Effect of Spring Precipitation on Summer Precipitation in Eastern China: Role of Soil Moisture

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ABSTRACT

The relation of spring (March–May) to summer (July–August) precipitation in eastern China is examined using observed data. It is found that when spring precipitation from the lower and middle reaches of the Yangtze River valley to northern China (the YRNC region) is higher (lower), more (less) summer precipitation occurs in northeastern China and the lower and middle reaches of the Yangtze River valley, and less (more) in southeastern China. The analysis of physical mechanism showed that higher (lower) spring precipitation in the YRNC region is closely related to wet (dry) spring soil moisture, which decreases (increases) the surface temperature and sensible heat flux in late spring. Because the memory of spring soil moisture in the YRNC region reaches about 2.4 months, the surface thermal anomaly lasts into the subsequent summer, resulting in a weak (strong) East Asian summer monsoon. A weak East Asian summer monsoon corresponds to an anomalous anticyclone and a cyclone over southeastern and northeastern China, respectively, in the lower troposphere. The anomalous anticyclone depresses the summer precipitation in southeastern China, and the anomalous cyclone promotes precipitation over northeastern China. The abnormal northerly and southerly winds associated with the anomalous cyclone and anticyclone, respectively, converge in the lower and middle reaches of the Yangtze River valley, inducing more summer precipitation there.

1. Introduction

Controlled by monsoon circulations, the precipitation temporal variation in China has distinct seasonality. The precipitation over eastern China in the East Asian monsoon region is mainly concentrated in summer (June–August), and the summer precipitation accounts for more than half (52%) of the annual total (Zhang 2015). The causes of summer precipitation variability have been extensively studied and it has been demonstrated that the oceanic thermal status as well as land surface process have a major impact on the variability of summer precipitation over eastern China (Wang et al. 2005; Huang et al. 2012; Zhang et al. 2013).

Many scientists have studied the factors affecting the spring (March–May) precipitation over China. It is also shown that the oceanic thermal status and land surface conditions can affect the spring precipitation. For example, a warmer land surface in continental East Asian continent and a colder sea surface in the surrounding ocean can lead to less (more) spring precipitation over southern China (the Yangtze–Huaihe River basin) (Zhao et al. 2009). Positive anomalies of spring precipitation tend to appear over southern China in the El Niño mature phase (Zhang et al. 1999; Zhang and Sumi 2002; R. H. Zhang et al. 2017). More snow in the Tibetan Plateau and Eurasian continent in preceding winter and spring is associated with enhanced spring rainfall over southern China (Cai 2001; Qian et al. 2003) and southeastern China (Wu and Kirtman 2007; Wu et al. 2009; Zuo et al. 2012), respectively. Some studies

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also demonstrate that the spring precipitation over southern China can be influenced by El Niño Modoki and preceding boreal winter Southern Hemisphere annular mode (Zheng and Li 2012; Li 2016).

The antecedent soil moisture can affect precipitation both locally and remotely. For example, Zhang et al. (2008) found that antecedent soil moisture may have significant impact on local precipitation through positive feedback mechanism mainly in arid to semiarid transition zones or in semihumid forest to grassland transition zones. Koster et al. (2014) and R. N. Zhang et al. (2017) demonstrated that the remote impact of soil moisture is through the phase locking and amplification of a planetary wave through the imposition of a spatial pattern of soil moisture at the land surface. Many studies have revealed that over eastern China the spring soil moisture can affect the summer precipitation (e.g., Zuo and Zhang 2007; Zhan and Lin 2011; Zhang and Zuo 2011; Meng et al. 2014; Zuo and Zhang 2016). Zhang and Zuo (2011) showed that when the spring soil is wetter over a vast region over eastern China from the lower and middle reaches of the Yangtze River valley to northern China (the YRNC region), northeastern China and the lower and middle reaches of the Yangtze River valley have abnormally higher precipitation in summer, while southeastern China and northern China have less summer precipitation. In fact, in spring the YRNC region is the place where the largest variability of precipitation occurs (Zuo and Zhang 2012), and spring precipitation is closely related to spring soil moisture over there (Liu et al. 2014). Therefore, here we propose the hypothesis that the spring precipitation over the YRNC region affects the soil moisture, which in turn impacts the summer precipitation over eastern China. In this study we will explore the connection of the spring precipitation with summer precipitation over eastern China by considering the memory of soil moisture. In the earlier studies of seasonal precipitation variability in China, summer and spring precipitation were studied separately. Few studies have paid attention to the effect of spring precipitation on the summer precipitation. The soil moisture memory refers to the fact that the antecedent climate signal can be stored in soil moisture and released later to exert a lagged effect on the climate. Entin et al. (2000) pointed out that the memory of spring soil moisture may have a feedback effect on the subsequent short-term climate variation by "remembering" the abnormal precipitation in spring. Thus, whether spring precipitation could affect summer precipitation by the memory of soil moisture is the issue to be explored in this study.

In the rest of this paper, section 2 presents the data and methodology, and section 3 discusses the relationship between spring and summer precipitation in eastern China. Section 4 examines the physical process by which the spring precipitation affects the summer precipitation via soil moisture. The paper ends with summary and discussion in section 5.

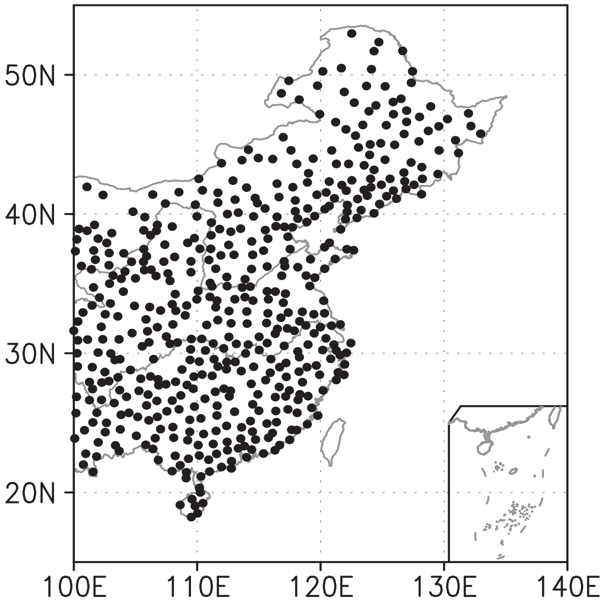

FIG. 1. Distribution of observational stations in eastern China to the east of 100°E.

2. Data and methodology

The observed monthly precipitation, surface temperature, and 2-m air temperature data employed in this study are provided by the China Meteorological Administration (CMA) from 486 stations in the period of 1981–2010. Eastern China is taken to be the area to the east of 100°E, where the East Asian summer monsoon prevails (Tao and Chen 1987; Zhang et al. 1996; Wang et al. 2004). The distribution of observational stations in China to the east of 100°E is shown in Fig. 1. The monthly sea surface temperature (SST) is from Hadley Center Sea Ice and Sea Surface Temperature dataset (HadISST) with a spatial resolution of 0.5° × 0.5° from 1981 to 2010.

According to Zuo and Zhang (2009) and Liu et al. (2014), the soil moisture from the ERA-Interim reanalysis (hereinafter referred to simply as ERA) is closest to the observations in central eastern China compared to other soil moisture reanalysis data. So our study employed the ERA soil moisture data in the first layer (0–7 cm) with a spatial resolution of 0.5° × 0.5° for the period of 1981–2010. For comparison in this study we also used the observed soil moisture data in the top

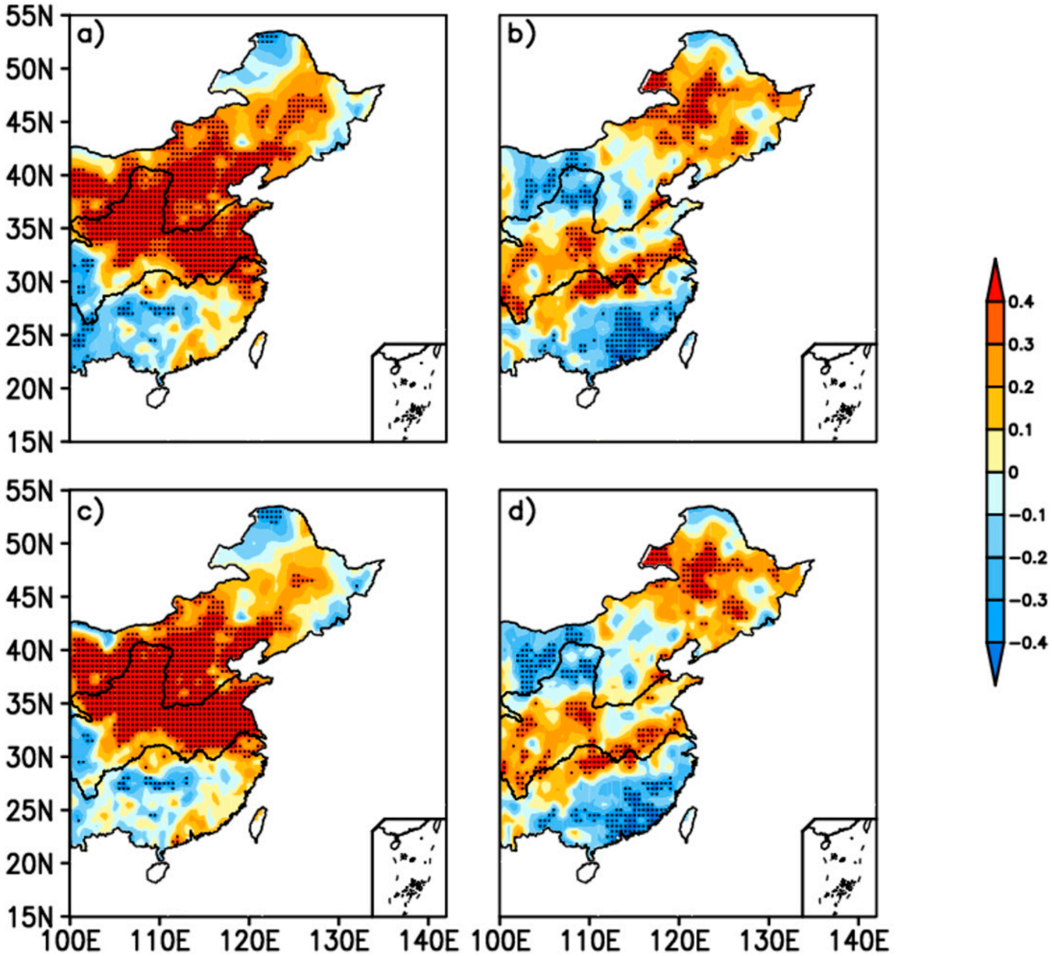

FIG. 2. Spatial distribution of the first SVD mode for (a) spring and (b) summer precipitation. (c),(d) As in (a),(b), but the parts in spring and summer precipitation linearly related to the spring Niño-3.4 SST are removed by the partial correlation analysis. The areas marked by dots indicate the correlation coefficients exceeding the 0.1 significance level.

10 cm, which are provided by CMA from 61 stations for the period of 1982–2010. Unless specifically stated, the soil moisture data in the text are from ERA. Many studies have demonstrated that the spring soil moisture anomalies in the top level have a significant impact on the summer rainfall over eastern China (e.g., Zuo and Zhang 2007; Zhang and Zuo 2011; Zuo and Zhang 2016). Additionally, we also used monthly sensible heat flux data from ERA with a spatial resolution of 0.5° × 0.5°.

In the present study, we defined the spring as the months from March to May and the summer from June to August, and the Niño-3.4 index as the average of SST anomalies in the region 5°N–5°S, 170°–120°W. The singular value decomposition (SVD) method (Prohaska 1976; Wallace et al. 1992) is applied in this study for investigating the relationship between spring and summer precipitation. The commonly used methods of correlation and regression analyses are also employed. To evaluate the influence of El Niño–Southern Oscillation (ENSO) on the relationship between spring and summer precipitation, a partial correlation analysis is applied. The partial correlation is also used to verify the effect of soil moisture on the relationship between spring and summer precipitation.

3. Relation of spring precipitation to summer precipitation in eastern China

Based on the station-observed precipitation, Figs. 2a and 2b depict the first SVD mode of spring and summer precipitation, with a variance contribution of 31.3% and a correlation coefficient of 0.80, for the period of 1981–2010. As shown in Fig. 2a, in spring negative

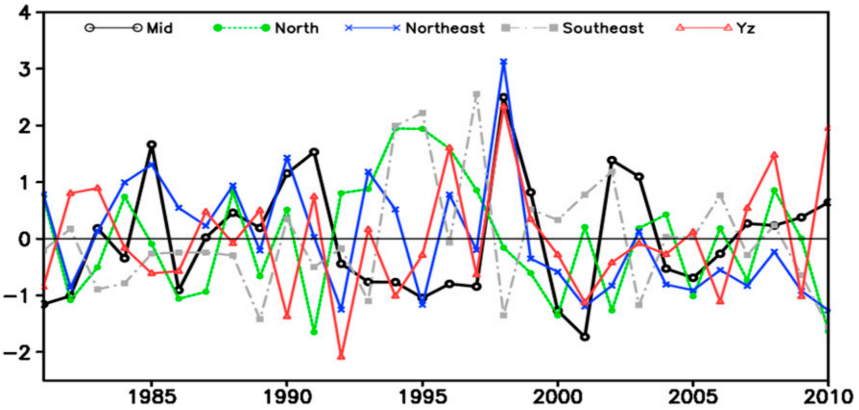

FIG. 3. Time evolutions of the standardized spring precipitation averaged in the YRNC region (Mid; 30°–43°N, 100°–120°E; black line), and standardized summer precipitation averaged in the Hetao area (North; 37°–42°N, 100°–110°E; green line), northeastern China (Northeast; 43°–50°N, 110°–125°E; blue line), southeastern China (Southeast; 21°–26°N, 112°–120°E; gray line), and lower and middle reaches of the Yangtze River valley (Yz; 29°–32°N, 108°–120°E; red line). The parts linearly related to the spring Niño-3.4 SST are removed.

anomalies of precipitation mainly exist in the southwestern part of eastern China and positive anomalies in a large region from the lower and middle reaches of the Yangtze River valley to northern China. The negative precipitation anomalies are not statistically significant, but in the region around 30°–43°N, 100°–120°E (the YRNC region) the statistical significance of the positive anomalies exceeds the 0.1 confidence level. Corresponding to the precipitation anomalies in spring, positive anomalies of summer precipitation occur in the lower and middle reaches of the Yangtze River valley (around 29°–32°N, 108°–120°E) and northeastern China (around 43°–50°N, 110°–125°E), and negative anomalies in southeastern China (21°–26°N, 112°–120°E) and the Hetao area (37°–42°N, 102°–110°E) (Fig. 2b). It is indicated that when the spring precipitation is higher over the YRNC region, northeastern China and the lower and middle reaches of the Yangtze River valley will have abnormally higher precipitation in summer, while southeastern China and the Hetao area receive less precipitation.

The distribution of spring precipitation anomalies shown in Fig. 2a resembles the first EOF mode of spring precipitation (Zuo and Zhang 2012; Liu and Fan 2012). In particular, the maximum values of both the first SVD and EOF modes for the spring precipitation appear in the YRNC region around 30°–43°N, 100°–120°E. Similarly, the summer precipitation anomalies shown in Fig. 2b are distributed analogously with the first EOF mode of summer precipitation (Deng et al. 2009; Zuo et al. 2011; Pang et al. 2014), with a tripolar pattern of precipitation anomalies from south to north in eastern China. Specifically, the center of more precipitation is located around the lower and middle reaches of the Yangtze River valley when both southeastern and northern China have a center of less precipitation. The analyses above indicate that the precipitation anomalies expressed by the first SVD mode in Figs. 2a and 2b represent well the principal features for the variability of both spring and summer precipitation. The areas where the prominent spring and summer precipitation anomalies appear in the first SVD mode are the places where the variability of spring and summer precipitation is most robust.

Previous studies have shown that ENSO has a significant influence on spring and summer precipitation in China (Huang and Wu 1989; Zhang et al. 1999; Zhang and Sumi 2002). To check if the relationship between spring and summer precipitation is affected by ENSO, the partial correlation analysis is applied to remove the parts linearly related to the Niño-3.4 (170°–120°W, 5°S–5°N) SST in spring. Figures 2c and 2d show the first SVD mode of spring and summer precipitation after removing the effect of ENSO. Figures 2c and 2d have similar patterns with Figs. 2a and 2b, respectively. Namely, after removing the effect of ENSO in spring, the higher spring precipitation in the YRNC region is still closely related to the higher summer precipitation in northeastern China and the lower and middle reaches of the Yangtze River valley, and the less precipitation in southeastern China and the Hetao area. Therefore, ENSO may have little effect on the relationship between the spring and summer precipitation revealed here.

To further verify the relationship between spring and summer precipitation, in Fig. 3 we show the standardized spring precipitation averaged in the YRNC region

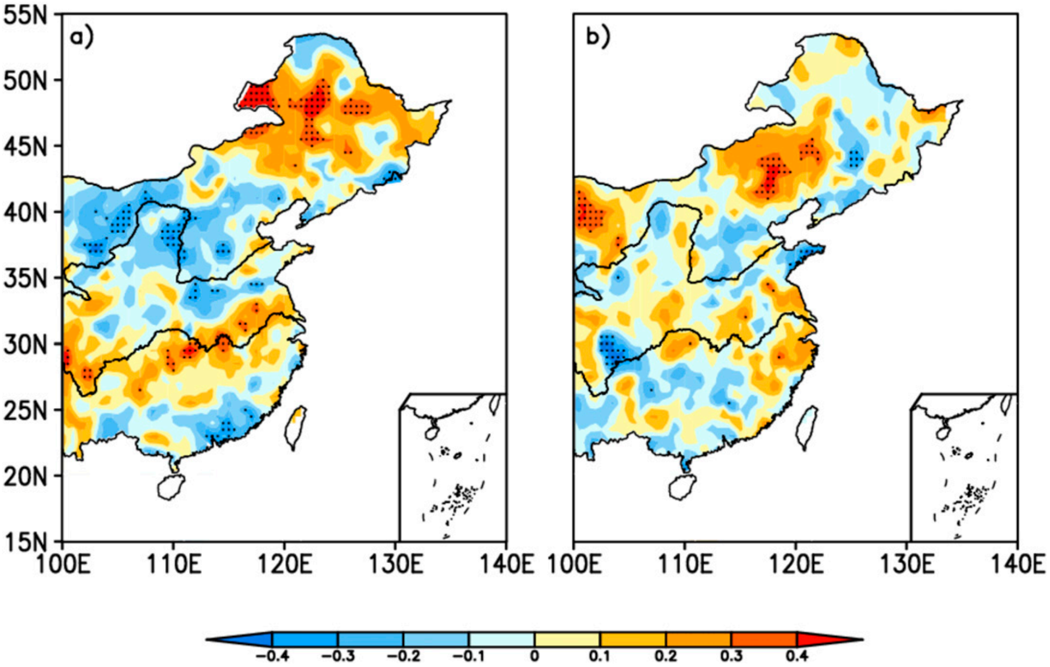

FIG. 4. Correlation coefficients (a) between the spring precipitation in the YRNC region and summer precipitation in eastern China after removing the parts linearly related to the spring Niño-3.4 SST and (b) between the spring Niño-3.4 SST and summer precipitation in eastern China after removing the parts linearly related to the spring precipitation in the YRNC region. The areas marked by dots indicate that the correlation coefficients exceeding the 0.1 significance level.

and standardized summer precipitation averaged in the Hetao area (37°–42°N, 102°–110°E), northeastern China (43°–50°N, 110°–125°E), southeastern China (21°–26°N, 112°–120°E), and the lower and middle reaches of the Yangtze River valley (29°–32°N, 108°–120°E) after removing the parts linearly related to the spring Niño-3.4 SST. As shown in Fig. 3, the variation of spring precipitation in the YRNC region is in phase with the summer precipitation in northeastern China and the lower and middle reaches of the Yangtze River valley, with the correlation coefficients being 0.42 and 0.34, respectively, exceeding the confidence level of 95%. On the contrary, the spring precipitation in the YRNC region is out of phase with the summer precipitation in the Hetao area and southeastern China, with the correlation coefficients being −0.31 and −0.39, exceeding the confidence level of 90% and 95%, respectively.

Similarly, after removing the effect of the Niño-3.4 SST, the partial correlation between the spring precipitation averaged in the YRNC region and the summer precipitation in eastern China was analyzed, and the partial correlation coefficients are shown in Fig. 4a. The partial correlation coefficients between spring and summer precipitation exhibit a tripolar pattern of negative, positive, and negative anomalies from south to north in eastern China, which is similar to the distribution of summer precipitation in the first SVD mode (Figs. 2b,d), indicating that the correlation is independent of ENSO. To see how ENSO in spring is related with the summer precipitation, the partial correlation coefficients between spring Niño-3.4 SST and summer precipitation were calculated after removing the effects of spring precipitation in the YRNC region. As shown in Fig. 4b, without considering the effect of spring precipitation in the YRNC region, the distribution of the partial correlation coefficients between the spring Niño-3.4 SST and summer precipitation distinctly differs from that between the spring and summer precipitation (Fig. 4a). The partial correlation coefficients do not show a well-defined pattern and the correlation become weak. There is no prominent positive correlation in the lower and middle reaches of the Yangtze River valley and negative correlation in the Hetao area and southeastern China. Although a notable area of positive correlation appears in northeastern China, the extent is smaller and its position shifts southward, different from what is shown in Fig. 4a. Thus it can be seen that the ENSO has little effect on the relationship between the spring and summer precipitation.

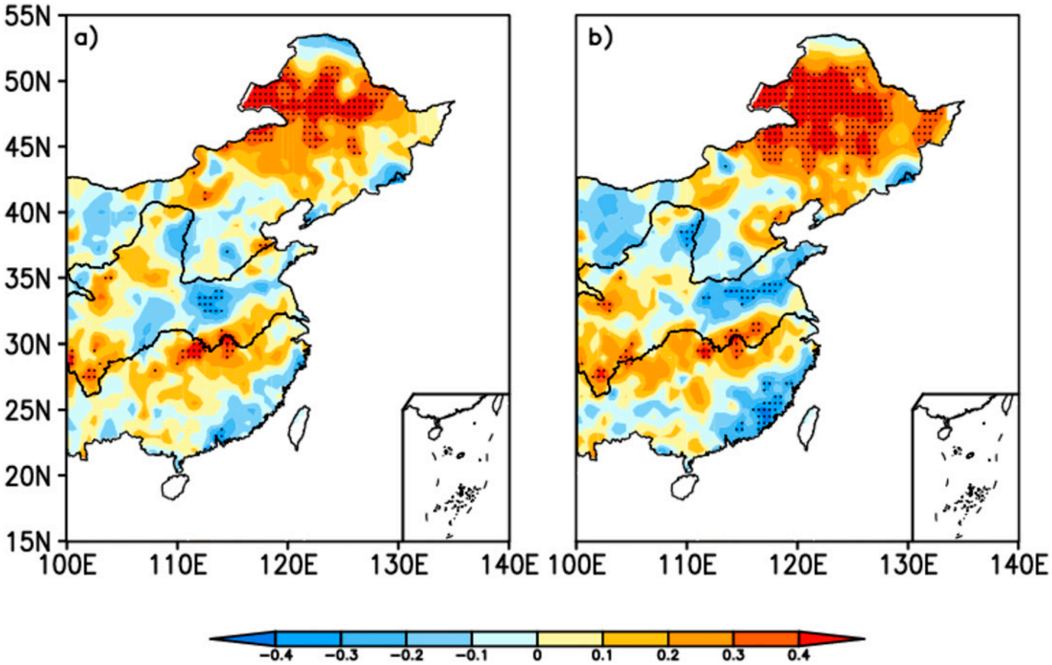

FIG. 5. Correlation coefficients of the summer precipitation in eastern China with spring (a) ERA-Interim soil moisture data for the period of 1981–2010 and (b) observational soil moisture data for the period of 1982–2010. The parts linearly related to the spring Niño-3.4 SST are removed. The dotted areas indicate that the correlation coefficients exceed the 0.1 significance level.

4. Physical processes by which the spring precipitation affects summer precipitation

To examine the processes by which spring precipitation affects summer precipitation, we first calculated the correlation coefficients between the spring (April–May) soil moisture in the YRNC region and the summer precipitation over eastern China (Fig. 5). As shown in Fig. 5, both the ERA soil moisture (Fig. 5a) and observed soil moisture (Fig. 5b) in spring over the YRNC region are positively correlated with the summer precipitation in northeastern China and the lower and middle reaches of the Yangtze River valley, and negatively correlated with that in southeastern China and northern China. Except in the Hetao area, the distribution of the correlation coefficients in Fig. 5 is very similar to that in Fig. 4a, which exhibits the relationship between spring precipitation in the YRNC region and summer precipitation is closely related to the spring soil moisture over the YRNC region. In comparing Fig. 5a with Fig. 5b, we can see that the results from ERA soil moisture are very close to those from the observed soil moisture. The similarity confirms that the ERA soil moisture is a good substitute for observed soil moisture in eastern China, which was reported by previous studies (Zuo and Zhang 2009; Liu et al. 2014). Owning to the spatial and temporal limitation of the observed soil moisture, we take the ERA soil moisture as a proxy in the subsequent analysis.

Considering the spring soil moisture can affect the surface thermal parameters in the YRNC region (Zhang and Zuo 2011), in Fig. 6 we give the standardized time series of spring precipitation, spring soil moisture, and 2-m air temperature in May over the YRNC region after removing the parts linearly related to the Niño-3.4 SST. As shown in Fig. 6, the spring soil moisture varies mainly in agreement with the spring precipitation but reversely with 2-m air temperature in May. When the spring precipitation is more (less) in the YRNC region, the local spring soil is correspondingly wet (dry), while the 2-m air temperature is lower (higher) in late spring, represented by May. Specifically, the correlation coefficient of the spring precipitation in the YRNC region with the local spring soil moisture reaches to 0.85 and with the May 2-m air temperature is −0.41, exceeding the significance level of 95%. Thus, higher spring precipitation in the YRNC region makes a wet soil (Liu et al. 2014) and so affects surface thermal balance, causing a lower surface temperature in late spring (Zhang and Zuo 2011).

Many studies have indicated that the effect of soil moisture on the short-term climate variability is due to its memory (Delworth and Manabe 1988; Vinnikov and Yeserkepova 1991; Entin et al. 2000; Koster and Suarez 2001; Wu et al. 2002; Lo and Famiglietti 2010;

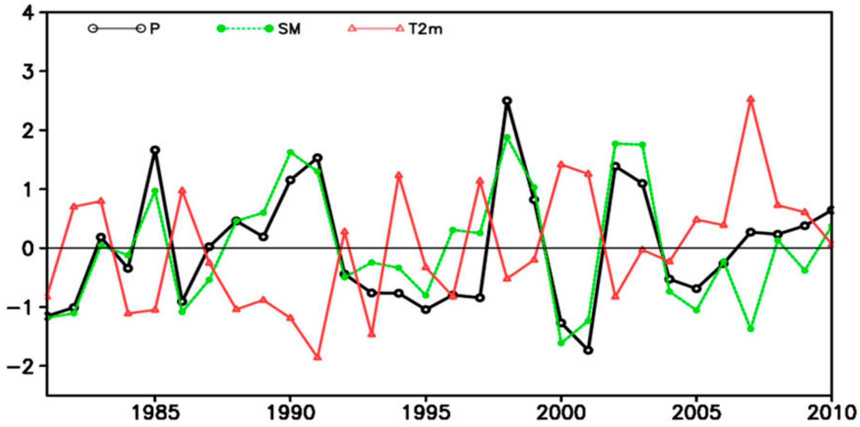

FIG. 6. Time evolutions of standardized spring precipitation (*P*; black line), spring soil moisture (SM; green line), and 2-m air temperature in May (T_{2m}; red line) over the YRNC region. The parts linearly related to the spring Niño-3.4 SST are removed.

Seneviratne et al. 2012). To investigate the physical reason in the relationship between spring and summer precipitation, we analyzed the memory of soil moisture over the YRNC region by using the method of lag autocorrelation (Entin et al. 2000). Considering that the precipitation may distinctly affect the soil moisture memory (Entin et al. 2000), we also employed the partial correlation method to remove the effect of precipitation in the calculation of lag autocorrelation by eliminate the linear parts of soil moisture related to the precipitation. The partial correlation coefficients of soil moisture in May with those in June and July are 0.66 and 0.42, which are statistically significant, exceeding the 0.05 level, and explain 44% and 18% of soil moisture variance in June and July, respectively. It is indicated that the soil moisture anomalies in the YRNC region can well persist from spring to summer. We calculated the soil moisture memory over the YRNC region by the formula $r = \exp(-1/t)$ defined by Entin et al. (2000), where r is the partial correlation coefficient of soil moisture in May with that in June and t is the time of soil moisture memory. The calculated soil moisture memory in May reaches to 2.4 months, which is long enough to affect the subsequent summer climate. The value of 2.4 months of soil moisture memory in the YRNC region is very close to the 2–3 months calculated by Yeh et al. (1984) in the midlatitudes and the 2 months reported by Entin et al. (2000) in central eastern China.

To check if the persistence of soil moisture can lead to the persistence of the surface thermal anomaly from late spring to summer, in Figs. 7a–c we give the surface sensible heat flux in May, June, and July regressed against the spring precipitation in the YRNC region. As shown in Fig. 7a, when the spring precipitation is higher in the YRNC region, the local sensible heat flux is lower in May due to a wet soil (Delworth and Manabe 1996; Zhang and Zuo 2011). In June (Fig. 7b) and July (Fig. 7c), in the YRNC region the local sensible heat flux is still generally lower although the significance areas decrease. This indicates that the lower sensible heat flux in the YRNC region could last from May to July, imposing a lagged influence on the subsequent summer climate. To analyze the role played by soil moisture memory, we removed the effect of spring (April–May) soil moisture in the regressed field of Figs. 7a–c by using the partial correlation method. As depicted by Fig. 7d, after removing the effect of spring soil moisture, the negative sensible heat flux becomes much weaker and the significance areas in the YRNC region sharply decrease in May. It can also be seen that the area of negative sensible heat flux is much smaller and there are few areas passing the significance test in June (Fig. 7e) and July (Fig. 7f), and the signs of the sensible heat flux anomalies over the eastern part of the YRNC region in June and the northern part of the YRNC region in July even become opposite to those in May. The analysis indicates that the abnormal sensible heat flux in May cannot last for long in the absence of the soil moisture anomaly, which in turn demonstrates that the memory of the soil moisture anomaly plays an important role in the persistence of the abnormal sensible heat flux from spring to summer.

Based on the analyses above, it is concluded that the spring precipitation alters the thermal balance in late spring (represented by May) by changing the soil moisture, and the persistence of abnormal soil moisture leads to the lasting of the abnormal sensible heat flux, which affects the subsequent summer climate. The altered thermal balance in summer may cause the change of atmospheric circulation, consequently leading to the

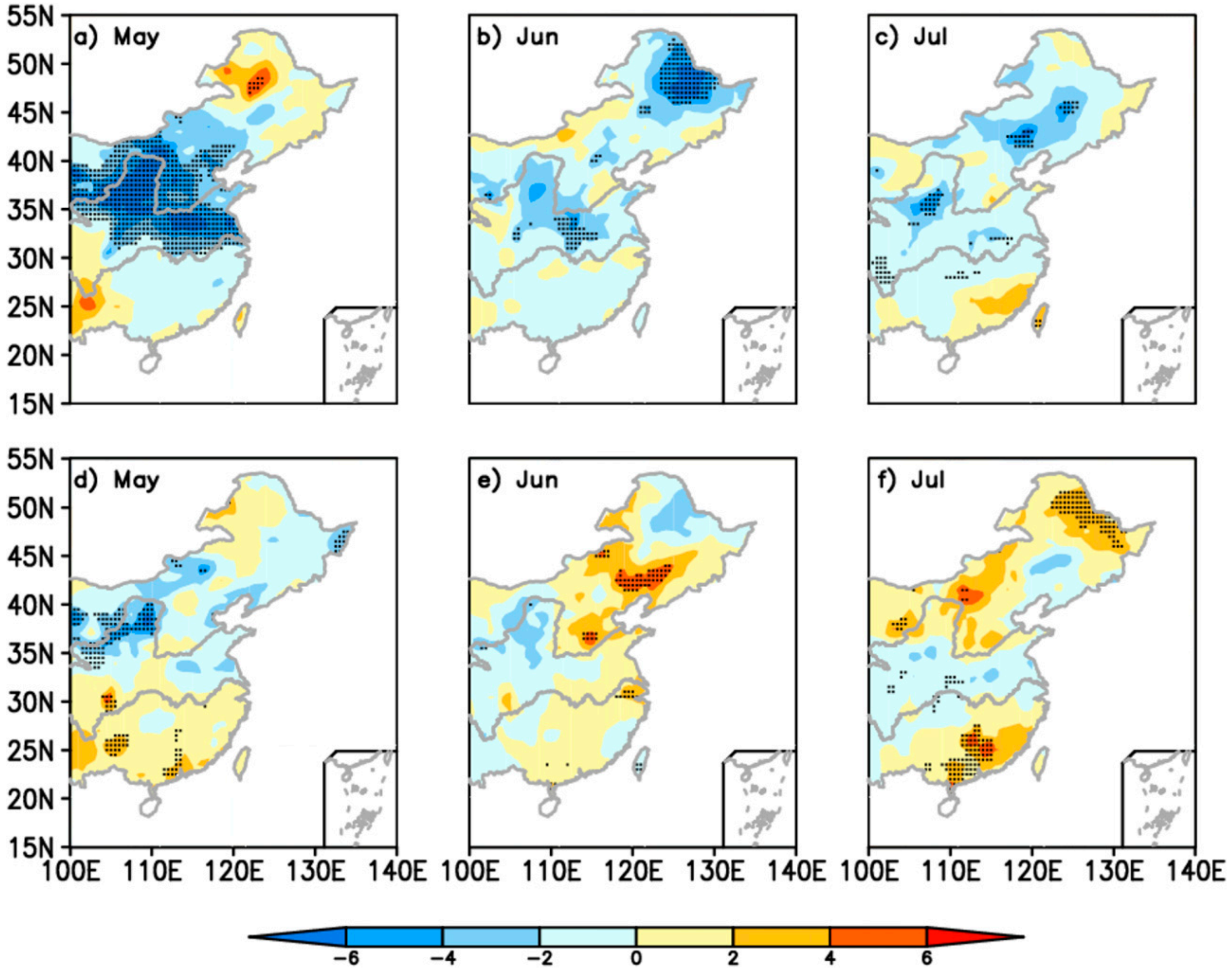

FIG. 7. Sensible heat flux in (a) May, (b) June, and (c) July regressed against the spring precipitation in the YRNC region (units: W m^{-2}). (d)–(f) As in (a)–(c), but the parts linearly related to the spring soil moisture in the YRNC region are removed. The areas marked by dots indicate that the correlation coefficients exceed the 0.1 significance level.

variation of precipitation. In Fig. 8 we give the atmospheric circulations at 850 hPa in summer regressed against the spring precipitation and soil moisture, respectively, in the YRNC region. As shown in Fig. 8a, when the spring precipitation is higher in the YRNC region, in summer there is an abnormal cyclone to the north of about 35°N over northeastern China, while an abnormal anticyclone appears to the south over southeastern China. As a result, the cyclone over northeastern China favors more precipitation and the anticyclone over southeastern China depresses the precipitation. The southerly winds from the anticyclone and northerly winds from the cyclone converge around the Yangtze River valley and promote the summer precipitation there. It is clear that the anomalous circulations associated with the spring precipitation in the YRNC region are responsible for the summer precipitation in eastern China shown in Fig. 5. To further verify the role played by soil moisture, we also give the summer circulations regressed against spring soil moisture in the YRNC region (Fig. 8b). The distribution of circulations in Fig. 8b is similar to that in Fig. 8a, manifesting the importance of the spring soil moisture in activating the abnormal circulations in summer.

The above analyses show that the higher spring precipitation in the YRNC region leads to a wet soil in spring and lower surface temperature in late spring, after which the sensible heat flux becomes abnormally negative. Because of the persistence of the wet soil the negative anomaly of sensible heat flux lasts into the following summer, resulting in anomalous atmospheric circulations over East Asia, which causes the abnormal summer precipitation in eastern China.

The summertime atmospheric circulations and precipitation over East Asia are mainly controlled by the East Asian summer monsoon, and the land–sea thermal

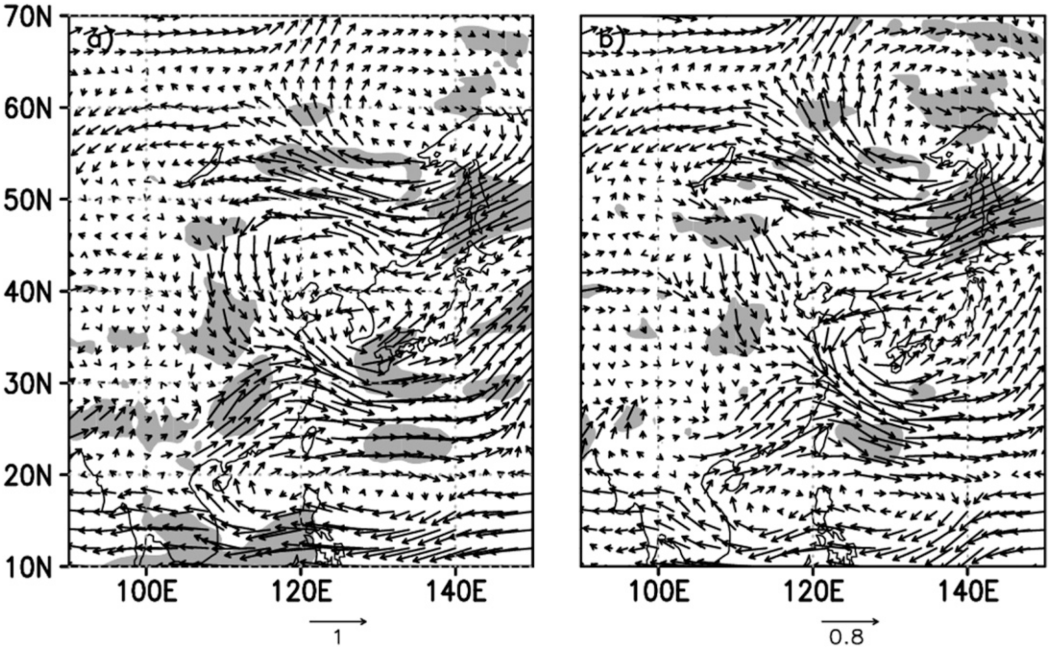

FIG. 8. Summertime atmospheric circulations at 850 hPa regressed against the (a) spring precipitation and (b) spring soil moisture in the YRNC region. The shadings indicate the areas exceeding the 0.05 significance level.

contrast between continental East Asia and the surrounding oceans is closely related to the intensity of the East Asian summer monsoon (Zhang et al. 2013). The lower surface temperature and negative anomalies of surface sensible heat flux over the YRNC region in late spring and summer can reduce the land–sea thermal contract and thus weaken the East Asian summer monsoon. In fact, the distributions of abnormal summer precipitation (Fig. 5) as well as the anomalous circulations (Fig. 8) correspond to a weak East Asian summer monsoon (Wang and Fan 1999; Huang 2004). To verify the results that more spring precipitation over the YRNC region weakens the East Asian summer monsoon, we chose two East Asian summer monsoon indexes, the East Asia–Pacific (EAP) index defined by Huang (2004) and Wang and Fan index (WFI) by Wang and Fan (1999), and the variations of them are shown in Fig. 9. As exhibited in Fig. 9, the spring precipitation and

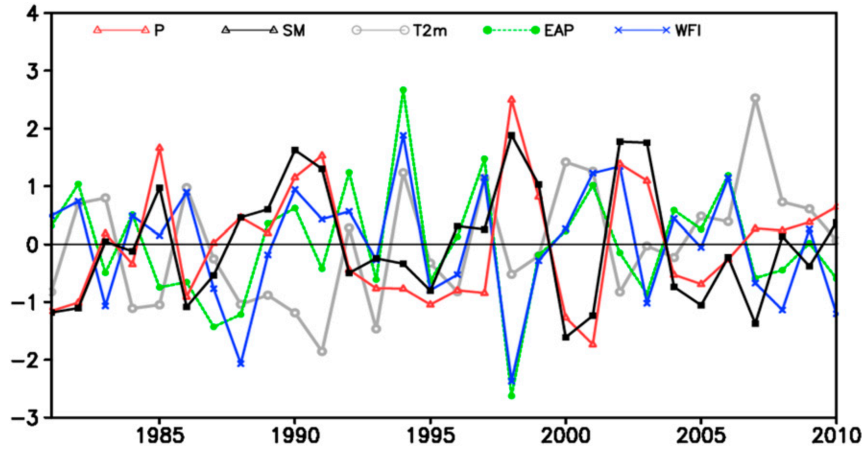

FIG. 9. Time evolutions of the standardized spring precipitation (P; red line), soil moisture (SM; black line), 2-m air temperature in May (T_{2m}; gray line) over the YRNC region, EAP index (EAP; green line), and WFI index (WFI; blue line). The EAP index (Huang 2004) and WFI index (Wang and Fan 1999) are two East Asian summer monsoon indexes and used to quantize the summer monsoon.

spring soil moisture vary oppositely with the surface temperature and summer monsoon indexes, indicating that a higher spring precipitation amount over the YRNC region corresponds to a lower surface temperature and a weak East Asian summer monsoon. The negative correlation coefficients of the spring precipitation over the YRNC region with the EAP and WFI indexes are −0.56 and −0.41, respectively, exceeding the 0.01 significance level. It can be seen that the weakened East Asian summer monsoon is responsible for the abnormal summer precipitation over eastern China and circulations over East Asia. It is worth mentioning that the memory of soil moisture plays an important role in the connection between spring and summer precipitation. The soil moisture memory induces the persistence of abnormal surface condition from spring to summer, which in turn influences the summer precipitation through altering the East Asian summer monsoon.

5. Summary and discussion

This study investigated the influence of spring precipitation on summer precipitation in eastern China. The results of SVD analyses showed that, when the YRNC region has more spring precipitation, the lower and middle reaches of the Yangtze River valley and northeastern China will have more summer precipitation, and less summer precipitation appears in southeastern China and the Hetao area. The correlation analysis utilizing the regional averaged data verifies the relationship between spring and summer precipitation revealed by the SVD analyses.

We further examined the physical process by which the spring precipitation affects summer precipitation. The results showed that higher spring precipitation in the YRNC region leads to higher spring soil moisture, resulting in lower surface temperature and less sensible heat flux in late spring (in May). Based on the lag autocorrelation, it is demonstrated that the soil moisture in May over the YRNC region has a memory of about 2.4 months. Owing to the soil moisture memory, the abnormal sensible heat flux associated with the spring precipitation and soil moisture anomalies can last into the subsequent summer, causing a narrowed surface thermal difference between land and sea and thus a weakened East Asian summer monsoon. Corresponding to a weak East Asian summer monsoon, the summertime atmospheric circulations over East Asia exhibits a cyclone anomaly and an anticyclone anomaly in northeastern China and southeastern China, respectively, in the lower troposphere. The lower-tropospheric abnormal southerly winds associated with the anticyclone anomaly meets with the northerly winds associated with the cyclone anomaly in the lower and middle reaches of the Yangtze River valley, promoting the summer precipitation in this region. At the same time, the cyclone anomaly is beneficial to increased summer precipitation in northeastern China, while the anticyclone anomaly leads to decreased summer precipitation in southeastern China.

In addition, we analyzed the effect of the spring Niño-3.4 SST by using the partial correlation method. The results showed that the influence of spring precipitation on summer precipitation is independent from ENSO. We also checked the effects of Niño-3.4 index in preceding winter (DJF) as well as in simultaneous summer (JJA) by using the same partial correlation method. The first SVD modes of spring and summer precipitation anomalies in both cases have little changes and are quite similar to the patterns shown in Fig. 2. Considering that El Niño Modoki can exert significant influence on spring rainfall over southern China (Feng and Li 2011), we further removed the effect of the spring El Niño Modoki index (Ashok et al. 2003) by partial correlation analysis, and the results show little effect of El Niño Modoki on the relationship between spring and summer precipitation. Similarly, we also analyzed the effect of soil moisture on the relationship between spring and summer precipitation by the same method. The results show that the persistence of abnormal surface conditions from late spring to summer results from the soil moisture memory, indicating that the memory of soil moisture plays an important role in the connection between spring and summer precipitation.

It should be noticed that that a positive local feedback between soil moisture and precipitation may exist during the persistence process of soil moisture anomalies from late spring to summer. As seen in Fig. 7, the positive regression values in Figs. 7e and 7f are comparable in magnitude to the negative regression values in Figs. 7b and 7c. Such features may be attributed to the positive local feedback process, which has been revealed in previous studies (e.g., Brubaker et al. 1993; Eltahir and Bras 1996; Zhang et al. 2008). Therefore, for fully understanding the persistence process of soil moisture anomalies, the local feedback process is worth investigating in the future. Additionally, the present study only focuses on the impact of soil moisture. The atmosphere can also be influenced by a range of land surface parameters (e.g., soil temperature, vegetation, etc.) besides the soil moisture. The impacts of other parameters should be important topics for future investigation.

Many previous studies have studied the factors affecting the spring precipitation and summer precipitation over eastern China separately. Our present study demonstrates the influence of spring precipitation on summer precipitation. The relation of spring precipitation to summer precipitation explored in our study is important not only in understanding the summer climate variability over eastern China, but also in providing a new method for short-term climate prediction of the East Asian summer monsoon.

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