Relationship Between Soil Temperature in May over Northwest China and the East Asian Summer Monsoon Precipitation

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ABSTRACT

This study investigates the relationship between the soil temperature in May and the East Asian summer monsoon (EASM) precipitation in June and July using station observed soil temperature data over Northwest China from 1971 to 2000. It is found that the memory of the soil temperature at 80-cm depth can persist for at least 2 months, and the soil temperature in May is closely linked to the EASM precipitation in June and July. When the soil temperature is warmer in May over Northwest China, less rainfall occurs over the Yangtze and Huaihe River valley but more rainfall occurs over South China in June and July. It is proposed that positive anomalous soil temperature in May over Northwest China corresponds to higher geopotential heights over the most parts of the mainland of East Asia, which tend to weaken the ensuing EASM. Moreover, in June and July, a cyclonic circulation anomaly occurs over Southeast China and Northwest Pacific and an anticyclonic anomaly appears in the Yangtze and Huaihe River valley at 850 hPa. All the above tend to suppress the precipitation in the Yangtze and Huaihe River valley. The results also indicate that the soil temperature in May over Northwest China is closely related to the East Asia/Pacific (EAP) teleconnection pattern, and it may be employed as a useful predictor for the East Asian summer monsoon rainfall.

Key words: soil temperature, the East Asian summer monsoon precipitation, the EAP teleconnection pattern

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1. Introduction

The impact of sea surface temperature (SST) on global and regional climate has been extensively investigated in the last few decades (e.g., Huang et al., 2004; Chen et al., 2006; Wu et al., 2012; Zhou et al., 2012). However, the influence of land surface and land-atmosphere interaction is comparatively less studied.

Soil moisture and soil temperature play important roles in the earth's climate system (Shukla and Mintz, 1982; Yeh et al., 1984; Tang et al., 1988). Some studies found that an anomaly in soil moisture can alter latent flux and subsequently influence the climate (Koster et al., 2004, 2006; Seneviratne et al., 2006; Zhang et al., 2008). There are also some studies exploring the effects of soil moisture on summer climate over East Asia and China (Zhang and Zuo, 2011; Zhang and Wu, 2011). The subsurface soil temperature represents the soil energy status, heat storage, and heat transfer conditions. However, soil temperature memory and the mechanisms through which it interacts with the atmospheric circulations are still not well understood (Xue et al., 2012). Tang et al. (1988) found that the seasonal anomalous patterns of soil temperature at 80-cm depth look similar to the patterns of precipitation in the subsequent season. Tang defined Geothermal Vortex (GV) with soil temperature at 3.2-m depth (Tang and Gao, 1997a, b), applied it to the prediction of precipitation, and found that most of the GVs are accompanied with a positive rainfall anomaly in the same season (Tang et al., 1998). Hu and Feng (2004) found that the soil enthalpy and

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ground surface temperature have a significant positive correlation with the anomalies of the lower-tropospheric geopotential height, and the soil enthalpy in the top 20–50-cm soil column can persist for 2–3 months. Qian et al. (2011) investigated the trend of soil temperature as an indicator of climate change, and correlated it with the climate change over Canada. Xue et al. (2012) studied the impact of spring subsurface soil temperature (SUBT) anomaly in the western U.S. on North American summer precipitation and investigated the possible mechanisms via a regional climate model. They have found that the anomalous cyclone induced by the surface heating due to the SUBT anomaly propagated eastward through Rossby wave train along the mean westerly flow.

Northwest China is a region with strong surface sensible heat flux, the variability of which may have important impacts on local and remote climate variability (e.g., Huang et al., 2002; Chen et al., 2009b; Zhou et al., 2009; Wang et al., 2012). Zhou and Huang (2006) found that the interdecadal variability of the difference between surface soil temperature and surface air temperature in arid and semi-arid regions of Northwest China in spring may be one of the causes of interdecadal variations of summer precipitation in North China.

It is well known that the summer monsoon rainband over East Asia moves northward seasonally. The rainband locates in South China from May to June, then moves northward to the Yangtze and Huaihe River valley (e.g., Tao and Chen, 1987; Ding, 2004; Chen et al., 2009a). The precipitation in the Yangtze and Huaihe River valley from June to July is called Meiyu in China. Several studies (Huang and Li, 1987; Nitta, 1987; Huang and Sun, 1992) found an anomalous teleconnection pattern in the vicinity of East Asia in summer, which is called the Pacific Japan (PJ) pattern or East Asia/Pacific pattern (hereafter EAP), associated with the anomalous summer climate in the vicinity of East Asia. Huang and Yan (1999) defined an EAP index with the 500-hPa geopotential height anomalies in summer, and found that the EAP index can describe the interannual variability of EASM well. Negative (positive) index corresponds to above (below) normal summer rainfall in the Yangtze and Huaihe River valley.

Northwest China locates over the upstream area of the EASM, and may thereby influence the EASM. This study takes an attempt to investigate the relationship between the May soil temperature over Northwest China and the EASM precipitation. The datasets and statistical methods used in this study are introduced in Section 2, followed by analysis of distribution modes and memories of soil temperature in Section 3. In Section 4, the correlation of soil temperature in May and the EASM precipitation in June and July is investigated. Section 5 discusses the possible physical mechanisms invovled in the results. Finally, Section 6 summarizes the whole paper.

2. Data and method

Although soil temperature data are widely available in China, the length of the data varies at different stations. In this study, the daily mean soil temperature data at depths of 0, 80, 160, and 320 cm provided by the China Meteorological Administration from 1971 to 2000 are used. The daily data are averaged into monthly mean values for the following analysis. The surface soil temperature is strongly influenced by synoptic weather processes, and the 160-/320-cm soil temperature is partly heated by the crust and partly influenced by climate perturbations (Tang and Zhang, 1994). Therefore, we choose 80-cm soil temperature for our analysis. Most of the stations have missing observations, so we have selected 16 stations (see Fig. 1 for their distribution) from the dataset, with data available from 1971 to 2000 for the arid/semi-arid areas, where the annual precipitation is less than 400 mm. A monthly mean value is obtained if there are more than 25 available values in the month. The monthly mean NCEP/NCAR reanalysis data at 17 pressure levels from 1000 to 10 hPa (Kalnay et al., 1996) are used in this study. The monthly global land precipitation data, called Precipitation Reconstruction Over Land (PREC/L), with a resolution of $0.5°\times0.5°$, are obtained from the US NOAA Climate Prediction Center (CPC) (Chen et al., 2002).

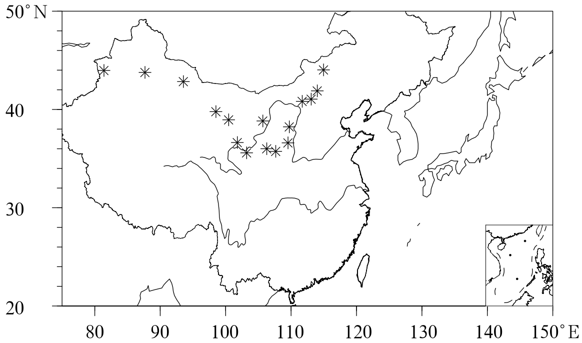

Fig. 1. Distribution of the 16 stations with soil temperature data at 80-cm depth from 1971 to 2000 in Northwest China.

3. Features and memories of the soil temperature

The 80-cm soil temperature data in May at all 16 stations are averaged and the mean May soil temperature time series over the region (solid line in Fig. 2) is obtained. The fast Fourier transform (FFT) method is utilized to extract the interannual variations in periods 2–8 yr. Hereafter, May soil temperature refers to the mean interannual variations of soil temperature in May (dashed line in Fig. 2). Warm and cold events are categorized based on the standard deviation of May soil temperature time series. If the standard deviation exceeds 0.5 (–0.5), warm (cold) events are defined. From 1971 to 2000, there are 8 warm (1972, 1978, 1981, 1987, 1989, 1992, 1994, and 1997) and 8 cold (1971, 1977, 1979, 1980, 1988, 1991, 1993, and 1996) events. We will illustrate the composite difference associated with warm minus cold May soil temperature in the following section.

According to Notaro et al. (2006), the memories of soil temperature in May and spring are calculated using the empirical equation:

$$P = \frac{1+\alpha}{1-\alpha}, \tag{1}$$

where P is persistence or memory and α is the one-month autocorrelation. The memories of May soil temperature in all the arid/semi-arid areas (Fig. 3) are longer than two months, which perhaps influence the climate on corresponding timescales.

Figure 4a shows annual variations of the temperature at different levels. The soil temperature at 80-cm depth is lower than surface soil and air temperatures over Northwest China from March to September, with maximum difference in July. Figure 4b shows that 25°–55°N averaged sea level pressure at 150°E becomes higher than that at 100°E in May, which indicates the shift of the land-sea thermal contrast. Thus, this study focuses on the influence of May soil temperature on the East Asian summer monsoon precipitation in the following months.

4. Relationship between May soil temperature and June–July precipitation

We now investigate the relationship between May soil temperature and the EASM precipitation during 1971–2000. Figure 5 shows composite differences of precipitation in June and July between warm and cold

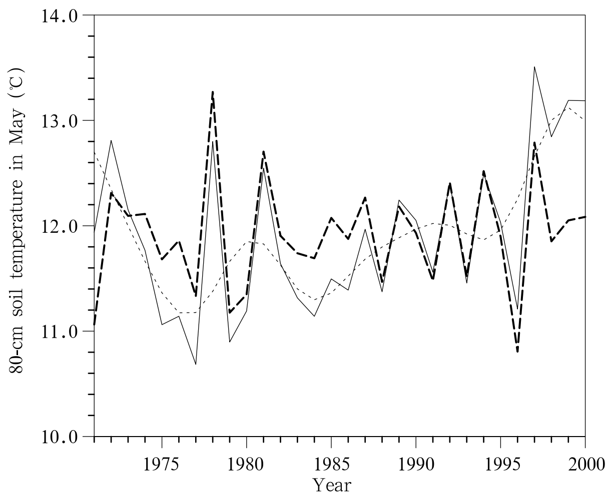

Fig. 2. Evolution of soil temperature at 80-cm depth in May during 1971–2000. The solid, dashed, and dotted lines represent the raw data, and the interannual and decadal variations, respectively.

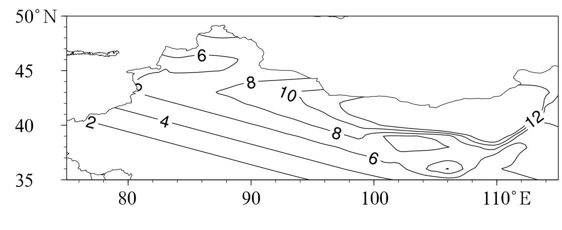

Fig. 3. Distribution of the memories of May soil temperature (unit: month).

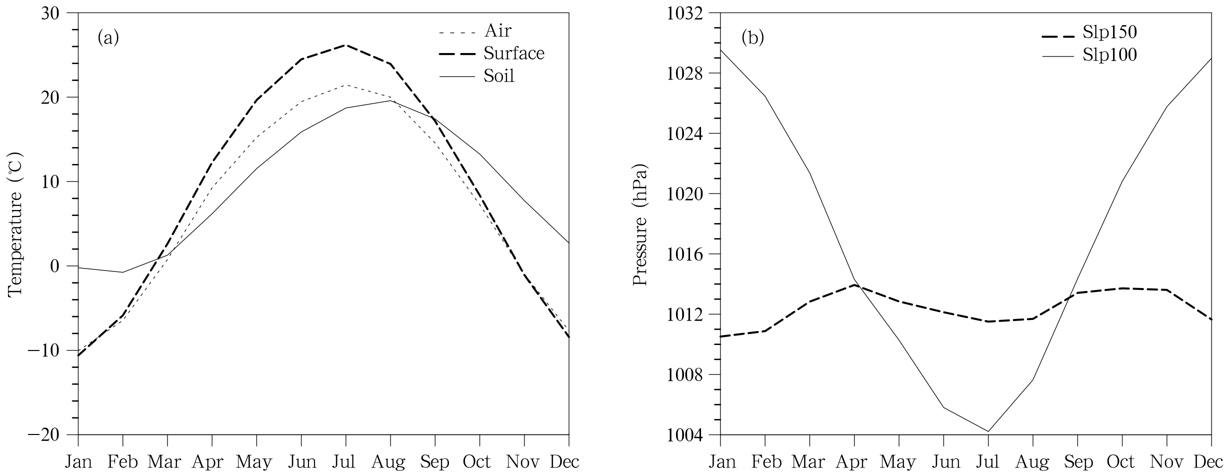

Fig. 4. Annual variations of (a) 80-cm soil temperature (solid line), surface soil temperature (long dashed line), and surface air temperature (short dashed line), and (b) sea level pressure averaged between 25° and 55°N at 100°E (solid line) and 150°E (dashed line) from 1971 to 2000.

soil temperature events. It is seen that May soil temperature is closely linked to the EASM rainfall. A negative rainfall center appears over the Yangtze and Huaihe River valley while a positive center exists over South China. This indicates that when May soil temperature is warmer, the Yangtze and Huaihe River valley (outlined by the dashed rectangular in Fig. 5) gains less rainfall whereas South China gains more rainfall in June and July. The correlation coefficient between May soil temperature and the average precipitation in the Yangtze and Huaihe River valley is –0.57, exceeding the 95% confidence level, showing a significant negative correlation.

5. Discussion of the physical mechanism

5.1 Composite differences of climate variables in May

Hu and Feng (2004) found that the positive soil enthalpy during April–June leads to warmer surface temperature, which results in positive geopotential height and temperature anomalies in the lower troposphere. Soil temperature might have induced such a circulation anomaly to influence the climate over East Asia. We have found that warmer soil temperature corresponds to warmer air temperature over the surface and in the lower troposphere (Fig. 6). Figure 7 displays the composite difference of 500-hPa geopotential height in May. A positive center to the west of the Lake Baikal, and a negative center in South China and Northwest Pacific can be seen clearly. This indicates that warm soil temperature in May might have played a major role in initiating positive geopotential height and temperature anomalies in the lower troposphere. After the onset of the EASM, the pressure over the continent becomes weaker than that over the ocean (Fig. 4b). The positive geopotential height anomaly over the mainland might weaken the EASM.

5.2 Composite differences of climate variables in June and July

We further compute the composite differences of climate variables in June and July. Figures 8a and 8b correspond to the composite wind at 850 hPa for 8 warm events and 8 cold events, respectively. As is known that southwesterlies prevail over South China in summer, but the intensity of the southwesterlies during the warm phase is significantly weaker than that during the cold phase (Fig. 8c). Figure 9a shows the composite difference of 200-hPa geopotential height, with negative values over South China and Northwest Pacific and positive values in the Yangtze and Huaihe River area. The composite differences of 500-hPa geopotential height (Fig. 9b) and sea level pressure (Fig. 9c) reveal the same pattern, indicating a barotropic structure in the troposphere. This baro-

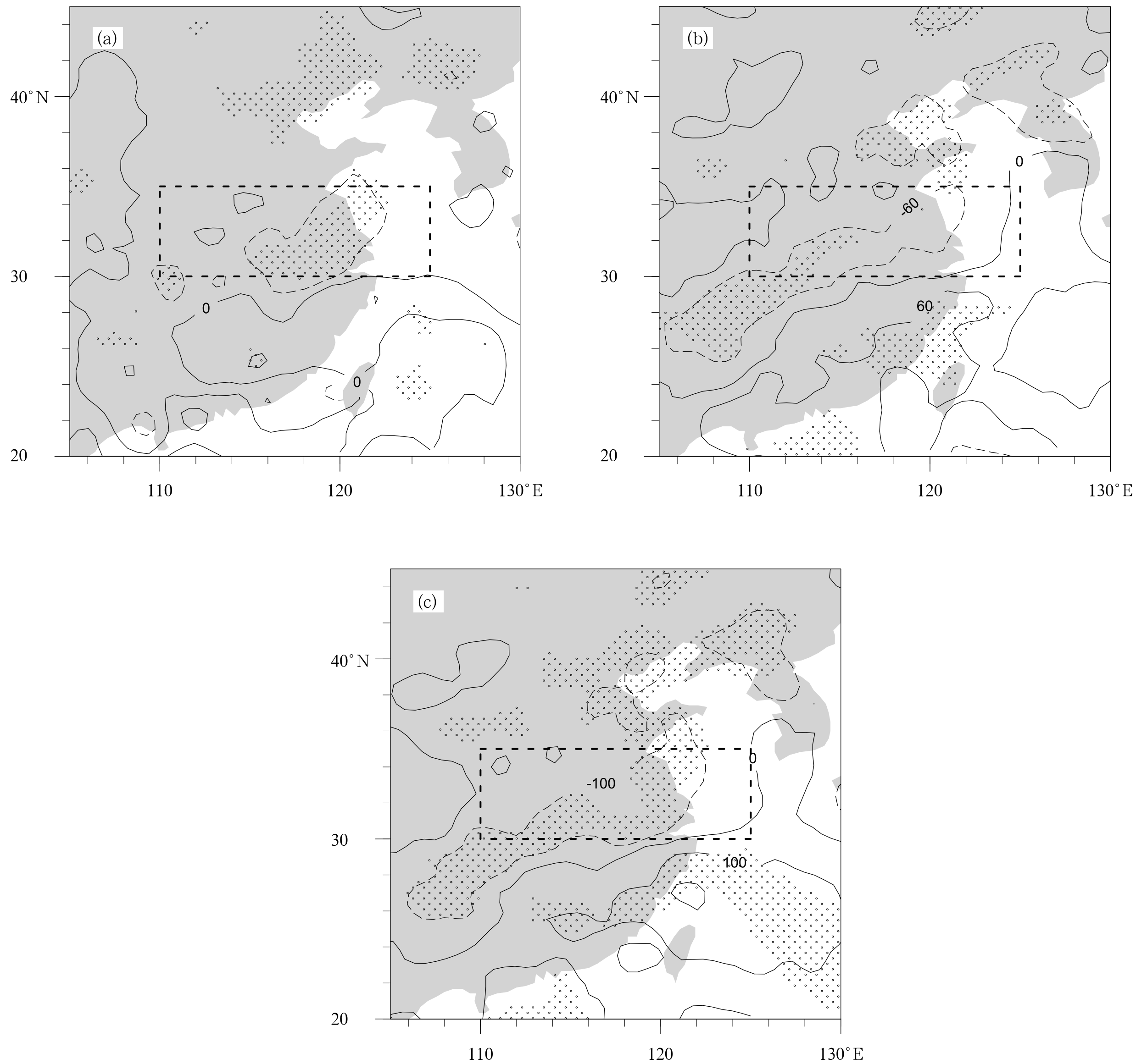

Fig. 5. Composite differences of precipitation in (a) June, (b) July, and (c) June and July. Dotted areas indicate the 90% confidence level, and the dashed rectangular frame represents the Meiyu area (30°–35°N, 110°–125°E).

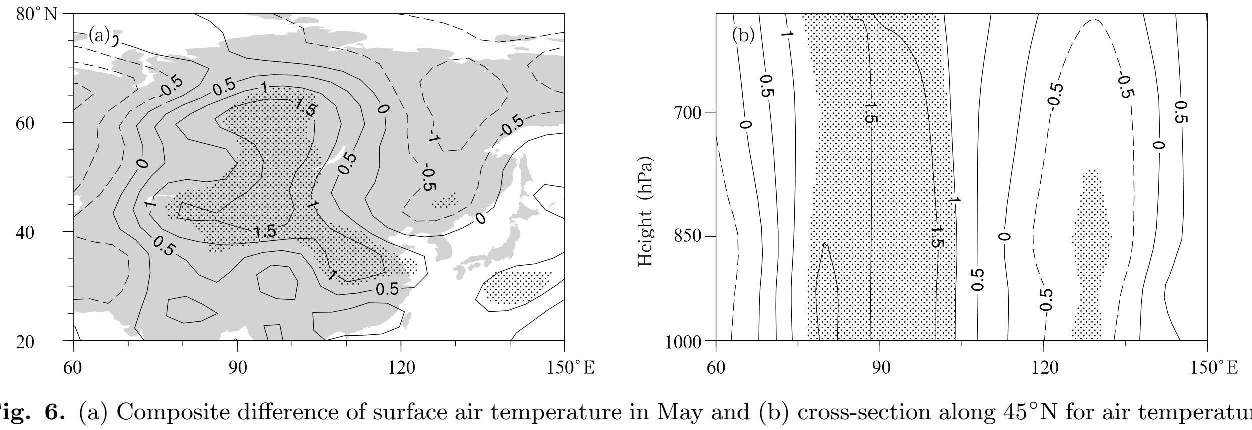

Fig. 6. (a) Composite difference of surface air temperature in May and (b) cross-section along 45°N for air temperature in May. Dotted areas indicate the 90% confidence level.

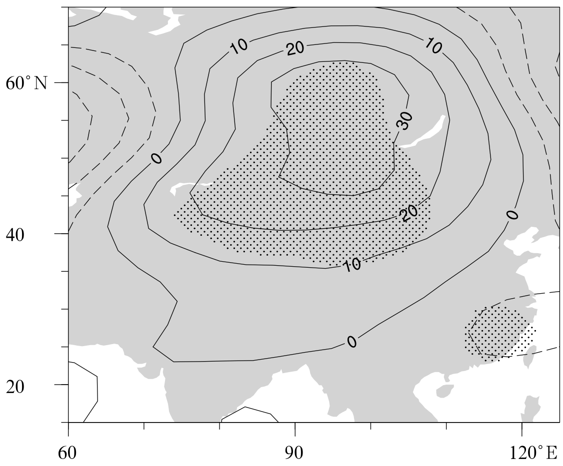

Fig. 7. The composite difference of 500-hPa geopotential height in May. Dotted areas indicate the 90% confidence level.

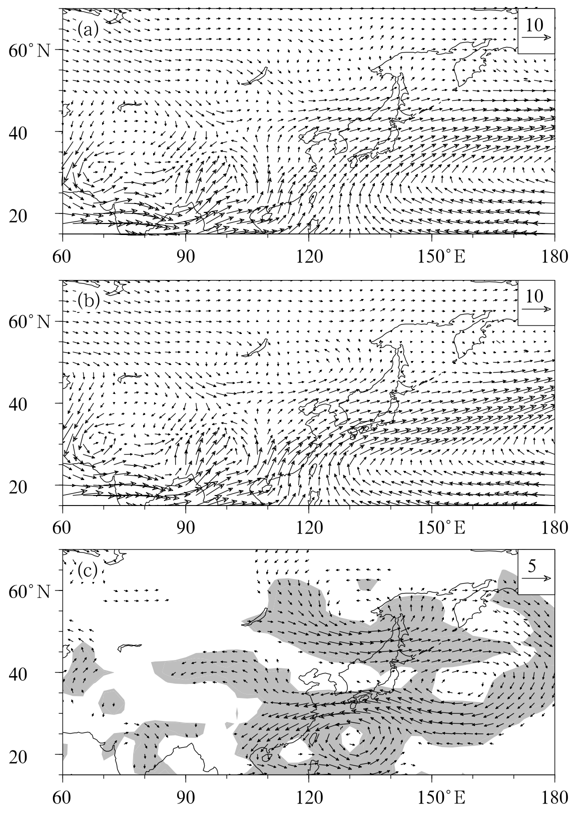

Fig. 8. Averaged 850-hPa wind in June–July for (a) warm events, (b) cold events, and (c) difference between (a) and (b). Shaded areas indicate the 90% confidence level.

tropic pattern in Fig. 9 resembles the East Asia/Pacific (EAP) teleconnection pattern, which is associated closely with the anomalous summer climate in the vicinity of East Asia. The composite difference of 850-hPa wind (Fig. 8c) also reveals more or less a similar pattern to that in Fig. 9, which shows a cyclonic (anticyclonic) anomaly center in southeastern China (the Yangtze and Huaihe River valley). It is obvious that weaker southwesterlies are not conducive to the precipitation over the Yangtze and Huaihe River valley. Huang (2004) defined an index of EAP, which fairly described the interannual variations of the EASM. He found that the summer rainfall in the Yangtze and Huaihe River valley was below normal under a positive EAP index. Figure 10 shows the time series of the EAP index in June–July and the interannual variation of May soil temperature. The EAP index is in the same phase with May soil temperature. The correlation coefficient between the EAP index in June–July and May soil temperature is 0.61, exceeding the 95% confidence level. Hence, May soil temperature in the

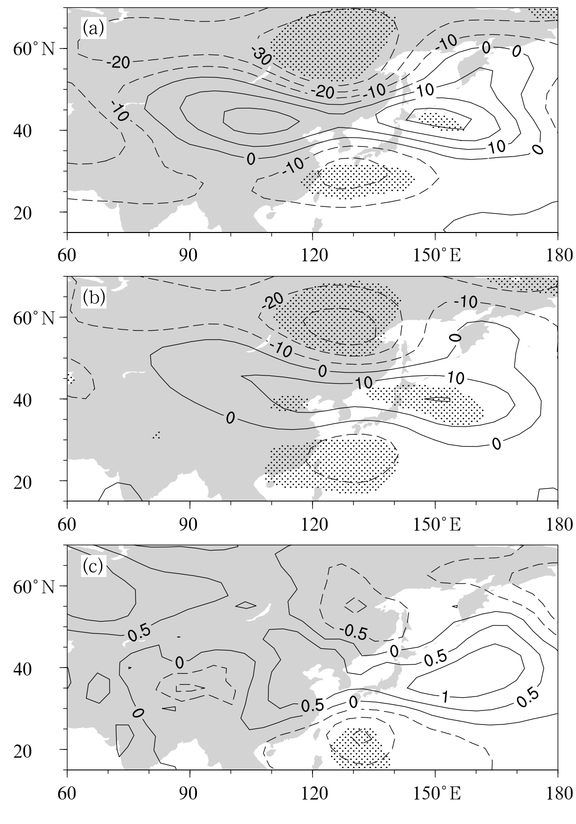

Fig. 9. June–July composite differences of (a) 200-hPa geopotential height, (b) 500-hPa geopotential height, and (c) sea level pressure. Dotted areas indicate the 90% confidence level.

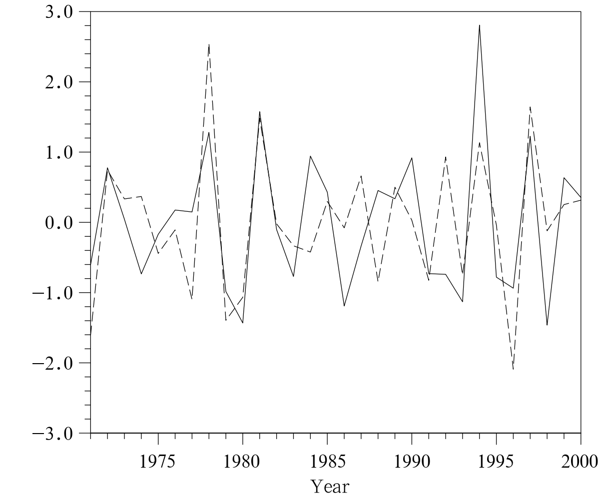

Fig. 10. Evolution of the EAP index in June–July (solid line) and the interannual variation of 80-cm soil temperature in May (dashed line).

arid/semi-arid regions might influence the intensity of the following EASM. Therefore, a close connection between May soil temperature and the summer meridional teleconnection pattern (EAP) is established.

It should be noted that, to verify if our results depend on the choice of the sample number, we have also computed the correlation coefficients for the individual variables. The main conclusions from the correlation analysis agree well with those from the composite analysis. In addition, to check whether the teleconnection is driven by the forcing of ENSO, we have performed the correlation analysis between the preceding Niño 3 index (Dec–Jan–Feb, Mar–Apr–May, and May) and May soil temperature, and also with the June–July EASM precipitation. The results indicate that the correlation coefficients in the first case (Dec–Jan–Feb) are within ±0.2, which are below the confidence level. In the second case (Mar–Apr–May), the correlation pattern does not show a consecutive positive-negative pattern as in Fig. 5. Therefore, May soil temperature is probably an independent factor for influencing the EASM precipitation.

6. Summary

This study investigates the relationship between May soil temperature and the EASM precipitation. The memories of May soil temperature at all the 16 stations in Northwest China are longer than 2 months. Warmer May soil temperature corresponds to less precipitation in the Yangtze and Huaihe River valley in June and July.

Possible physical mechanisms are further discussed. Warmer May soil temperature in Northwest China corresponds to warmer air temperature and positive anomaly of geopotential height over mainland of East Asia in the lower troposphere. The positive height anomaly might weaken the following southwesterlies over East Asia. At 850 hPa, there are anomalous cyclonic and anticyclonic circulations in the southeastern China and Northwest Pacific regions, respectively. The composite difference of geopotential height between wram and cold soil temperature events in May in Northwest China shows an EAP-like pattern. All the above factors prevent the delivery of water vapor by the southwesterlies to the Yangtze and Huaihe River valley, leading to the decreased rainfall in the Yangtze and Huaihe River area. This study demonstrates that May soil temperature in Northwest China is closely associated with the EAP index. The warm May soil temperature anomaly is favorable for the establishment of EAP, which favors less rainfall in the Yangtze and Huaihe River valley. Therefore, we may consider warmer May soil temperature as a predictor of positive phase of the EAP pattern. The possible mechanism we have proposed in this study needs to be further validated with high quality data and high-resolution model simulations.

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