Impact of the Middle and Upper Tropospheric Cooling over Central Asia on the Summer Rainfall in the Tarim Basin, China

YONG ZHAO

Institute of Desert Meteorology, China Meteorological Administration, Urumqi, Xinjiang, China

ANNING HUANG, YANG ZHOU, AND DANQING HUANG

School of Atmospheric Sciences, Nanjing University, Nanjing, Jiangsu, China

QING YANG, YUFEN MA, MAN LI, AND GANG WEI

Institute of Desert Meteorology, China Meteorological Administration, Urumqi, Xinjiang, China

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ABSTRACT

The changes in summer rainfall over the Tarim Basin, China, and the underlying mechanisms have been investigated using the observed rainfall data at 34 stations and the NCEP–NCAR reanalysis data during the period of 1961–2007. Results show that the summer rainfall over the Tarim Basin, which exhibits a significant increasing trend during the last half century, is closely related to the summer middle and upper tropospheric cooling over central Asia. Mechanism analysis indicates that the middle and upper tropospheric cooling over central Asia results in a location farther south of the subtropical westerly jet over western and central Asia with anomalous southerly wind at lower levels and ascending motion prevailing over the Tarim Basin. Such anomalies in the atmospheric circulations provide favorable conditions for the enhanced summer rainfall over the Tarim Basin. Further analysis suggests that the weakened South Asian summer monsoon (SASM) could be potentially responsible for the middle and upper tropospheric cooling over central Asia. This is largely through the atmospheric responses to the diabatic heating effect of the SASM. A weakened SASM can result in an anomalous cyclone in the middle and upper troposphere over central Asia. The western part of the anomalous cyclone produces more cold air advection, which leads to the cooling. This study suggests indirect but important effects of the SASM on the summer rainfall over the Tarim Basin.

1. Introduction

The mean precipitation has significantly changed across many regions in recent decades (Solomon et al. 2007). Extensive studies have been conducted for rainfall variations in China, but most of these studies were focused on the changes in the summer precipitation over eastern China (Nitta and Hu 1996; Weng et al. 1999; D. Q. Huang et al. 2011; Zhu et al. 2013). Less attention has been paid to the arid regions in northwest China despite the fact that small rainfall changes in these very arid regions could have significant social, economic, and environmental consequences.

The Tarim Basin located in northwest China is the largest inland basin in China. Because it has low atmospheric moisture content and it is dominated by the prevailing descending motion produced by the thermal forcing of the Tibetan Plateau (Yeh and Koo 1955; Fan and Cheng 2003), the Tarim Basin is characterized by an extreme arid climate with mean annual precipitation below 100 mm (Zhang and Deng 1987). Furthermore, the Tarim Basin is one of the largest centers in northern China with high dust storm occurrence. It is identified as the most distant and most important source area of dust deposits for the northern Pacific (Iwasaka et al. 1988; S. G. Wang et al. 2003). Therefore, climate change over the Tarim Basin can have far-reaching climatic impacts

Corresponding author address: Dr. Anning Huang, School of Atmospheric Sciences, Nanjing University, No. 22 Hankou Road, Nanjing, Jiangsu 210093, China.
E-mail: anhuang@nju.edu.cn

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at both local and regional spatial scales. Revealing the mechanism of its precipitation variations has become an area of active research in recent decades.

Previous observational results suggested that precipitation in Xinjiang had experienced significant decadal changes in the late 1980s. Such changes were different from the changes that occurred in eastern China (Shi et al. 2002; Zhou et al. 2009). A persistent drought has occurred in northern China since 1976, but the rainfall over the Tarim Basin of northwest China has showed a significant increasing trend and presented a strong moistening signal in recent decades (Shi et al. 2003; S. D. Wang et al. 2003; Huang et al. 2006). Many studies concentrated on exploring the potential mechanisms leading to the drought in northern China. For example, Huang et al. (2006) pointed out that the drought in northern China was well related to the positive anomalous pattern of the sea surface temperature in the tropical central and eastern Pacific. Ju et al. (2006) suggested that the strong Arctic Oscillation played an important role in northern China's persistent droughts over the past 20 years. In addition, the interdecadal change of the summer rainfall over northern China is well correlated with winter snow in the Tibetan Plateau and the Pacific decadal oscillation (Qian et al. 2003; Zhang et al. 2007). G. Huang et al. (2011) and Chen and Huang (2012) pointed out that the interannual variability of the summer rainfall in the arid and semiarid regions was well related to the upper tropospheric circulation teleconnection in the Northern Hemisphere. Some recent studies showed the so-called ‘‘south wet and north dry’’ pattern in eastern China corresponded well to the weakening trend of the thermal forcing in the Tibetan Plateau (Liu et al. 2012).

However, the reasons for the increase in rainfall over the Tarim Basin are still unclear, with fewer studies being devoted to exploring the underlying processes causing such changes. Some studies argued that the increased precipitation over the Tarim Basin was closely related to the expansion of oases and increasing farming irrigation (Zhang and Shi 2002; Zhao et al. 2012). Yang and Zhang (2007) pointed out that the summer precipitation over Xinjiang was closely related to the anomalous atmospheric circulation systems over central Asia. These unresolved scientific arguments prompt us to further diagnose the atmospheric dynamical and physical processes associated with the changes of the summer precipitation over the Tarim Basin.

Several studies showed that the tropospheric temperature variations had significant regional features that had a close relation with observed regional climate variations. Zhou and Zhang (2009) found a significant cooling center over East Asia and two warming centers over the North Atlantic and North Pacific in July and August. The strong upper tropospheric cooling over East Asia weakened the East Asian summer monsoon and resulted in a tendency for increasing droughts over northern China and floods over the Yangtze River valley (Yu et al. 2004). The upper tropospheric temperature also showed a prominent cooling in late spring over central China (30°–40°N, 110°–125°E), which was well related to the droughts over south China (Xin et al. 2006; Yu and Zhou 2007). However, the above discussions were focused on East Asia and it is unclear whether the moistening trend over the Tarim Basin is also correlated with the upper tropospheric cooling in recent decades. Our preliminary results showed that the increased summer rainfall over the Tarim Basin was concurrent with a cooling in the middle to upper troposphere (600–300 hPa) over central Asia (35°–45°N, 60°–80°E), which is closely correlated with the South Asian summer monsoon (SASM), whose interannual and interdecadal variations significantly affect regional and global climate (Lawrence and Webster 2001). Earlier studies showed that the summer precipitation over northwest China increased during the years of earlier onset of the SASM (Xu and Qian 2006). Mason and Goddard (2001) and Mariotti et al. (2005) pointed out that the precipitation over central and southwest Asia was also derived from tropical moisture sources and well associated with tropical climate variability. Yang et al. (2009) also found that the precipitation over Xinjiang was well correlated with the SASM rainfall over India.

The main objectives of the current study are to pay specific attention to exploring the potential linkage between the increased summer rainfall over the Tarim Basin (Hu et al. 2002; Shi et al. 2003) with the summer middle-upper tropospheric cooling over central Asia and the causes associated with the cooling. The analysis mainly concentrates on the variations at an interannual time scale. To illustrate the possible linkage between the increased summer rainfall over the Tarim Basin and the middle-upper tropospheric cooling over central Asia and the underlying mechanisms, we will answer the following questions: How does the middle to upper tropospheric cooling over central Asia result in the increased summer rainfall over the Tarim Basin? Is the tropospheric cooling over central Asia associated with the SASM? What are the possible underlying mechanisms?

The paper is organized as follows: Section 2 gives a brief description of the study domain, observational rainfall data, and atmospheric circulation data used in this study. The influencing processes of the middle-upper tropospheric cooling over central Asia on the summer rainfall over the Tarim Basin are discussed in section 3. Section 4 explores the possible linkage

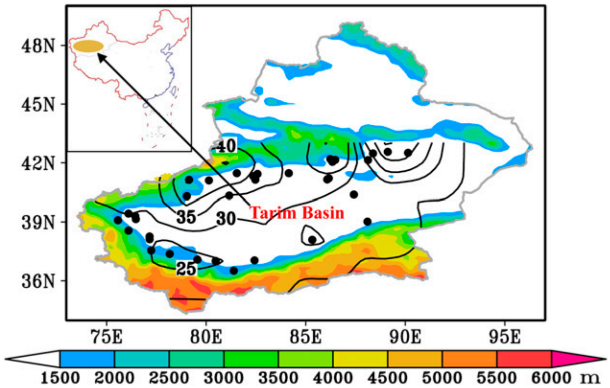

FIG. 1. The climatology of the summer rainfall (contour, mm) and the locations of the observation stations (dots) in the Tarim Basin. Shaded areas indicate the terrain height.

between the summer middle-upper tropospheric cooling over central Asia and the SASM. A summary and discussion are given in section 5.

2. Study domain and data

The Tarim Basin is located in southern Xinjiang province in northwest China (Fig. 1) with an area of around $5.3 \times 10^5 \mathrm{km}^2$. It is the largest inland basin in China and surrounded by the Tianshan Mountains to the north, the Kunlun Mountains (the northern edge of the Tibetan Plateau) to the south, the Pamirs Plateau to the west, and the Altun Mountains to the east. In recent years more attention has been paid to the observed moistening trend over the Tarim Basin (Hu et al. 2002; Shi et al. 2003). In this study, we focus on its summer rainfall, which accounts for 50%–60% of the annual total precipitation over this arid region (Zhang and Deng 1987). Figure 1 shows the spatial distribution of the summer rainfall averaged over 1961–2007 together with the locations of the 34 rainfall stations, from which the observed rainfall datasets are compiled and quality controlled by the Xinjiang Meteorological Information Center. It can be noticed that the summer rainfall below 50 mm is located in most part of the basin with higher amounts in the Tianshan Mountains.

The summer precipitation index (SPI) over the Tarim Basin is derived from the normalized summer rainfall regionally averaged over the 34 stations for the period between June and August. To assess if the relocation and instrument changes of some stations contaminate the data quality, the cumulative deviations test (Buishand 1982) has been used to detect the homogeneity of the precipitation data series for each station during 1961–2007. The results (not shown) suggested that the precipitation data from the 34 stations are homogeneous at more than a 95% significance confidence level.

In addition, the National Centers for Environment Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al. 1996) and the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data (Uppala et al. 2005) are used to reveal the large-scale atmospheric circulation patterns. Because the results are similar between these two datasets and the NCEP–NCAR data cover a longer period, in this analysis we only concentrate on the results based on the NCEP–NCAR reanalysis data. An index of SASM (SASMI) is derived from the reanalysis data during 1961–2007 according to the definition of Webster and Yang (1992). This index shows the zonal wind shear between 850 and 200 hPa averaged over South Asia (0°–20°N, 40°–110°E). Throughout this study, we concentrate on the analysis of the results averaged over the boreal summer months (June–August).

3. The influencing processes of the middle and upper tropospheric cooling over central Asia on the Tarim Basin summer rainfall

In recent years, most attention has been paid to studying the observed upward trend of summer rainfall in Xinjiang, of which the Tarim Basin shows an even more pronounced moistening signal than the rest of the region (Shi et al. 2002, 2003). As shown in Fig. 2a, the Tarim Basin summer rainfall presents a distinct upward trend (over 95% significance confidence level) during the period of 1961–2007. By using the Mann–Kendall test (Mann 1945; Kendall 1975), it is confirmed that the sudden change in the SPI occurred around 1987, indicating that the Tarim Basin has become wetter since 1987 (Fig. 2b).

Both reanalysis datasets and radiosonde datasets consistently show that an upper tropospheric cooling is prominent over central Asia in recent decades. This is similar to the cooling over East Asia (Zhang and Zhou 2013), which is well correlated with the precipitation over eastern China (Yu et al. 2004; Xin et al. 2006). Whether the middle-upper tropospheric cooling over central Asia is also related to the moistening over the Tarim Basin or not is still an open question. To answer such questions, further analyses are conducted in the following sections.

Figure 3a shows the regressions of latitude–height cross section of the summer air temperature averaged along 60°–80°E against the SPI. The middle to upper tropospheric (600–300 hPa) air temperature over the regions between 35° and 45°N significantly decreases during the positive phase of SPI. The regressions of the mean air temperature between 600 and 300 hPa against the SPI are shown in Fig. 3b. It can be noticed that the

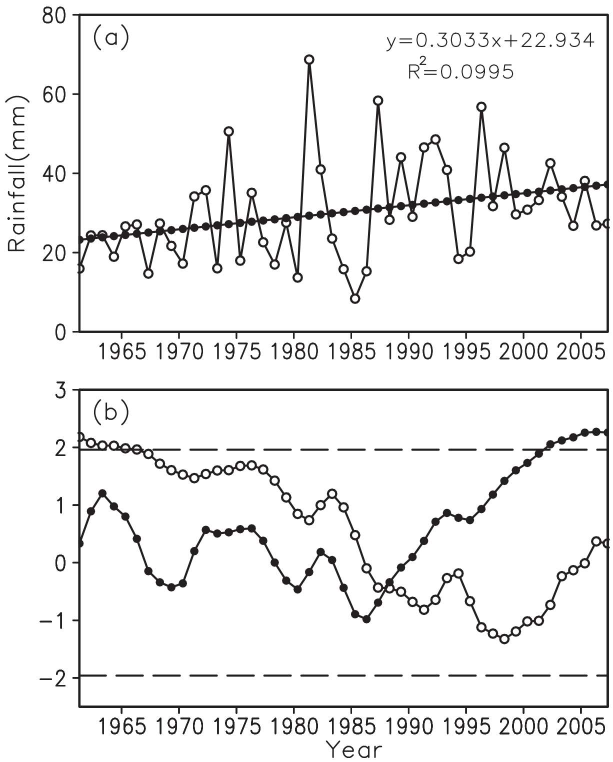

FIG. 2. (a) The interannual variation of summer rainfall regionally averaged over the Tarim Basin (open circle line) and its linear trend (solid circle line) during 1961–2007. (b) The forward (solid circle line) and backward (open circle line) statistic rank series in the Mann–Kendall test of the SPI. The dashed line indicates the 5% significance level of the Mann–Kendall test.

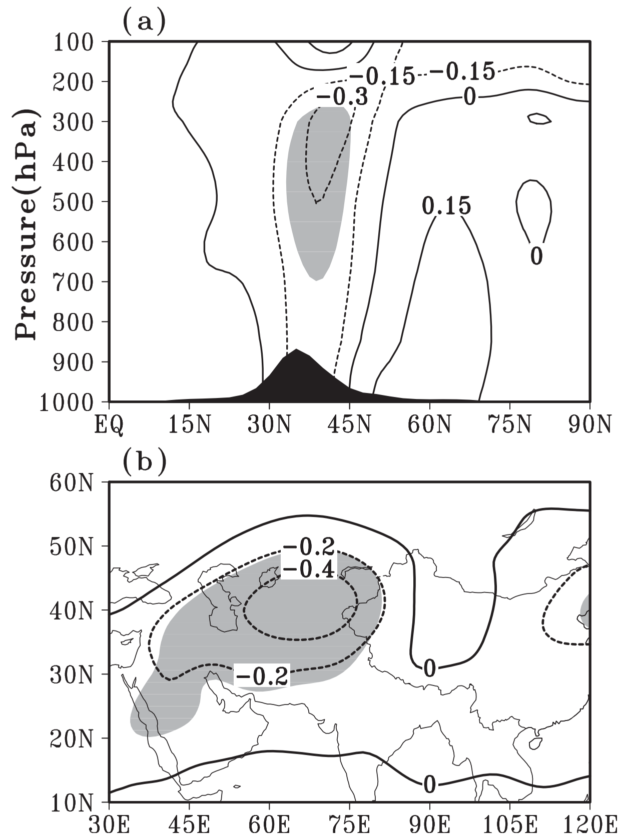

FIG. 3. Regressions of (a) latitude–height cross section of the summer air temperature (contour, °C) averaged along 60°–80°E and (b) air temperature (contour, °C) vertically averaged from 600- to 300-hPa levels against the SPI. Regions over the 95% significant confidence level in (a) and (b) are shaded.

positive SPI is closely associated with significantly decreased summer air temperature in the middle to upper troposphere over central Asia. These results suggest that the summer rainfall over the Tarim Basin has a close correlation with the summer air temperature in the middle to upper troposphere over central Asia. Similar results can be obtained by using the ERA-40 data (not shown). According to the results given above, the middle-upper troposphere temperature index (MUTTI) is defined by the normalized air temperature in the middle to upper troposphere (600–300 hPa) regionally averaged over central Asia (35°–45°N, 60°–80°E) during 1961–2007. Figure 4 shows the time series of the MUTTI over central Asia and the SPI over the Tarim Basin during 1961–2007. The SPI and MUTTI exhibit a strong correlation of −0.63, which is over 99% significant in confidence level, indicating that the summer precipitation over the Tarim Basin is significantly correlated with the middle to upper tropospheric air temperature.

Now we further examine how the air temperature anomalies in the middle to upper troposphere over central Asia affect the atmospheric dynamical and moisture conditions associated with the summer rainfall generation over the Tarim Basin. Yu et al. (2004) found that the upper tropospheric cooling at 300 hPa resulted in a southward displacement of the upper-level westerly jet stream over East Asia and a weakened East Asian

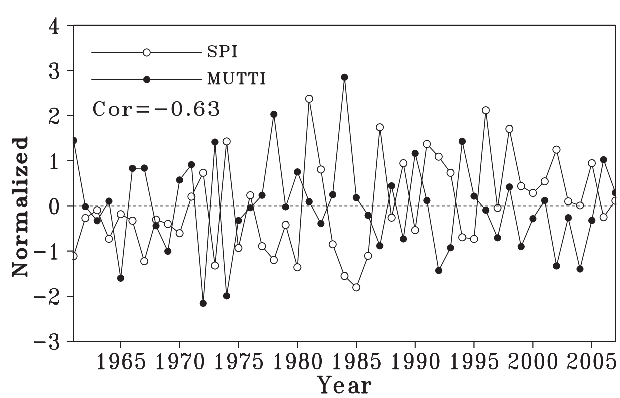

FIG. 4. Time series of the summer MUTTI and the SPI during 1961–2007.

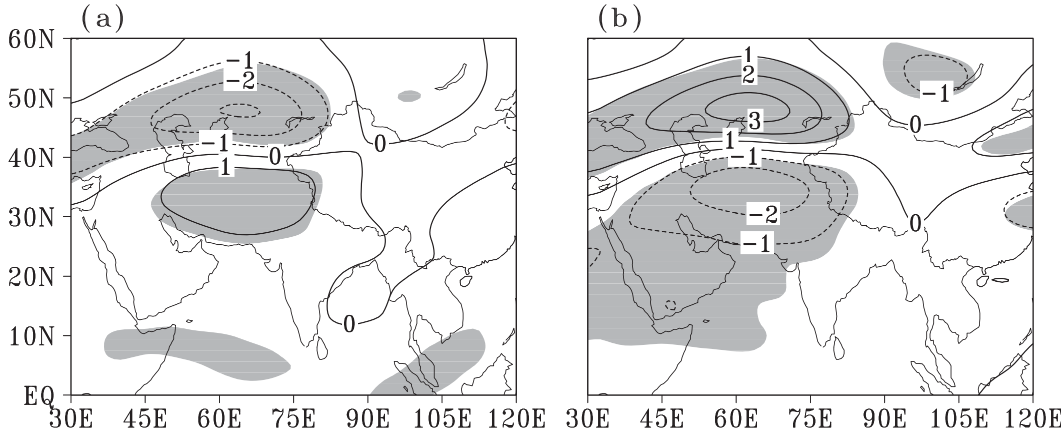

FIG. 5. Regressions of the summer 200-hPa zonal wind against (a) the SPI and (b) the MUTTI (contour, m s^{-1}). Regions over the 95% significant confidence level in (a) and (b) are shaded.

summer monsoon with increased droughts over northern China and floods over the Yangtze River valley. The subtropical westerly jet over western and central Asia is also one of key atmospheric systems affecting the summer rainfall over Xinjiang (Zhang et al. 2006; Yang and Zhang 2008). Our recent study has analyzed the relationship of the position variation of the westerly jet at 200 hPa over western and central Asia with the summer rainfall over northern Xinjiang (Zhao et al. 2014). In the present study, we focus on investigating the relation of the middle to upper tropospheric cooling over central Asia with the westerly jet and its effects on the Tarim Basin summer rainfall. Figure 5a shows the regressions of the summer 200-hPa zonal wind against the SPI. It is clear that during the period of positive SPI a significantly strengthened zonal wind exists over the domain of 30°–45°N, 50°–80°E, which reflects the position variation of the subtropical westerly jet. Regressions of the summer 200-hPa zonal wind against the MUTTI (Fig. 5b) show common features as in Fig. 5a but with opposite signs. It is obvious that during the period of negative MUTTI the pattern of the summer 200-hPa wind anomalies over central Asia is consistent with the one for the positive SPI. Further analysis shows that an anomalous cyclone is observed in the middle to upper tropospheric cooling region of central Asia (not shown). This is in good agreement with what is expected from the thermal wind relationship. Such an anomalous cyclonic system strengthens the zonal wind over the Arabian Peninsula, leading to the subtropical jet axis shifting farther south.

The anomalous circulation in the middle troposphere over central Asia significantly affects the summer rainfall over Xinjiang (Zhang et al. 1986). As shown in Fig. 6a, an anomalous cyclone at the 500-hPa level is located over central Asia during the positive phase of SPI. Corresponding anomalous southerly wind prevailing over

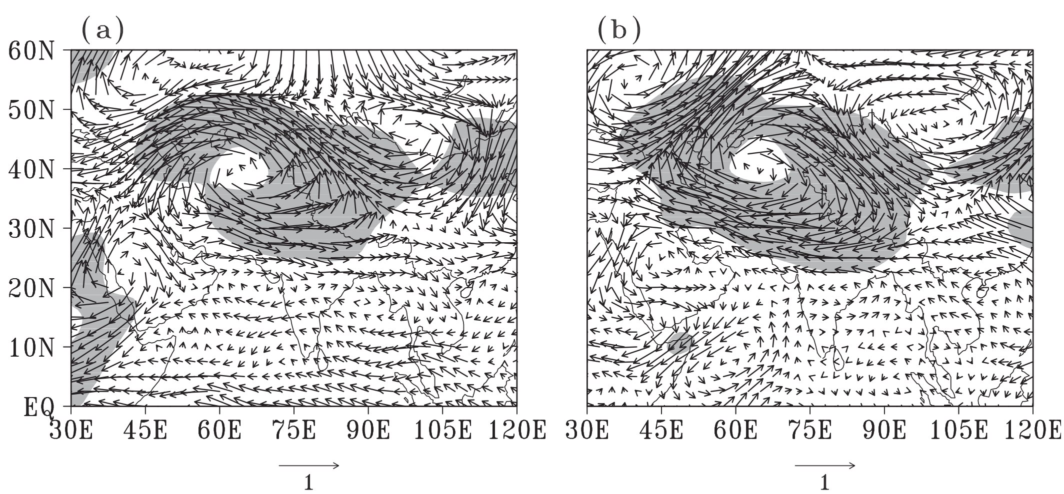

FIG. 6. Regressions of the summer 500-hPa wind vector against (a) the SPI and (b) the MUTTI (vector, m s^{-1}). Regions over the 95% significant confidence level in (a) and (b) are shaded.

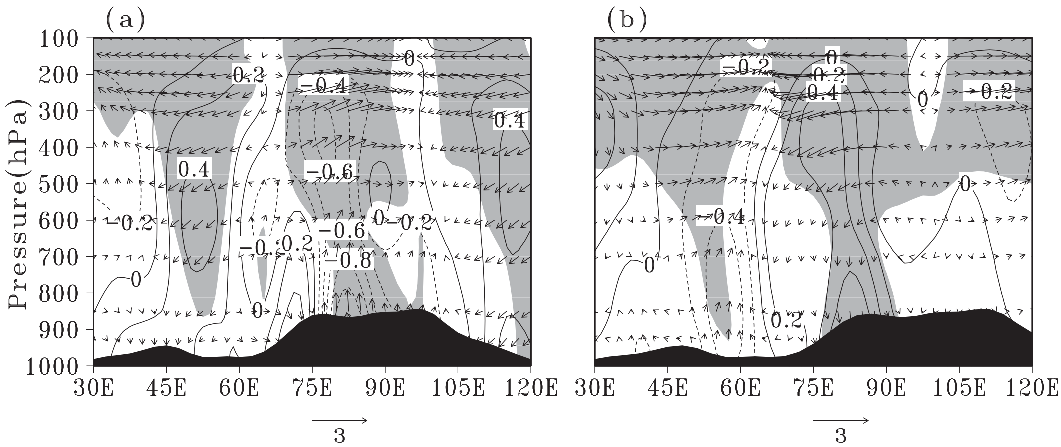

FIG. 7. Regressions of longitude–height cross section of the summer vertical velocity (ω, contour interval 1×10^{-2} hPa s^{-1}) and the meridional wind and vertical velocity ($-\omega$) vector averaged along 35°–45°N against the (a) SPI and (b) MUTTI. Regions over 95% significant confidence level in (a) and (b) are shaded for meridional wind and vertical velocity vector.

Xinjiang is favorable for the warm and wet air penetrating from the low latitudes to the Tarim Basin and more rainfall generation. Figure 6b displays the regressions of the summer 500-hPa wind vector against the MUTTI. An anomalous cyclone that plays a very important role in forecasting summer rainfall over Xinjiang (Zhang et al. 2012) can also be found over central Asia during the period of negative MUTTI.

The Tarim Basin is generally dominated by the prevailing downdrafts due to the thermal forcing of the Tibetan Plateau (Yeh and Koo 1955). The strength of vertical motion is well related to the dry and wet variation in northwest China (Wu and Qian 1996; Qian et al. 2001). As shown in Fig. 7a, the positive SPI is associated with an ascending motion over the Tarim Basin. Figure 7b further demonstrates that the vertical motion in the region is closely related to MUTTI. Ascending motions can be found over the Tarim Basin during the period of negative MUTTI. Meanwhile, the negative MUTTI is accompanied by remarkable anomalous south winds over the Tarim Basin. The anomalous south winds leads to more water vapor transportation and hence more rainfall over the Tarim Basin.

The results shown above suggest that the middle-upper tropospheric cooling can result in beneficial circulation conditions for the summer rainfall generation over the Tarim Basin. Now we investigate the effect of the MUTTI on the water vapor transport, which is another important factor influencing the rainfall generation over the Tarim Basin. Figure 8a shows the regressions of the water vapor flux vertically integrated from 700 to 300 hPa against the SPI. The positive SPI is significantly associated with an anomalous anticyclone over the Indian Peninsula and cyclone over central Asia.The anomalous southwest winds in the northwest side of the anomalous anticyclone over the Indian Peninsula first strengthen the transport of the water vapor from the tropical Indian Ocean into the midlatitude regions. Then the anomalous southwest winds in the southeast side of the anomalous cyclone over central Asia continue to intensify the transport of the water vapor from the midlatitude regions to farther north areas, such as the Tarim Basin, from East Asia to central Asia. Above results suggest that the transport process of water vapor is different from those over the East Asian monsoon region. For the Tarim Basin, how the warm and moist air in the low latitudes is transported into the regions is a two-step process, involving matching circulation anomalies in the tropics and midlatitudes.

It is clearly shown in Fig. 8b that the negative MUTTI is accompanied by a significantly enhanced cyclonic moisture transport pattern dominating central Asia. This resembles the features shown in Fig. 8a, suggesting that the cooling in the middle to upper troposphere provides a favorable moisture condition for the summer rainfall formation over the Tarim Basin. Although the Tibetan Plateau located in the south of the Tarim Basin is very high and can limit the water vapor from the tropics being directly deposited into the basin, from the results shown in Figs. 7 and 8 one can see that the key route of water vapor transport related to the summer rainfall over the Tarim Basin is mainly located in the valley (50°–65°E) between the Tibetan Plateau and Iranian Plateau where the mean terrain height is less than 1500 m, so it is credible that the water vapor from the tropical Indian Ocean can be transported to central Asia (Tarim Basin) under favorable circulation conditions. Such results are also consistent with previous studies showing that rainfall in the central and southwest Asia is

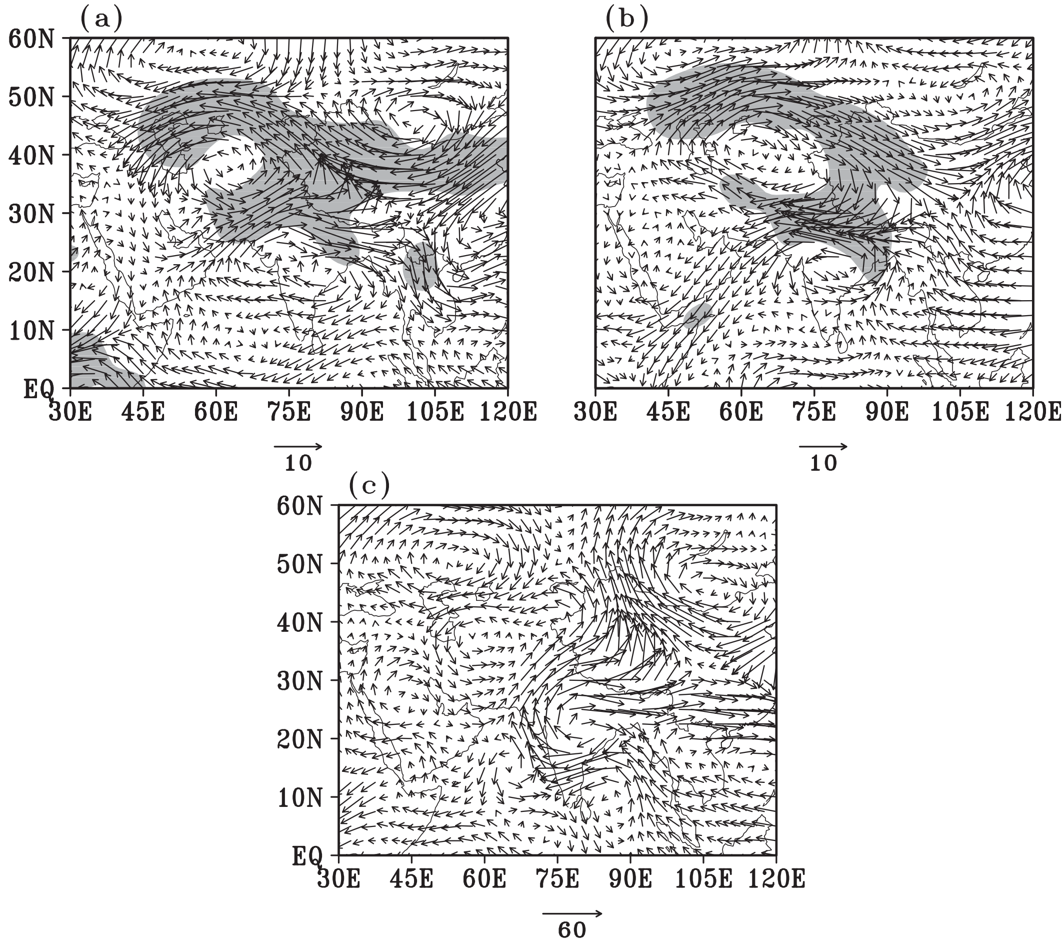

FIG. 8. Regressions of the summer water vapor flux vertically integrated from 700 to 300 hPa against (a) the SPI and (b) the MUTTI (vector, kg m^{-1} s^{-1}). (c) As in (a), but for the composite map of rainy days in the strong SPI years (SPI > 1.0) minus the monthly mean climatology. Regions over the 95% significant confidence level in (a) and (b) are shaded.

associated with tropical moisture sources (Mason and Goddard 2001; Mariotti et al. 2005).

Taking into account that the Tarim Basin is characterized by extremely arid climate, with very limited rainy days each year, it is a legitimate question whether the monthly data used in the analysis here are able to reflect the underlying processes influencing summer rainfall in the basin. In particular, we need to examine whether we can see the linkage between the rainfall generation in the basin and the moisture source from the tropics in these rainfall events based on the synoptic analysis. For this purpose, we have conducted some basic synoptic composite analysis to illustrate such processes. In the analysis, when more than half of the rainfall stations in the basin received rainfall on the same day, we define it as a rainy day in the basin. The total numbers of the rainfall events are 113 for the period of 1961–2007. There were 45 (68) rainy events in summer before (after) 1987. So the decadal variation of such events is consistent with the monthly rainfall analysis. We then calculated the anomalies of the moisture transport vertically integrated from 700 to 300 hPa during the rainy days against the monthly mean climatology in summer. Figure 8c shows such composite analysis for the rainy events during the strong SPI years (when the SPI > 1.0). We can clearly see a remarkable moisture source originating from the Arabian Sea and Indian subcontinent into the valley between the Tibetan Plateau and Iranian Plateau. This moisture source can be further transported into the Tarim Basin. This synoptic analysis confirms that the moisture source from the tropical Indian Ocean is important in determining the summer rainfall over the Tarim Basin.

Finally, to better summarize the key circulation characteristics associated with the middle to upper tropospheric cooling, we have calculated the correlations between the MUTTI and the SPI with three key indices:

TABLE 1. The correlation coefficients of the SWJPI, MTVI, and LTVI derived from NCEP–NCAR reanalysis data with the MUTTI and SPI during the period of 1961–2007. The parentheses indicate presents the correlation coefficients calculated by ERA-40 data during the period of 1961–2002, and all values are significant at the 99% confidence level.

	MUTTI	SWJPI	MTVI	LTWI
Correlation coefficients with MUTTI	1.0 (1.0)	−0.74 (−0.78)	−0.71 (−0.75)	−0.55 (−0.53)
Correlation coefficients with SPI	−0.63 (−0.68)	0.53 (0.60)	0.65 (0.58)	0.61 (0.42)

1) the subtropical westerly jet position index (SWJPI), which is defined by the normalized difference in the regionally averaged summer 200-hPa zonal wind between the area bounded by 30°–45°N, 50°–80°E and the area bounded by 45°–60°N, 50°–80°E during 1961–2007; 2) the middle tropospheric meridional wind index (MTVI), which is defined by the normalized summer 500-hPa meridional wind velocity regionally averaged over central Asia (35°–45°N, 75°–90°E) during 1961–2007; and 3) 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 35°–45°N, 75°–90°E during 1961–2007.

Table 1 gives the correlation coefficients of the SWJPI, MTVI, and LTWI with the MUTTI and the SPI, respectively. The correlation coefficients of the SWJPI, MTVI, and LTWI with the MUTTI are −0.74, −0.71, and −0.55. All are statistically significant at the 99% confidence level. The SPI correlation coefficients with the SWJPI, MTVI, and LTWI are 0.53, 0.65, and 0.61, respectively. Results here demonstrate that the farther southward shift of the subtropical westerly jet, strengthened southerly wind, and ascending motion in the lower troposphere are important impacting factors for the increased summer rainfall over the Tarim Basin. All these features are captured by the MUTTI. Similar results can be obtained by using ERA-40 reanalysis data (Table 1).

4. Linkage between the summer middle and upper tropospheric cooling over central Asia and the SASM

In this section, we focus on understanding what has caused the middle and upper tropospheric cooling over central Asia. Recent studies have shown that the SASM and rainfall were well related to the midlatitude circulation in North Hemisphere and upper tropospheric temperature over central Asia (Kripalani et al. 1997; Yang et al. 2009). The possible connection between the air temperature in the middle and upper troposphere and the SASM will be explored.

The relationship between the SASMI and the MUTTI is shown in Fig. 9a. It has a correlation of 0.36, which is statistically over a 95% significant confidence level. Figure 9b shows the regressions of summer temperature vertical structure (averaged for 60°–80°E) against the SASMI. During the period of negative SASMI the air temperature in the middle and upper troposphere from 600 to 300 hPa between 35° and 45°N becomes much cooler. The negative center is located around 300 hPa, a spatial pattern resembling the regressions against the SPI (Fig. 3a). Figure 9c displays the regressions of the air temperature vertically averaged from 600 to 300 hPa against the SASMI. The air temperature in the middle and upper troposphere over central Asia decreases during the period of negative SASMI. This is not an unexpected result as it in fact reflects the dominant role of tropical Asian monsoon diabatic heating in governing the global climate system. Associated with strong ascending motion and atmospheric deep convections in the SASM region, significant condensation heating is released to the atmosphere over the monsoon region, which can force large-scale atmospheric circulation responses. Taking the well-known Matsuno–Gill-type response to tropical forcing (Matsuno 1966; Gill 1980) as such an approximation to such diabatic heating, one would expect a low-level cyclonic pattern and upper-level anticyclonic pattern in the northwest flank of the heating source (roughly over the Indian monsoon region). Indeed, the regressions of 300-hPa wind against the SASMI show such a feature (Fig. 9c). One can see an anticyclonic pattern west of the Tibetan Plateau in the upper troposphere corresponding to the strengthened SASM. Therefore, with a weakened SASM, an anomalous cyclonic pattern would exist in the west of the Tibetan Plateau. Such a cyclonic pattern corresponds to cold air advection and hence a cooling over central Asia.

5. Conclusions and discussion

Recent studies have identified a significant increase of the summer rainfall over the Tarim Basin during the past several decades (Hu et al. 2002; Mao et al. 2006), but there is not enough understanding of the processes responsible for such an increase. Zhang and Shi (2002) and Zhao et al. (2012) attributed this increase of summer rainfall to local land-use change. In this study, we found that the Tarim Basin summer rainfall is closely related to the cooling in the middle to upper troposphere (600–300 hPa) over central Asia. Based on our analysis, the

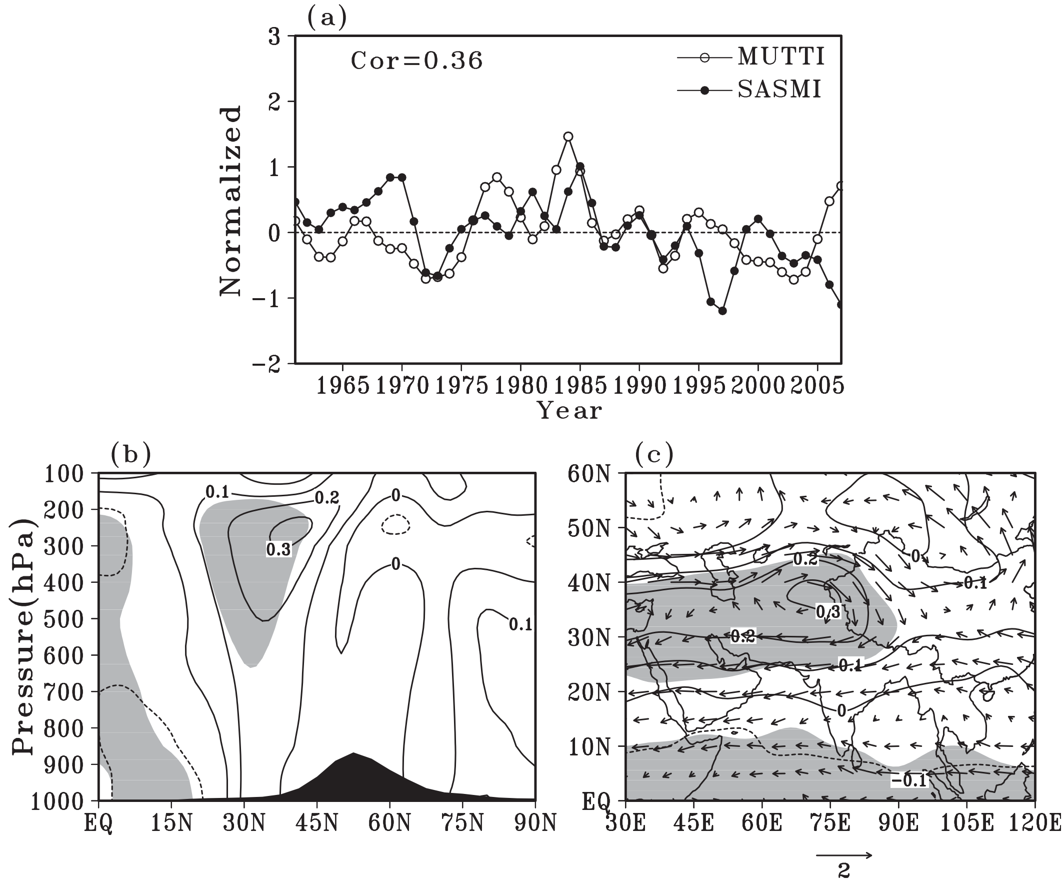

FIG. 9. (a) The time series of the summer MUTTI and the SASMI during 1961–2007. (b) Regressions of latitude–height cross section of the summer air temperature averaged along 60°–80°E against the SASMI (contour, °C). (c) Regressions of the air temperature (contour, °C) vertically averaged from 600 to 300 hPa and wind vector (m s^{-1}) at 300 hPa against the SASMI. Regions over the 95% significant confidence level in (b) and (c) are shaded.

possible linkage mechanism between the MUTTI and the summer rainfall over the Tarim Basin can be summarized as follows: the cooled middle and upper atmosphere over central Asia results in the location of the subtropical westerly jet farther southward and anomalous descending motion prevailing over the cooling region and an anomalous cyclone over central Asia at 500 hPa, which leads to anomalous southerly wind over the east of the cooling region. It also corresponds to an ascending motion and provides favorable dynamical conditions for the increased rainfall over the east of the cooling region.

Further analysis suggests that the SASM is likely to play an important role in the summer middle and upper tropospheric cooling over central Asia. We are fully aware that the cause-and-effect relationship between weakened monsoon and weakened land–sea thermal contrast is still an unsettled debate in the scientific community (Bollasina et al. 2011; Zuo et al. 2012). However, based on the Matsuno–Gill response to tropical diabatic heating, in this analysis we give a plausible explanation as to how the SASM is linked to the middle and upper tropospheric cooling over central Asia as shown in the schematic diagram of Fig. 10a. With the Matsuno–Gill-type response to the SASM diabatic heating, one can expect a high-level anticyclonic circulation in the northwest of the heating source (roughly over the Indian monsoon region). As shown in the regression map of 300-hPa wind against the SASMI (Fig. 9c), the anticyclone is located in the west of the Tibetan Plateau. When the SASM is weak, then cyclonic anomalies are expected. With this cyclonic pattern, the enhanced cold air advection results in cooling in the middle and upper troposphere over central Asia. Indeed, in the regression map of 600–300-hPa temperature against the SASMI (Fig. 9c), one can see a cooling pattern over central Asia during the period of negative SASMI.

Another important process modulating the summer rainfall variations in the Tarim Basin is related to the moisture transport. In this study, we have paid particular

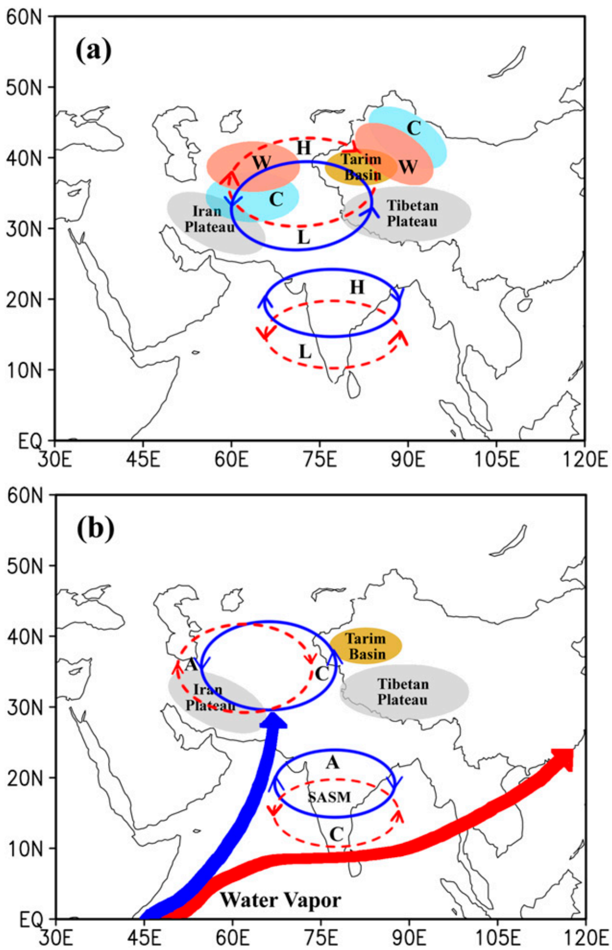

FIG. 10. (a) The schematic diagram of the SASM affecting the middle and upper tropospheric air temperature over central Asia. The letter H (L) indicates high (low) pressure; W (C) indicates warming (cooling). (b) As in (a), but for water vapor transport; the letter A (C) indicates anticyclone (cyclone), and the bold blue solid (red dashed) line in (a) and (b) indicates the anomalous water vapor transport during the weakened (strengthened) SASM years.

attention to investigate whether and how the tropical moisture source in the tropical Indian Ocean region can influence the summer rainfall over the Tarim Basin. We have proposed a two-step process as illustrated by the schematic diagram in Fig. 10b. First of all, the anticyclonic anomalies at lower levels over the Indian subcontinent region correspond to the weakened SASM (Figs. 8b,c). The southerly wind in the western part of the anomalous anticyclone is favorable for the warm and moisture air carried by the Somalia jet to penetrate farther northward into the lower valley between the Iranian Plateau and the Tibetan Plateau. Second, the middle and upper tropospheric cooling responding to the weakened SASM causes the subtropical jet to shift farther southward and create cyclonic flow in the middle troposphere (Fig. 6b). Under this setup of the midlatitude circulation anomalies, the moist air transported from the tropics can be further carried into the Tarim Basin, providing more summer rainfall there.

Based on this analysis, we emphasize that the impact of the SASM on the rainfall variations over the Tarim Basin involves two aspects: one is that the SASM affects the middle and upper tropospheric temperature structure, which in turn modulate the subtropical jet position and the regional circulation, and the other is that the SASM influences the moisture transport through a two-step process as illustrated by Fig. 10b. We have emphasized its indirect effects. The mechanisms related to the summer rainfall over the Tarim Basin are complex. Although we have shown possible linkages between the SASM and the summer middle and upper tropospheric cooling over central Asia and the anomalous atmospheric circulations associated with the summer rainfall over the Tarim Basin, the underlying physical mechanisms are still open questions. For example, we only studied plausible mechanisms for how the SASM affects the middle and upper tropospheric air temperature over central Asia, but we have not investigated the cause of the SASM variations. Observational analysis and our preliminary CMIP5 model evaluations found that the SASM experienced a weakening tendency in recent decades. However, the cause–effect relationship between the weakened land–sea thermal contrast and weakened monsoon is still not fully understood (Zhou et al. 2008a,b; Zuo et al. 2012). Bollasina et al. (2011) argued that the monsoon changes could be mainly attributed to human-influenced aerosol emission. So in order to understand the different contribution of the temperature changes over central Asia and the tropical Indian Ocean to the weakening SASM and further affect the Tarim Basin summer rainfall, more statistical and numerical studies need to be conducted in future work. Our preliminary analysis of the models from phase 5 of the Coupled Model Intercomparison Project (CMIP5; not shown) suggests that most of the current climate models can reproduce the weakened SASM and its impacts on the summer rainfall variations over the Tarim Basin. In the future studies, we will report a comprehensive analysis of these models' results in current and future climate simulations and use them to test the mechanism proposed here based on the observational data.

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