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ORIGINAL PAPER

The impacts of the summer plateau monsoon over the Tibetan Plateau on the rainfall in the Tarim Basin, China

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Abstract The impacts of the summer plateau monsoon (PM) over the Tibetan Plateau on summer rainfall over the Tarim Basin in northwest China are investigated, based on the observed rainfall data at 34 stations and the NCEP/NCAR reanalysis data during 1961 to 2007. Results showed that the PM is well correlated to the summer rainfall over the Tarim Basin. Process analysis shows that strong PM corresponds to an anomalous cyclone over the Tibetan Plateau in the middle troposphere and an anomalous anticyclone in the upper troposphere over northwest part of Tibetan Plateau. They result in cold air moving from high latitudes into Central Asia over the western part of Tibetan Plateau. The concurrences of the cooling in the middle-upper troposphere over Central Asia leads to an anomalous cyclone over Central Asia at 500 hPa and the anomalous descending motions prevailing over the cooling region. Associated with this anomaly, there are enhanced southerly winds and corresponding ascending motion over the Tarim Basin located in the east of the cooling region. These processes lead to more summer rainfall over the Tarim Basin.

1 Introduction

In the past several decades, rainfall has changed significantly across many regions worldwide (IPCC 2007). The causes of such rainfall variations in China have been investigated in many earlier studies, but most of them were concentrated on the monsoon regions in eastern China (Weng et al. 1999; Huang et al. 2011; Zhu et al. 2013). Though rainfall over northwest China, especially in the western part of northwest China, has also experienced significant changes (Shi et al 2002; Hu et al., 2002), less attention has been paid to the arid regions such as the Tarim Basin where small rainfall changes could have significant ecological and environmental consequences.

The Tarim Basin is dominated by extreme arid climate with annual rainfall below 100 mm (Zhang and Deng 1987), and the most parts of the basin are occupied by desert. As one of the largest centers of dust storm occurrence in northern China (Wang et al. 2003), the Tarim Basin is identified as the farthest and important source area of dust deposits in the northern Pacific (Iwasaka et al. 1988). Previous studies suggested that the increasing rainfall over the Tarim Basin has contributed to the decreases in the dust storm occurrence during the past several decades (Chen et al. 2003; Li et al. 2008). So changes in the rainfall over the Tarim Basin not only have local climatic and environmental consequences but also have far-reaching impacts. Observational results suggested that the rainfall changes over the Tarim Basin showed different features from those over eastern China (Hu et al. 2002; Zhou and Huang, 2003). Yang and Zhang (2007) pointed out that the summer rainfall over the Tarim Basin is well related to the anomalous circulation patterns over Central Asia. Zhang and Shi (2002) and Zhao et al. (2012) suggested that the increasing farming irrigation had important effects on the increased rainfall over the Tarim Basin. However, the reasons for the increases in rainfall over the Tarim Basin are still unclear.

Earlier studies have indicated that the plateau monsoon (PM) over the Tibetan Plateau has important effects on the weather and climate in the surrounding areas of Tibetan Plateau and is also a key factor causing the arid climate in

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northwest China (Tang 1993; Bai et al. 2005). The PM is formed due to the surface wind cyclonical (anticyclonical) rotation in summer (winter) resulted from the seasonal variations of surface heat source over the Tibetan Plateau. It is independent from the South Asian monsoon and East Asian monsoon (Ye et al. 1957; Xu and Gao 1962; Tang et al. 1979; Li and Duan 2011). Recent studies suggested that strong PM corresponds to more summer rainfall over the Sichuan Basin and northwest China (Bai et al. 2005; Qi et al. 2009). The summer rainfall over the Tarim Basin, which is northwest to the Tibetan Plateau, also showed very close relationship with the PM (Bai et al. 2005), but the mechanisms and processes related to the PM's impacts on the summer rainfall over the Tarim Basin are still unclear so far. The aim of this paper is to investigate the impacts of the PM on the summer rainfall over the Tarim Basin and further explore the possible physical mechanisms.

The paper is organized as follows: study domain, data, and analytical method are given in Section 2. The statistical analysis of the connections between the PM over the Tibetan Plateau and the summer rainfall over the Tarim Basin and the possible mechanisms are shown in Section 3. Finally, the main conclusions and discussions are given in Section 4.

2 Study domain, data, and analytical method

2.1 Study domain

The Tarim Basin is located in southern Xinjiang province in northwest China (Fig. 1) and is the largest inland basin in China. It is surrounded by the Tianshan mountains to the north, the Kunlun mountains to the south, and the Pamirs Plateau to the west. Observational results showed that the Tarim Basin presented significant wetting trend in recent years (Hu et al. 2002; Shi et al. 2002). In current study, we focus on its summer rainfall, which accounts for 50–60 % of the annual

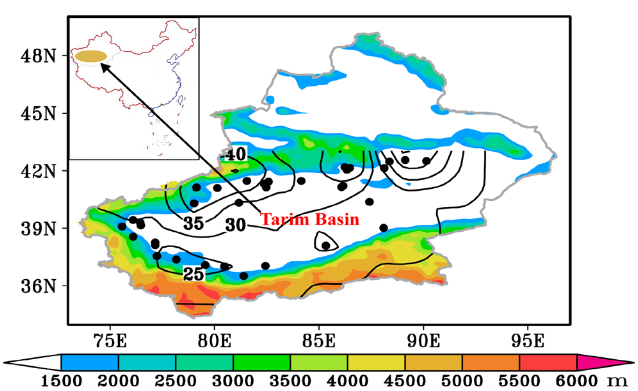

Fig. 1 The climatology of rainfall (contour, mm) in JJA and the locations of the observation stations (*dots*) in Tarim Basin. *Shaded colors* indicate the terrain height

total rainfall over this arid region (Zhang and Deng 1987). Figure 1 shows the distribution of the summer rainfall together with the locations of the 34 rainfall observed stations used in this analysis. The summer rainfall below 50 mm is located in most part of the Tarim Basin with higher amount in the areas north to the Tianshan mountains.

2.2 Data

The rainfall data used in this study are from the 34 meteorological stations over the Tarim Basin compiled by the Xinjiang Meteorological Information Center during 1961 to 2007. To assess if the relocation and instrument changes of some observation stations have contaminated the quality of data, cumulative deviations test (Buishand 1982) has been used to detect the homogeneity of the precipitation data series for each station used in this analysis. The results suggested that the precipitation data of the 34 stations used in this study are homogeneous at more than 95 % confidence level. The National Centers for Environment Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kalnay et al. 1996) are used to reveal the large scale atmospheric circulation patterns. All data mentioned above are averaged for the boreal summer months (June, July, and August or JJA).

2.3 Analytical method

A summer precipitation index (SPI) is defined in this analysis by the June–August precipitation regionally averaged over the 34 observation stations across the Tarim Basin. In this study, we use the index to reveal underlying processes influencing the rainfall variations over the basin.

The spatial distribution of the summer mean geopotential height and horizontal wind at 600 hPa averaged over 1961 to 2007 (Fig. 2) exhibits a low pressure center over the Tibetan Plateau corresponding with the horizontal wind rotating cyclonically. This leads to the northeast (southwest) wind prevailing over northern (southern) part of the Tibetan Plateau. Accordingly, the geopotential height is lower over the center of the Tibetan Plateau than that over the surrounding areas. Thus Tang et al. (1984) developed a PM index as follows:

$$\mathrm{PMI} = H_1^{'} + H_2^{'} + H_3^{'} + H_4^{'} - 4H_0^{'}$$

Where $H_0^{'}$ denotes the geopotential high anomaly at 600 hPa at the location of (90° E, 32.5° N). $H_1^{'}$, $H_2^{'}$, $H_3^{'}$, and $H_4^{'}$ are the geopotential high anomaly at 600 hPa at the position of (80° E, 32.5° N), (90° E, 25° N), (100° E, 32.5° N), and (90° E, 40° N), respectively. It is obvious that the larger (smaller) values of PMI represent stronger (weaker) summer PM.

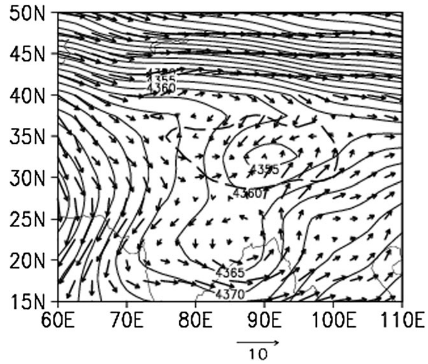

Fig. 2 The climatology of geopotential height (contour, gpm) and horizontal wind (vector, m s^{-1}) in JJA at 600 hPa during 1961 to 2007. The domain bounded by *dashed line* indicates the terrain height over 3000 m

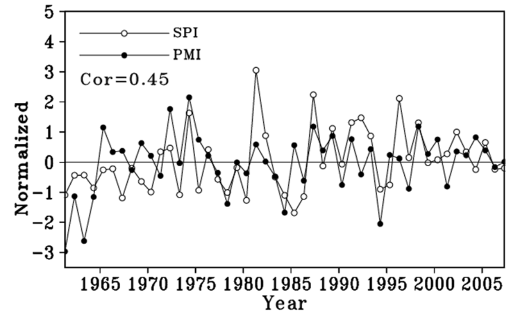

Fig. 4 Time series of the PMI and SPI in JJA during 1961 to 2007

3 Results

3.1 Anomalous atmospheric circulations associated with strong/weak summer PM

Figure 3a shows the time series of the PMI for the period of 1961 to 2007. In this analysis, the years with the normalized PMI exceeding ±0.5 standard deviation are treated as the strong/weak PM years. Fourteen strong PM years (1965, 1969, 1972, 1974, 1975, 1981, 1985, 1987, 1989, 1991, 1998, 1999, 2000, and 2004) and 11 weak PM years (1961, 1962, 1963, 1964, 1978, 1984, 1986, 1990, 1994, 1997, and 2001) are therefore selected for the composite analysis of atmospheric circulation anomalies associated with strong/weak PM. As shown in Fig. 3b, c, an anomalous cyclone (anticyclone) prevails over the whole Tibetan Plateau and its surrounding areas in the strong (weak) PM years. It is clear that the Tarim Basin is dominated by southeast (northwest) wind anomalies in the strong (weak) PMI years, indicating that the climate over the Tarim Basin can be affected by the changes in the atmospheric circulations associated with the PM variations. In fact, previous studies also showed that the Plateau Monsoon has close relationship with summer rainfall over the Tarim Basin (Tang 1993). In addition, Tang et al. (1979) investigated the effects of the onset of PM on seasonal variation of rainfall over the Tibetan Plateau and its surrounding areas. They found the rainfall showed significant seasonal variations

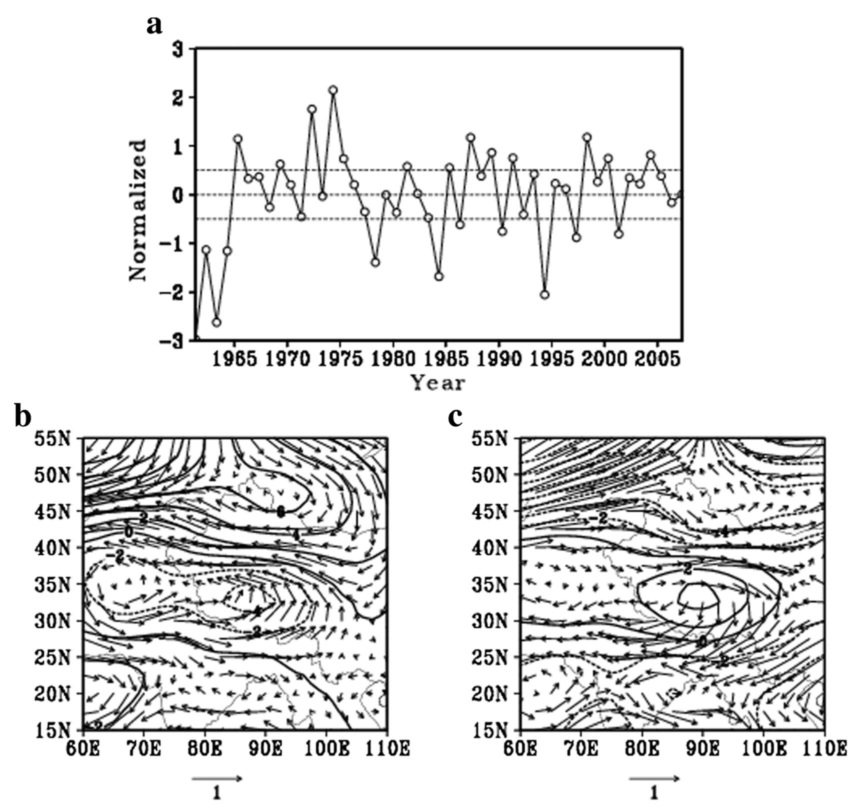

Fig. 3 **a** The interannual variations of summer PMI in JJA during 1961 to 2007, with the *dashed lines* indicating ±0.5 standard deviation, **b** the composite anomalies of summer geopotential height (contour, gpm) and horizontal wind (vector, m s^{-1}) at 600 hPa during strong summer PM years, and **c** weak summer PM years, respectively

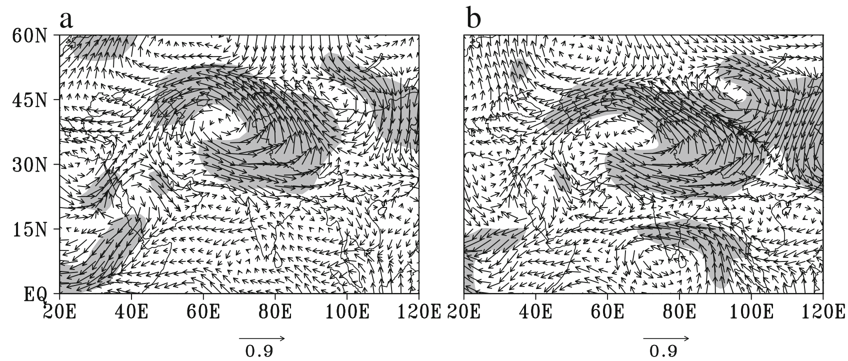

Fig. 5 Correlations of the SPI (**a**) and PMI (**b**) with the wind vector at 500 hPa in JJA. Regions over the 95 % significant confidence level are *shaded*

in the Tarim Basin and western part of Sichuan basin associated with PM. According to the above results, the index defined by Tang et al. (1984) can well present the PM phenomenon and its anomalous features over the Tibetan Plateau. Therefore, in this analysis, this index is used to further investigate the relation of PM with summer rainfall in the Tarim Basin.

3.2 The relationships between summer PM and the summer rainfall over the Tarim Basin

Figure 4 shows that the PMI is strongly correlated with SPI over the Tarim Basin during 1961 to 2007 with a correlation of 0.45, which is over 99 % significant level. The composite of summer rainfall anomalies over strong/weak PM years shows that most part of the Tarim Basin is occupied by positive (negative) rainfall anomalies during the strong (weak) PM years (not shown). One legitimate question is how the PM influences the summer rainfall over the Tarim Basin. To answer this question, we further show the impacts of the PM on the regional atmospheric circulations. Figure 5 gives the correlations of the SPI and PMI with 500 hPa wind. An anomalous cyclone at 500 hPa level is located over Central Asia during the positive phase of SPI (Fig. 5a), which is considered as one of the key circulation patterns related to the summer rainfall in the Tarim Basin (Zhang et al. 1986; Yang and Zhang 2007).Corresponding anomalous southerly wind over the Tarim Basin is favorable for the warm and wet air penetrating from the low latitudes to the Tarim Basin and more rainfall generation. Figure 5b shows similar features to those in Fig. 5a, indicating that the strong summer PM can lead to an anomalous cyclone at 500 hPa level over Central Asia which provides atmospheric circulations beneficial to more summer precipitation over the Tarim Basin.

Because of the thermal forcing of the Tibetan Plateau, the Tarim Basin is generally dominated by a descending motion (Ye et al. 1957). The strength of the vertical motion is therefore well related to the dry and wet variation in northwest China (Wu and Qian 1996; Qian et al. 2001). Figure 6a shows the correlations between the SPI and vertical velocity field over the Tarim Basin. It is obvious that positive SPI is associated with an anomalous ascending motion over the Tarim Basin. The anomalous ascending motions can be found over the Tarim Basin during the period of strong summer PM. Meanwhile, the strong PM is accompanied by remarkable anomalous southerly winds over the Tarim Basin. The intensified vapor transportation associated with the anomalous southerly winds and the strengthened ascending motions result in more rainfall over the Tarim Basin during the strong summer PM years.

3.3 The possible mechanism of summer PM affecting the summer rainfall over the Tarim Basin

From the results mentioned above, the summer PM has important effects on the atmospheric circulations associated with the summer rainfall anomalies in the Tarim Basin. Figure 7a further

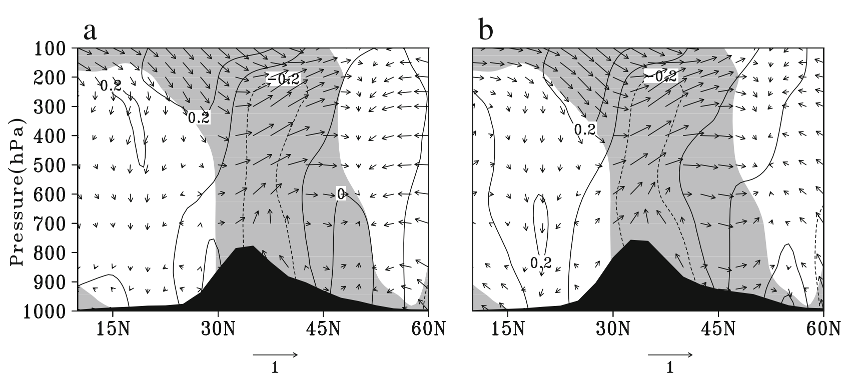

Fig. 6 **a** Latitude-height cross-section of correlations between the SPI and vertical velocity (contour) and the meridional wind and vertical velocity component (vector) averaged along 75–95° E in JJA, **b** as **a** but for the PMI. Regions over 95 % significant confidence level in **a** and **b** are *shaded*

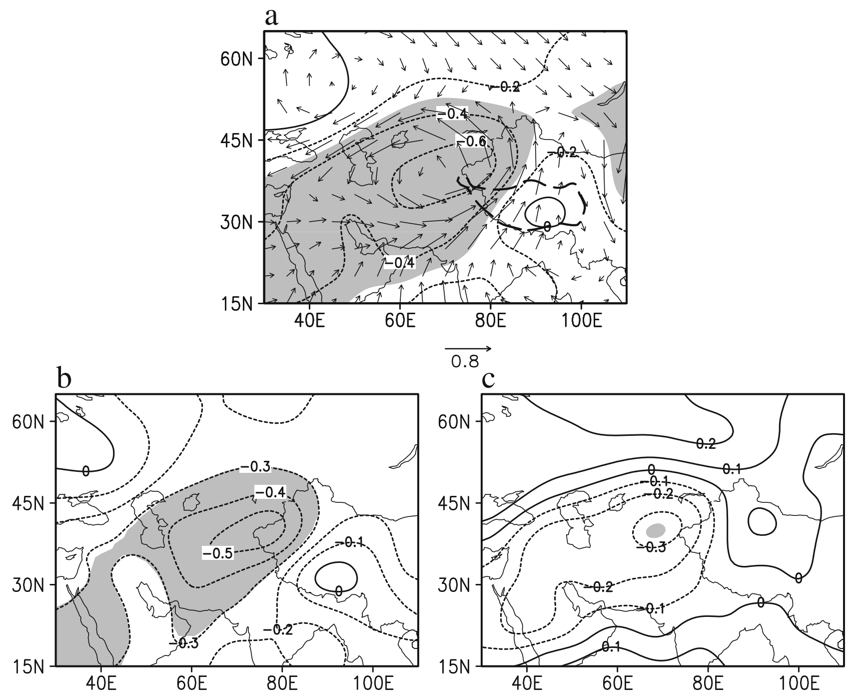

Fig. 7 **a** Correlations of the air temperature vertically averaged from 500 to 200 hPa and wind vector at 200 hPa with the PMI in JJA, **b**partial correlation of the air temperature vertically averaged from 500 to 200 hPa with the PMI in JJA after excluding the effect of SPI variations, **c** as **b** but for correlations with the SPI after excluding the effect from PMI variations. Regions over 95 % significant confidence level in **a** and **b** are *shaded*. The *thick dashed line* in **a** presents the terrain height over 3000 m

displays the correlations of air temperature vertically averaged from 500 to 200 hPa and wind vector at 200 hPa with the PMI. The air temperature in the middle and upper troposphere over Central Asia decreases during the strong summer PM years. On one hand, an anomalous cyclone over the Tibetan Plateau (Fig. 3b) corresponded to the strong PM, leading to northeast wind prevailing over Central Asia which is favorable for the cold advection from high latitudes. On the other hand, the heating of latent heat during the period of summer PM plays an important role over the Tibetan Plateau (Yanai and Song 1992; Yanai and Li 1994). It can result in anomalous anticyclone in the upper troposphere over the northwest part of the PM region (Liu et al 1999; Li and Duan 2011), which is well matched in Fig. 7a. The anomalous anticyclone can move more cold air from high latitudes into Central Asia, above all contribute to the cooling in the middle and upper troposphere over Central Asia.

Previous studies pointed out that the tropospheric temperature variations had a close relationship with the regional climate variations. For example, the strong upper tropospheric cooling over East Asia weakened the East Asian summer monsoon (Yu et al. 2004). In addition, the cooling in the upper troposphere in late spring over central China was well related to the droughts over southern China (Xin et al. 2006). One of previous studies also showed that the summer rainfall over the Tarim Basin is well related to the middle-upper tropospheric temperature over Central Asia (Zhao et al. 2014). To distinguish the cause-effect relationship between the PM over the Tibetan Plateau, the summer rainfall over the Tarim Basin and the middle-upper tropospheric temperature over Central Asia, Fig. 7b, c gives the partial correlation calculations. As shown in Fig. 7b, the partial correlations between the middle-upper tropospheric temperature and the PMI are still significant after

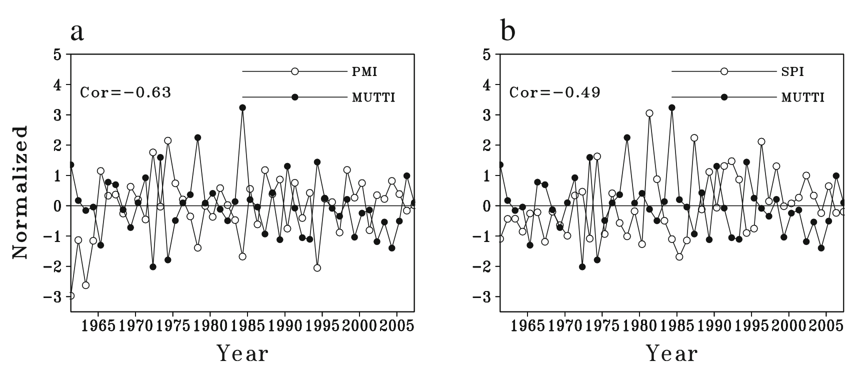

Fig. 8 **a** Time series of the PMI and the MUTTI during 1961 to 2007 in JJA, **b** as **a** but for the SPI and the MUTTI

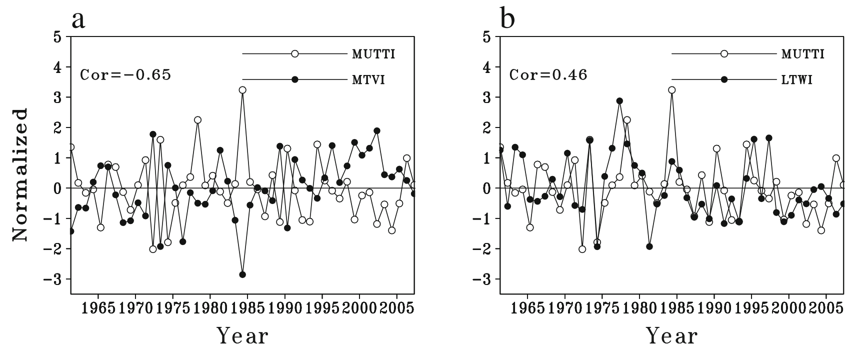

Fig. 9 **a** Time series of the MUTTI and the MTVI in JJA during 1961 to 2007, **b** as **a** but for the MUTTI and the LTWI

excluding the SPI contributions. The partial correlation results are similar to the features in Fig. 7a. In contrast, in Fig. 7c, the partial correlations between the middle-upper tropospheric temperature and the SPI are very weak after excluding the influence from PMI. This confirms that the PM causes the variations of middle-upper tropospheric temperature over Central Asia which then contributes to the rainfall variations in the Tarim Basin.

To further investigate the impact mechanism of how the PM influences the summer rainfall over Tarim Basin through the tropospheric cooling, we have calculated a middle-upper troposphere temperature index (MUTTI) defined by the normalized air temperature in the middle-upper troposphere (500–200 hPa) regionally averaged over Central Asia (60–80° E, 35–45° N) during 1961 to 2007. Figure 8a shows the time series of the PMI and the MUTTI during 1961 to 2007. The PMI and MUTTI exhibit a strong correlation of −0.63 which is over 99 % significant confidence level, indicating that the summer PM is closely correlated with the air temperature in the middle-upper troposphere over Central Asia. Figure 8b shows the time series of the MUTTI and the SPI during 1961 to 2007. The results indicate that the summer middle-upper tropospheric air temperature over Central Asia is closely related to the summer rainfall over the Tarim Basin with a strong correlation of −0.49, which is over the 99 % significant confidence level.

The study of Yu et al. (2004) pointed out that the cooling in the upper troposphere over East Asia can cause the position of subtropical westerly jet further south. This can further weaken the East Asian summer monsoon. Then what are the effects of the cooling in the middle-upper troposphere on circulations over Central Asia? To better summarize the key circulation characteristics associated with the middle-upper tropospheric cooling, we have calculated the correlations of the MUTTI with two key indices: (1) the middle tropospheric meridional wind index (MTVI), which is defined by normalized summer 500 hPa meridional wind regionally averaged over Central Asia (75–95° E, 35–45° N) during 1961 to 2007; (2) the low tropospheric vertical wind index (LTWI), which is defined by the normalized summer 700 hPa vertical velocity ($-\omega$) regionally averaged over the region bounded by 75–95° E and 35–45° N during 1961 to 2007. Figure 9 demonstrates the interannual variations of the MUTTI with MTVI (Fig. 9a) and LTWI (Fig. 9b), respectively. The correlations coefficients of MUTTI with MTVI and LTWI are −0.65 and 0.46, which are over 99 % significant confidence level. A strong PM corresponds to a cooling in the middle-upper troposphere. This can then lead to the formations of anomalous cyclone according to the theory of thermal wind. Such circulation anomalies cause anomalous southerly winds prevailing over the Tarim Basin. Then.anomalous southerly wind from low latitudes and anomalous northerly wind from high latitudes can generate anomalous ascending motions over the Tarim Basin and thereafter more rainfall over the basin.

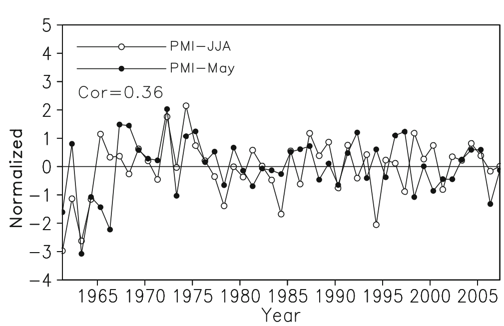

Fig. 10 Time series of the PMI in May and JJA during 1961 to 2007

4 Conclusions remarks and discussions

In this study, our results show that the summer PM has a statistically significant relationship with the summer rainfall over the Tarim Basin during 1961 to 2007, with a correlation coefficient of 0.45. The variations of summer PM are well related to the atmospheric circulation associated with the summer rainfall over the Tarim Basin. Further analysis shows that strong PM corresponds to an anomalous cyclone over the Tibetan Plateau in the middle troposphere and an anomalous anticyclone in the upper troposphere over northwest part of Tibetan Plateau. Such circulation anomalies result in cold air moving from high latitudes into Central Asia over western part of Tibetan Plateau. Meanwhile, the cooling in the middle-upper troposphere over Central Asia associated with strong PM an anomalous cyclone over Central

Asia at 500 hPa and the anomalous descending motions prevailing over the cooling region. This leads to anomalous southerly winds and corresponding ascending motion over the Tarim Basin which is located in the east of the cooling region. The enhanced southerly winds are favorable for the penetration of tropical warm and moist air into the basin and result in more summer rainfall over the Tarim Basin.

In the current study, we have only investigated the relationships between the summer PM and the summer rainfall over the Tarim Basin and further explored the possible influencing mechanisms. However, the mechanism related to the summer PM variation itself is not discussed. Previous studies pointed out that positive vortex source caused by the heating of the Tibetan Plateau is the key factor to maintain the cyclonic circulation at boundary layer over the Tibetan Plateau (Wu and Liu 2000) and the thermal forcing plays an important role in forming the PM. To reveal the influencing mechanisms of the PM on the summer rainfall over the surrounding areas of the Tibetan Plateau, the impacts of the heat source and its spatial distributions and seasonal variations over the Tibetan Plateau on the PM need to be revealed in the further work. In addition, the studies of Tang et al. (1984) found that the PM exhibited good persistence in some months. Our study indeed confirms that the PM indices in May and in JJA are well correlated, with a correlation coefficient of 0.36 (Fig. 10). This suggests that the thermal anomalies over the Tibetan Plateau in May can persist still in the boreal summer season and then affect the summer monsoon to some extent (Duan et al. 2003; Zhao and Qian 2009). However, whether the PM in May can be indicative to the summer rainfall over the Tarim Basin is still an open question to be further investigated.

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