated into the eastern Pacific (EP) and western Pacific (WP); the results show that both the EP and WP have equal effects in forcing the convection over Maritime Continent (not shown).

Next, we discuss the relative roles of tropical PO and IO SSTAs in driving convection over the Maritime Continent and rainfall over southern China in boreal summer. Figure 12a shows the atmospheric OLR and rainfall response to the prescribed SSTAs in both the tropical PO and IO. The pronounced negative OLR anomalies appear in the IO whereas positive OLR anomalies are dominant over the Maritime Continent and SCS. As expected, if the SSTS is prescribed only over the IO, the atmospheric response remains the same but with even greater amplitude (Fig. 12b). To the contrary, when only the SSTAs over the PO are given, no significant convection anomalies over the Maritime Continent or rainfall change over southern China occurred. The above three simulations confirmed that IO SSTAs determine the convection anomalies and southern China rainfall change through anomalous Walker and Hadley cells in boreal summer.

To sum up, the simulations of the ECHAM model confirmed the hypothesis that the PO decadal SST pattern drives the Walker and local Hadley circulation and causes drought over southern China in boreal spring, whereas the IO decadal SST pattern controls the Walker and local Hadley circulations and leads to wetter conditions over southern China in boreal summer.

5. Conclusions and discussion

In this study a multivariate empirical orthogonal function (MV-EOF) analysis method was used to reveal dominant circulation and rainfall patterns over East Asia. Both the GPCP rainfall and NCEP reanalysis wind data for the period of 1979–2010 were used. The analysis domain is confined in the region of 10°–50°N, 100°–140°E. The variables used for the MV-EOF analysis include the seasonal mean anomalies of precipitation and zonal and meridional winds at 850 hPa. The MV-EOF analysis is conducted for boreal spring and summer seasons.
FIG. 10. (left) Longitude-vertical (averaged over 5°S–15°N) and (right) latitude-vertical sections (averaged over 105°–130°E) of climate mean state (1979–2010) of wind vector (with vertical p-velocity multiplied by $-100$) along with the distributions of rainfall (blue, left vertical axis, mm day$^{-1}$), OLR (red, right vertical axis, W m$^{-2}$), and SST (purple, second right vertical axis, °C) fields and in boreal (top) spring and (bottom) summer in ECHAM with prescribed climatological SST.
The MV-EOF analysis shows a significant decadal shift around the mid-1990s in the low-level circulation and rainfall fields in both boreal spring and summer. For the boreal spring season, the first PC of the MV-EOF exhibits a marked decadal change around the mid-1990s. For the boreal summer season, the second PC shows a pronounced decadal shift around the mid-1990s. We further noted that the decadal rainfall change over southern China experienced an out-of-phase relationship between boreal spring and summer; that is, the

Fig. 11. Composite differences (sensitivity experiments minus control experiment) of OLR (contour, anomalies exceeding 5 W m$^{-2}$ are shaded) fields along with the zonal distribution of OLR (red, left axis, W m$^{-2}$) and SST (purple, right axis, °C) averaged over 5°S–15°N and meridional distribution of OLR (red, top axis, W m$^{-2}$) and precipitation (blue, bottom axis, mm day$^{-1}$) averaged over 105°–130°E: (a) SEN_MAM_B minus CTRL, (b) SEN_MAM_I minus CTRL, and (c) SEN_MAM_P minus CTRL.

The MV-EOF analysis shows a significant decadal shift around the mid-1990s in the low-level circulation and rainfall fields in both boreal spring and summer. For the boreal spring season, the first PC of the MV-EOF exhibits a marked decadal change around the mid-1990s. For the boreal summer season, the second PC shows a pronounced decadal shift around the mid-1990s. We further noted that the decadal rainfall change over southern China experienced an out-of-phase relationship between boreal spring and summer; that is, the
spring rainfall tends to decrease from the pre-1994 period to the post-1994 period, whereas the summer rainfall tends to change in an opposite way.

The diagnoses of observations reveal the different SST decadal changes in the tropical PO and IO between boreal spring and summer. In boreal spring, the composite differences of the SST field between the pre-1994 and post-1994 periods indicate a La Niña–like pattern with warming in the western Pacific and cooling in the eastern Pacific. Indian Ocean SST anomalies are relatively weak. Associated with the La Niña–like SSTA pattern in the Pacific is the anomalous Walker circulation with strengthened convection over the Maritime Continent, which connects to anomalous subsidence and negative rainfall anomalies over southern China through the local anomalous Hadley circulation. In boreal summer, decadal SST signals over the tropical IO strengthened and extended to the entire IO basin while the SST
anomalies in the eastern Pacific greatly weakened. Associated with this decadal SSTA pattern is anomalous Walker circulation with suppressed convection over the Maritime Continent, which links to anomalous ascent and positive rainfall anomalies over southern China through the local anomalous Hadley circulation.

The numerical simulations suggest a season-dependent basin SST control scenario. In boreal spring the Pacific Ocean SST controls whereas in boreal summer the Indian Ocean SST controls. In boreal spring, the SSTA pattern in PO strengthens convection over the Maritime Continent and leads to enhanced downdraft and negative rainfall anomalies over southern China through strengthened local Hadley circulation, whereas in boreal summer the SSTA pattern in the IO leads to suppressed convection over the Maritime Continent. This favors strengthening the East Asian monsoon trough through a weakened local Hadley cell, leading to positive rainfall anomalies over southern China.

One issue related to the decadal SSTA change is whether the La Niña–like pattern is attributed to the asymmetry of extreme ENSO events. To examine this issue, we conduct a sensitivity test by recalculating the composite mean SST difference with three El Niño years (1982/83, 1986/87, 1991/92) in the pre-1994 period and three La Niña years (1998/99, 1999/2000, 2007/08) in the post-1994 period removed. The epochal SST difference still exhibits a similar La Niña–like pattern as in Figs. 7a and 7b (not shown). Therefore, we conclude that the La Niña–like SSTA is mainly a result of the decadal variability rather than the asymmetry of extreme ENSO events. So far, it is still unclear whether the decadal SSTA change as shown in the current study is caused by external anthropogenic forcing or internal natural variability and why the decadal SSTA pattern evolves from boreal spring to summer in such a way.

Acknowledgments. This work was supported by NSF Grant AGS-1106536, ONR Grant N00014-1210450, the National Basic Research Program of China (Grant 2013CB430202), a project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), and by the International Pacific Research Center that is sponsored by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

REFERENCES


——, ——, and ——, 2000b: Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part II: Meridional structure of the monsoon. J. Climate, 13, 4326–4340.


