SCIENCE CHINA
Earth Sciences

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https://doi.org/10.1007/s11430-017-9202-1

An overview of the influence of atmospheric circulation on the climate in arid and semi-arid region of Central and East Asia

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Received June 15, 2017; revised January 10, 2018; accepted April 10, 2018; published online July 12, 2018

Abstract The arid and semi-arid (ASA) region of Asia occupies a large area in the middle latitudes of the Northern Hemisphere, of which the main body is the ASA region of Central and East Asia (CEA). In this region, the climate is fragile and the environment is sensitive. The eastern part of the ASA region of CEA is located in the marginal zone of the East Asian monsoon and is jointly influenced by westerly circulation and the monsoon system, while in the western part of the ASA of CEA, the climate is mainly controlled by westerly circulation. To understand and predict the climate over this region, it is necessary to investigate the influence of general circulation on the climate system over the ASA region of CEA. In this paper, recent progress in understanding the relationship between the general circulation and climate change over the ASA region is systematically reviewed. Previous studies have demonstrated that atmospheric circulation represents a significant factor in climate change over the ASA region of CEA. In the years with a strong East Asian summer monsoon, the water vapor flux increases and precipitation is abundant in the southeastern part of Northwest China. The opposite situation occurs in years when the East Asian summer monsoon is weak. With the weakening of the East Asian summer monsoon, the climate tends to dry over the semi-arid region located in the monsoon marginal zone. Recently, owing to the strengthening of the South Asian monsoon, more water vapor has been transported to the ASA region of Asia. The Plateau summer monsoon intensity and the precipitation in summer exhibit a significant positive correlation in Central Asia but a negative correlation in North China and Mongolia. A significant positive correlation also exists between the westerly index and the temperature over the arid region of CEA. The change in the westerly circulation may be the main factor affecting precipitation over the arid region of Central Asia.

Keywords General circulation, Monsoon, Westerly, Central and East Asia (CEA), Arid and semi-arid (ASA)

Citation: Liu Y, Wu C, Jia R, Huang J. 2018. An overview of the influence of atmospheric circulation on the climate in arid and semi-arid region of Central and East Asia. Science China Earth Sciences, 61, https://doi.org/10.1007/s11430-017-9202-1

1. Introduction

In the central latitudes of Asia (36°–52°N, 50°–120°E) is distributed the largest arid and semi-arid (ASA) region, which is a transitional zone between the equator and mid-high latitudes, in the Northern Hemisphere (Wang, 2006). In this region, rainfall is scarce, water resources are highly limited, and the ecological environment is extremely fragile (Huang et al., 2013) and sensitive to global climate change and human activities (Ding, 2007). Since the 20th century, the climate has shown a continuous warming trend over the ASA region of Central and East Asia (CEA) (Jacoby et al., 1996; Ma and Gao, 1997; Ding and Wang, 2001; Zhao et al., 2006). Recently, a large number of studies have demonstrated that the climate over the ASA region of Northwest China is becoming warmer and wetter (Xu, 2001; Hu et al., 2003; Shi et al., 2003; Yang and Li, 2008; Zhang et al., 2008; Wang et al., 2008). It has also been found that precipitation over the arid regions of Mongolia and western Inner Mongolia has tended to decline over recent years (Zhang et al.,

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2004). The most recent studies have revealed that the warming trend over recent years is most significant for the ASA region, particularly for the semi-arid region, which contribute about 44% to global annual mean land-surface temperature trend (Huang J P et al., 2012, 2015a, 2015b, 2017a, 2017b). Therefore, to better understand global warming and predict the future climate more accurately, it is essential to study climate change over the ASA region of Asia.

The climate over the ASA region is affected not only by natural factors, such as general circulation and sea surface temperature (SST) variation (Hunt, 2000; Giannini et al., 2003), but also by anthropogenic factors, such as the increasing concentration of greenhouse gases (Li et al., 2004; Ma and Fu, 2007) and changes in land use (Charney, 1975; Rotenberg and Yakir, 2010; Liu et al., 2011; Huang et al., 2014). However, the relative contributions of these factors to climate change over the ASA region remain unclear. In addition, owing to the currently limited understanding of the mechanisms of climate change over the ASA region, the complex and dynamic nature of these mechanisms, the absence of sufficiently comprehensive numerical simulations, and the detailed mechanism of climate change over the ASA region remain largely unclear (Huang et al., 2013).

As a significant part of the climate system in the mid-latitudes of the Northern Hemisphere, the influence of atmospheric circulation on the climate of the ASA region of Asia cannot be ignored. Understanding the response of atmospheric circulation to global warming and its influence on the ASA region is one important aspect of elucidating the mechanisms underlying the formation and evolution of the climate of the ASA region of Asia. Regarding the influence of atmospheric circulation on the climate of the ASA region of Asia, a number of studies based on site observations, data reanalysis, and numerical simulations have been performed (Zhang, 1999; Zhang et al., 2002; Wang B J, 2003; Wang et al., 2004; Huang et al., 2006; Chen et al., 2011; Qi, 2014; Zhang H L et al., 2016a). Focusing on the ASA region of CEA, this paper systematically reviews recent progress in understanding the relationship between atmospheric circulation and climate change to determine the important scientific issues that need to be resolved in the future.

2. Characteristics of the climate of the arid and semi-arid region of Central and East Asia

The ASA region of CEA (36°–52°N, 50°–120°E) (Tang et al., 2002; Wang C H, 2003; Huang J P et al., 2012; Wang et al., 2012) extends from the western part of the Caspian Sea to the northeast of China (Wang et al., 2010), covering five Central Asian countries, Mongolia, Northwest China, and some regions in western North China, as illustrated in Figure 1.

The ASA region of CEA is a transitional zone that connects the northern high latitudes and the equatorial and low latitudes. This region is bordered to the west by the Ural Mountains, to the east by the Mongolian Plateau, and to the south by Iran and the Tibetan Plateau (Staubwasser and Weiss, 2006). Owing to the topographical blocking of the water vapor from the westerlies, the East Asian and South Asian monsoons cannot easily penetrate deep into the interior regions, leading to a dry climate over the ASA region of CEA. The ASA region of East Asia mainly lies in northern Mongolia (northern part of the Mongolian Plateau), the northeastern corner of Kazakhstan, and parts of Northwest China and western North China (Wang, 2006), and is covered by grasslands, deserts, and plains subject to semi-desertification and significantly affected by the East Asian monsoon and the South Asian monsoon (Bai, 2010). The ASA region of Central Asia is located in the center of Eurasia and is bordered to the west by the Caspian Sea and to the east by the arid regions of Northwest China and the Mongolian Plateau (Chen et al., 2011). The ASA region of Central Asia is the main body of the arid area in Asia and the largest arid zone in the world (Shen et al., 2013), covered by deserts such as the Gobi Desert and plateaus, and affected by the westerly circulation and the North Atlantic Oscillation (Aizen et al., 2001).

With global warming, the temperature over the ASA region of CEA has shown an obvious increase over recent decades (Chen et al., 2009b; Zhang Y et al., 2016). The warming trend over the ASA region of Central Asia is even more significant (Wang et al., 2008; Yao et al., 2014). Meanwhile, there has also been a significant change in the distribution of precipitation over this region. The precipitation over the ASA region of East Asia is more in the east but less in the west, while the annual mean precipitation in Central Asia has tended to increase over the arid region (Chen et al., 2011) and decrease over the semi-arid region (Li, 2015). Some of the semi-humid and semi-arid areas in the center of Northeast China have turned into semi-arid areas, whereas the arid area of East Asia has shrunk while the semi-arid area has expanded overall (Zhao et al., 2014; Li, 2015). Simultaneously, a similar situation with a reducing arid area but increasing semi-arid area has been observed in Central Asia (Li, 2015).

In terms of the changes in the climate of the ASA region of CEA, although some observations have been reported, further study of the mechanisms of climate change in this region is still needed. Among the factors influencing regional and global climate change, general circulation is one of the most significant natural factors. As the global climate changes, the general circulation also changes commensurately. This review summarizes the recent progress in this field with a focus on the influences of monsoon systems and westerly circulation on the climate over the ASA region of CEA.

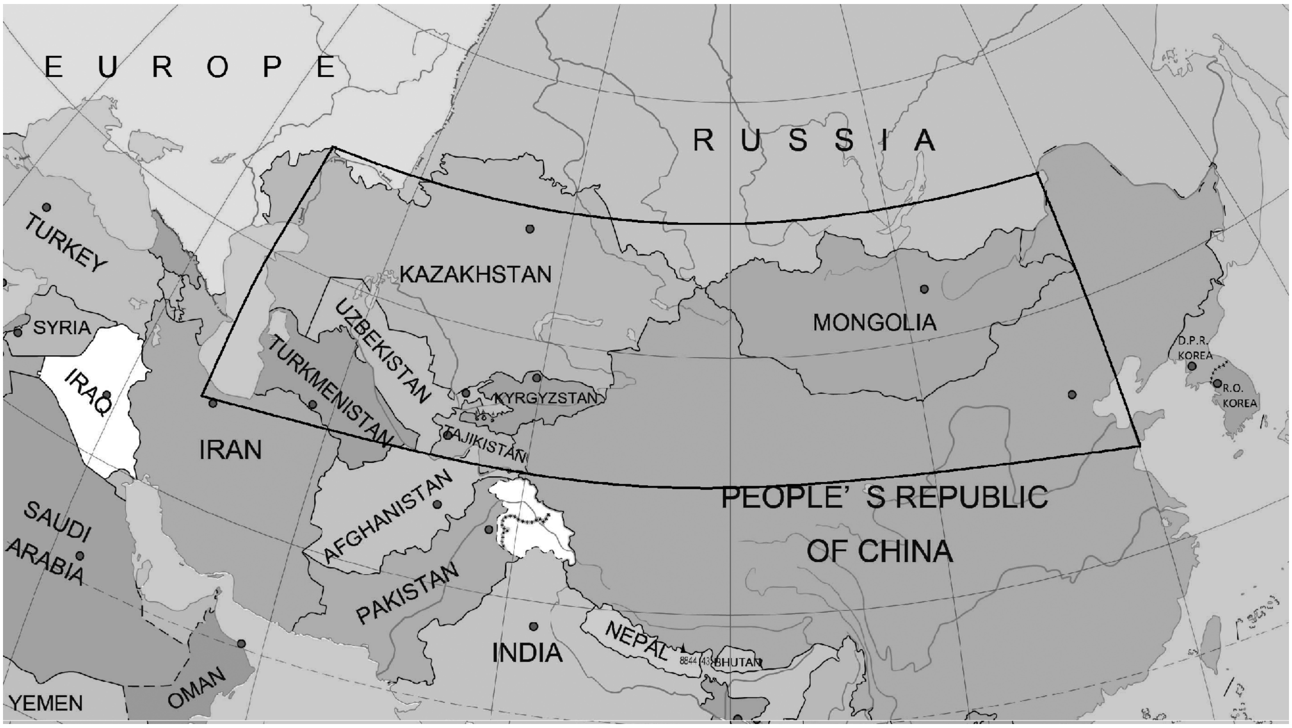

Figure 1 Map of the ASA region of CEA (black box in this figure).

3. Influence of monsoon systems on the climate of the arid and semi-arid region of Central and East Asia

As a fundamental background of the weather system on various scales, atmospheric circulation plays a significant role in the climate of the ASA region of CEA. This review mainly focuses on the progress that has been made regarding the influences of the Asian monsoon system, the westerly belt, and the wave trains and jet streams in the westerly belt on the climate of the ASA region of CEA. The Asian monsoon system consists of three interrelated but independent subsystems termed the East Asian monsoon, South Asian monsoon, and Plateau monsoon (Bai et al., 2011). These monsoon subsystems play important and distinct roles in the transport of water vapor. In summer, the meridional transport of water vapor by the East Asian monsoon is more substantial than zonal transport, while the South Asian monsoon transports water vapor mainly in the zonal direction (Huang et al., 1998). The Plateau monsoon plays a significant role in transporting water vapor inland from the Bay of Bengal (Xu and Gao, 1962; Tang et al., 2007).

3.1 Influence of the East Asian monsoon

The East Asian monsoon plays an important role in the water vapor transport process (Zhou et al., 2008), in which both the monsoon intensity and the direction of movement contribute to changing the climate of the ASA region. The earlier the edge of the East Asian monsoon reaches the most northerly position, the earlier the monsoon retreats, the shorter the duration of the monsoon, and more prone to be dry over the semi-arid region (Wang et al., 2004). In general, in the ASA region of CEA, the areas affected by the East Asian monsoon are mainly located to the east of 100°E (Zhang H L et al., 2016b), including the semi-arid areas of North China, the eastern part of Northwest China, and the eastern part of Mongolia. These areas are located in the transitional zone between the monsoon and westerly regions and are also affected by the westerly circulation (Xing and Wang, 2017).

Recently, with the changing global climate, the East Asian monsoon has tended to become weaker (Wang, 2001; Jiang and Wang, 2005). This has been particularly the case since the mid-1970s. With the weakening of the East Asian monsoon, the ASA region of CEA has tended to be dry in the marginal area of the East Asian summer monsoon (Wang, 2001; Xu et al., 2006; Zhu et al., 2012; Zuo et al., 2012). In addition, to a certain extent, the change in the precipitation over the monsoon region has some effects on the precipitation over the adjacent region. For example, there is a positive correlation between the precipitation over the arid region of Northwest China and that over the East Asian monsoon region (Liu et al., 2013), which also has same influence on the aridity index. Furthermore, a change in the location of the edge of the East Asian monsoon also affects the wet-dry fluctuation over the ASA region of CEA (Zhang H L et al., 2016b), in which the response of each region is different. As shown in Figure 2, the aridity index for the semi-arid region of the Loess Plateau, which belongs to the area affected by the East Asian monsoon, is significantly related to the monsoon edge and most sensitive to the advance and retreat of the northernmost edge of the monsoon, whereas North China is less sensitive and Northeast China is least sensitive.

For the semi-arid region of North China, the East Asian summer monsoon plays an important role in water vapor transport. The path, source, and sink of water vapor transport determine the precipitation over this region (Ran, 2014). The weakened East Asian summer monsoon induces the moisture carried by the monsoon to converge over the Yangtze River basin and the water vapor transported to North China to decrease, resulting in a decrease in the summer precipitation over North China (Huang and Zhou, 2004; Huang et al., 2008). When the East Asian monsoon is strong, the warm and humid airstreams from the western Pacific are strong and transported to North China and Northeast China (Figure 3), and the wind fields favor an increase in the precipitation over the semi-arid region of North China, and vice versa. Overall, recent studies have shown that the East Asian summer monsoon has tended to weaken, leading to a drier climate at the edge belts of the East Asian monsoon in the SAS region of East Asia (Xu et al., 2006; Zhu et al., 2012; Zuo et al., 2012). Consequently, the East Asian summer monsoon is essential for water vapor transport over the northern semi-arid area of China.

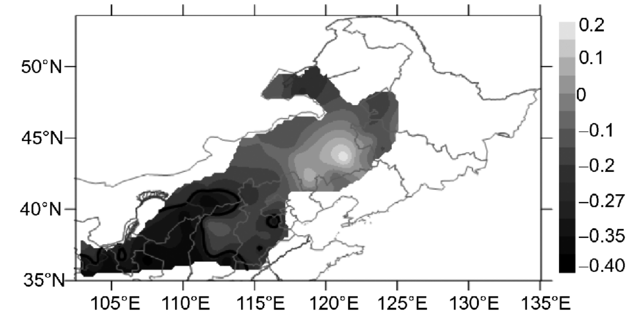

Figure 2 Spatial distribution of the correlation coefficient between the aridity index over the semi-arid region of China and the monsoon margin. Black solid lines denote significant correlations at the 95% confidence level (Zhang H L et al., 2016b).

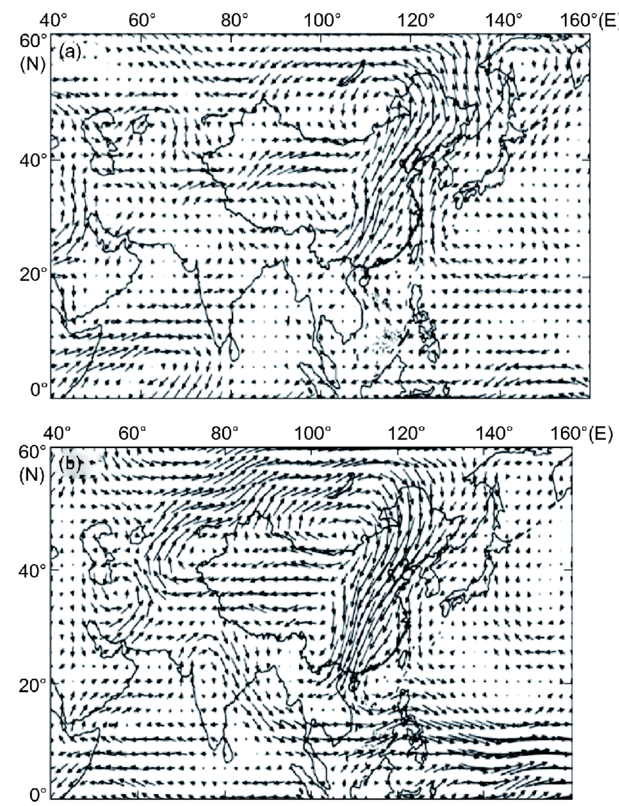

Figure 3 Distribution of horizontal wind field (unit: m s^{-1}) at 850 hPa for years with more (a) or less (b) precipitation over the semi-arid region (Ran et al., 2014).

3.2 Influence of the South Asian monsoon

The South Asian monsoon transports water vapor mainly in the zonal direction (Huang et al., 1998). Figure 4 depicts the time series of South Asian summer monsoon indices calculated using the algorithm of Li and Zeng (2005). It can be seen that the South Asian summer monsoon exhibited a weakening trend prior to the mid-1980s and then tended to strengthen after this period. After 2005, the South Asian summer monsoon showed a significantly weakening trend.

The South Asian monsoon can affect the summer climate of East Asia by influencing the transport of water vapor from the Bay of Bengal. When the South Asian monsoon is strong, the transport of water vapor over North China is enhanced significantly. Conversely, when the South Asian monsoon is weak, the transport of water vapor over North China is significantly reduced (Zhang, 1999; Xu et al., 2002). In addition, the monsoon precipitation in South Asia and the summer precipitation in Xinjiang exhibit a clear negative correlation (Yang et al., 2009; Zhao et al., 2014). As indicated in Figure 4, since the 1980s, the increasingly strong South Asian monsoon and weakening westerly circulation have caused more water vapor to be transported from the Indian Ocean via the Bay of Bengal and the Arabian Sea to the ASA region of Asia (Wyrtki, 1989; Staubwasser and Weiss, 2006), which is one of the causes of the increase in precipitation over the arid region of Central Asia during recent years (Bai, 2010). Since the early 21st century, with the weakening of the South Asian monsoon, the South Asia High has shifted southeastwards (Wei et al., 2012). Furthermore, the westerly jet in the middle latitudes of Asia has shifted to the southeast, resulting in updrafts in Central Asia and downdrafts in the areas of East China affected by the East Asian summer monsoon, as shown in Figure 5. The

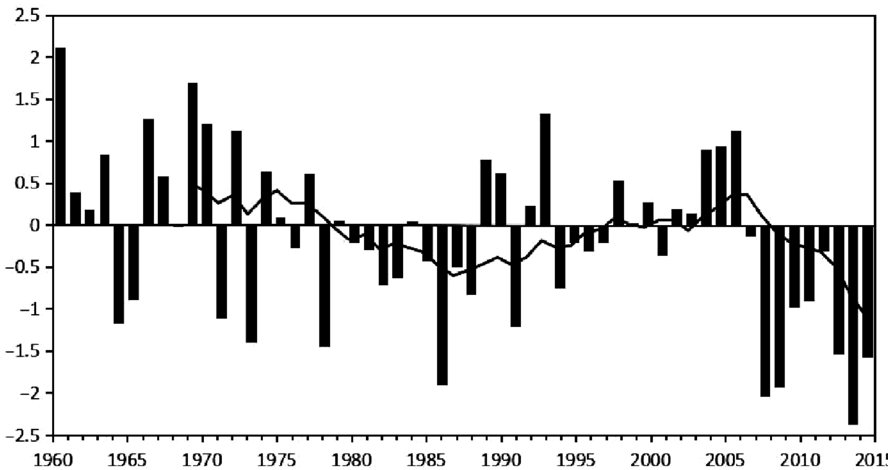

Figure 4 Time series of the normalized South Asian summer monsoon indices from 1961 to 2016.

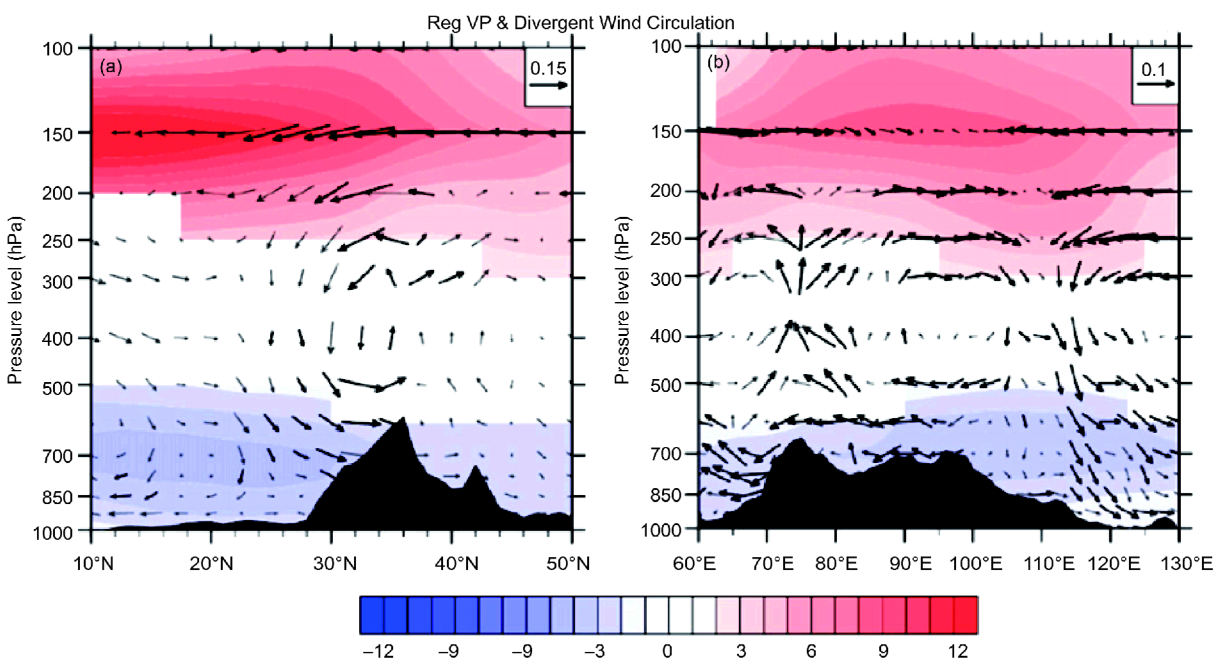

Figure 5 (a) Latitude-altitude cross section in the 70°–85°E region and (b) longitude-altitude cross section in the 35°–42.5°N region for the regressed velocity potential with a significance level exceeding 0.05 (shading; 10^5 m^2 s^{-1}), and vertical circulations (vectors, thick dark ones represent a significance level exceeding 0.05; m s^{-1} and −0.1 Pa s^{-1} for meridional and vertical components, respectively) against the SAHI. The black areas in (a) and (b) indicate the average elevation along 70°–85°E and 35°–42.5°N, respectively (Wei et al., 2017).

anomalies of vertical circulation have induced a precipitation increase in Central Asia, in turn making it wetter in the arid region of Central Asia (Wei et al., 2017). In addition, the South Asian monsoon can affect the precipitation over the western Indian Ocean through the equatorial Rossby waves, thus affecting the Silk Road Pattern, causing precipitation anomalies over the semi-arid region of North China and the arid region of Central Asia (Hong, 2016), which will be discussed in more detail below.

On the basis of existing studies, it can be seen that changes in the South Asian summer monsoon are closely related to the transport of water vapor to the ASA region of Asia via two routes. Its enhancement (weakening) is closely related to an increase (decrease) in precipitation in the semi-arid region of North China (Zhang, 1999; Xu et al., 2002), whereas there exists a negative correlation between the monsoon intensity and summer precipitation in Xinjiang (Yang et al., 2009; Zhao et al., 2014). In addition, in view of the influence of variation in the South Asian monsoon strength on precipitation in different regions of the ASA region of East Asia, different studies have reported different findings (Staubwasser and Weiss, 2006; Bai, 2010; Wei et al., 2017), which can mainly be attributed to differences in the methods applied and the uncertainty of the data. Therefore, to clarify the influence of the South Asian monsoon on the climate in the ASA region of CEA, further studies based on observational data, mechanism analysis, and numerical simulation should be performed in the future.

3.3 Influence of the Plateau monsoon

The Tibetan Plateau, known as the "Asian water tower", is a huge heat source in summer and a cold source in winter, which induces the formation of the Plateau monsoon (Tang, 1993). Changes in the thermal conditions of the Tibetan Plateau will further cause the Plateau monsoon to change, which will in turn affect the surrounding climate. Studies have confirmed that the movement of air driven by the thermal properties of the Tibetan Plateau acts like a huge pump (the plateau "heat pump" phenomenon), regulating the changes in the Asian monsoon system (Wu et al., 2004, 2007, 2009, 2012, 2014). The Plateau monsoon exhibits obvious interannual and interdecadal variations (Bai et al., 2001), including an increasing trend from 1958 to 2010 (Hua et al., 2012).

The results indicate that, when the Plateau summer monsoon is active over the Tibetan Plateau, the upper layer atmosphere is controlled by the low-pressure system and the southerly air flow, which is beneficial for the northward movement of the South Asian summer monsoon from the Bay of Bengal, is maintained on the east side. In contrast, when the Plateau summer monsoon is interrupted, the upper layer atmosphere is controlled by the high-pressure system and the northerly air flow, which blocks and weakens the South Asian summer monsoon and reduces the water vapor transport from the bay of Bengal to the north, is maintained on the east side (Tang et al., 2007). Depending on its intensity, the Plateau summer monsoon can have various effects on precipitation in different regions of the ASA of CEA. For example, when the Plateau Summer monsoon is weak, it is conducive to the descending movement in the arid region of Northwest China, causing the phenomenon of drough; conversely, when the plateau surface heating is enhanced to make the plateau summer monsoon strong, it is conducive to the ascending movement in the arid region of Northwest China. As a result, precipitation is increased in the northern part of Xinjiang, Qinghai, and the area to the east of the Yellow River (Wu and Qian, 1996). In addition, the Plateau summer monsoon has a significant influence on summer precipitation in the ASA region of Central Asia. As presented in Figure 6, there is a significant positive correlation between the Plateau summer monsoon index and summer precipitation from the Tarim Basin to the eastern Tibetan Plateau and to the middle and lower reaches of the Yangtze River. However, the summer rainfall in North China, Mongolia, and other regions exhibit negative correlations with the Plateau summer monsoon index. The above observations can be explained by the south wind anomalies over the Central Asia accompanied by convergence when the Plateau summer monsoon is strong, which favors the transport of water vapor to this region. However, in North China, there is an anomalous northeast flow that blocks the southwest flow of water vapor, and vice versa, as shown in Figure 7 (Qi et al., 2015).

At present, although a great deal of attention has been paid to the Plateau monsoon, understanding of its influence on the climate of the ASA region of CEA remains limited. Most of the existing studies in this field were based on statistical analyses. In the future, the physical mechanisms responsible for the influence of the Plateau summer monsoon on the climate over the ASA region of CEA need to be explored further.

4. Influence of the westerly circulation on the climate of the arid and semi-arid region of Central and East Asia

The westerly circulation includes zonal and meridional circulations. Generally, the zonal circulation involves the straight westerly circulation like the westerly belt long wave, which controls the climate over the region by transporting the water vapor in the central and western area of the ASA region of Central Asia. The meridional circulation is a north–south airflow, including the blocking high, Eurasian (EU) teleconnection pattern, Silk Road pattern (SRP), and the meridional shifting of the Asian jet stream. All of these north-south airflows have significant effects on the climate in the ASA region of CEA.

4.1 Influence of zonal circulation

Large parts of the ASA region of CEA is affected by the westerly circulation except for the monsoon-influenced region including the semi-arid areas in the eastern part of Northwest China and the western part of North China (Wang, 2006). In terms of the precipitation pattern, there is an obvious difference between the areas affected by the westerly circulation and those affected by the Asian monsoon (Chen et al., 2008, 2009a), in which the annual mean precipitation decreases from the marginal zone to the center of the ASA region of Asia. In the eastern area, the East Asian summer monsoon is the main system responsible for precipitation in summer; however, in the western area, the westerly circulation prevails and the water vapor is transported by the prevailing westerly belt in the mid-latitudes (Chen et al., 2010), which leads to precipitation mainly in winter (Bai, 2010).

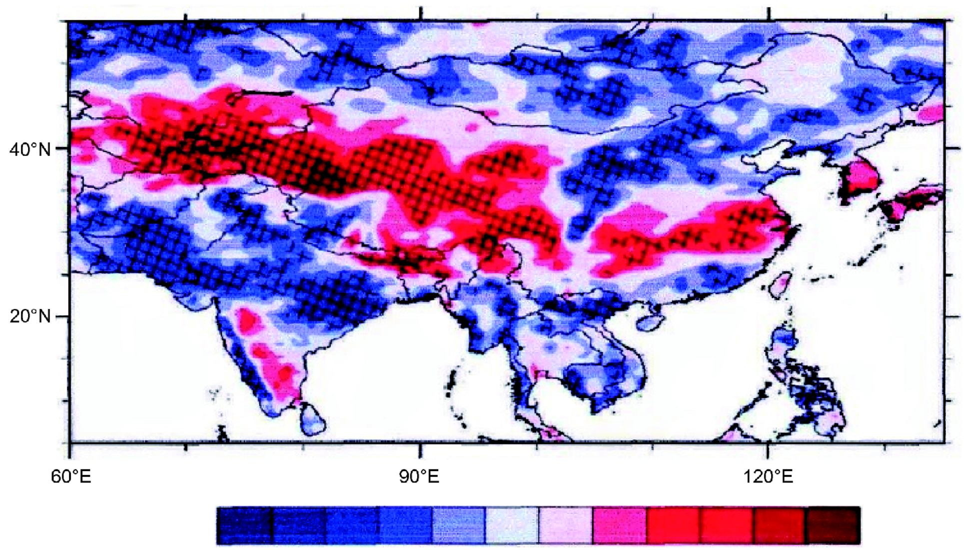

Figure 6 Distribution of the correlation coefficients between the Plateau summer monsoon index and summer precipitation in Asia from 1951 to 2010. Black slopes denote a significance level exceeding 0.05 (Qi, 2014).

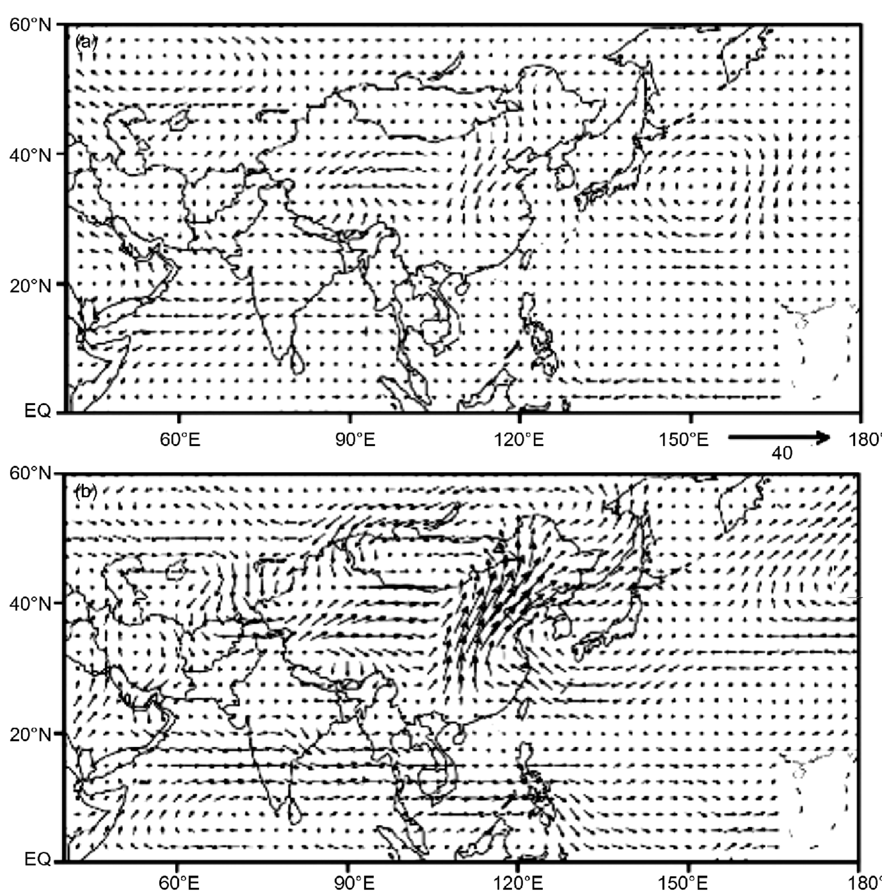

Figure 7 Distribution of averaged moisture flux anomalies in (a) strong and (b) weak Plateau summer monsoon years. Unit: kg m^{-1} s^{-1}. The shaded areas have passed the significance level at 0.05 (Qi et al., 2015).

Over the past 100 years, the climate in the westerly-affected arid region of CEA has exhibited a significant warming trend (Wang, 2006), in which there is an obvious positive correlation between the air temperature and the westerly index. Recently, especially since the mid-1980s, the regional westerly circulation over the arid region in the center of Asia has significantly weakened (Bai, 2010), making it easier for the East Asian monsoon to carry water vapor to the west and northwest. The transport of water vapor by the East Asian monsoon converges with that by the South Asian monsoon, which is one of the possible reasons for the increase in precipitation in the ASA region of East Asia. Over the past 80 years, precipitation in the arid region of Central Asia has exhibited a complex response to global warming, in which the precipitation in the Central Plains and Kyrgyzstan regions has shown a fluctuating increase related to the westerly circulation in the mid-latitudes (Chen et al., 2011). As shown in Figure 8, in the winter, there is a positive correlation between the precipitation and westerly index in the arid region of Central Asia (Li et al., 2008; Huang W et al., 2012). When the westerly index is high, that is, the westerly circulation is dominated by zonal circulation, there is greater precipitation in winter in the arid region of Central Asia.

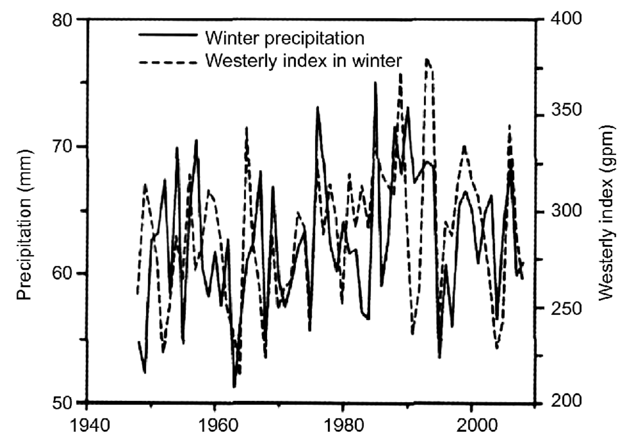

Figure 8 Time series of the westerly index (unit: gpm) in winter (50°W–50°E) and winter precipitation (unit: mm) in arid region of Central Asia (Huang W et al., 2012).

4.2 Influence of meridional circulation

Besides the zonal westerly circulation, the fluctuating meridional circulation significantly affects the climate in the ASA region of CEA. The blocking on the westerly belt can strongly influence the weather and climate, and its location and duration affect the regional climate in the ASA region of CEA. When the blocking is located in the Ural Mountains, air temperatures over most parts of North China, Kazakhstan, and Mongolia decrease (Ji et al., 2008). In contrast, when the blocking lies in the middle and high latitudes of East Siberia and East Asia, severe summer drought will occur in North China (Sun and Gao, 2000). During periods with frequent occurrence of blocking, severe droughts occur in the North China and Inner Mongolia regions (Bi and Ye, 1990; Zhang and Yang, 1996). As a result of the blocking-induced westerly branches in the mid-latitudes of East Asia, the drought may be caused by reduced water vapor transport to North China owing to the weakened East Asian summer monsoon and southward shifting of the rain belt (Li and Sun, 2003). Furthermore, in the summer, the meridional shift of the Asian jet stream is the dominant mode of the upper-level zonal wind in the troposphere over the Eurasian continent (Hong, 2016). The meridional shift of the westerly jet in the mid-upper troposphere may be an important factor responsible for the precipitation change over the arid region of Central Asia. As shown in Figure 9, when the subtropical jets over western Asia are stronger, precipitation over the ASA of CEA to the west of 100°E increases. In contrast, when the jet streams over both East and West Asia significantly increase and shift northward, the summer precipitation over the ASA of CEA to the east of 100°E increases, which may be related to the secondary circulation stimulated by the jet stream (Wang et al., 2012).

In addition, the interaction of interdecadal variations of the EU teleconnection pattern at mid-high latitudes (Wallace and Gutzler, 1981) and the East Asian-Pacific (EAP) teleconnection from the tropical western Pacific has led to an anticyclonic anomaly over North China since the mid-1970s, which induces severe reduction of summer precipitation in the semi-arid region of North China owing to the weakened easterly wind in this region (Huang et al., 2008). Meanwhile, there exists a quasi-steady Rossby teleconnection wave train (Lu et al., 2002), the SRP, which is located in the same position as the ancient Silk Road (Wu, 2014) from North Africa to Eurasia. SRP is the dominant mode of high-level tropospheric meridional wind over the Eurasian continent in summer (Chen, 2013). When the negative phase of SRP is significant, precipitation in the semi-arid region of North China increases (Hsu and Lin, 2007). Some studies have reported the existence of an obvious correlation between SRP and summer precipitation in the ASA region of Northwest China (Chen and Huang, 2012). As indicated in Figure 10, the change in upper tropospheric circulation over Eurasia affects the interannual variation of summer precipitation in the arid region of Northwest China and the summer monsoon regions in eastern China.

5. Concluding remarks

Owing to global warming, the air temperature over the ASA region of CEA has tended to increase significantly, while precipitation exhibits a pattern involving low precipitation in the east and high precipitation in the west. In East Asia, it tends to be wetter in the arid region but drier in the semi-arid region. In the ASA region of Central Asia, except for a weak wet trend in some regions of north and central Pakistan, it tends to be drier. The monsoon system and westerly circulation play significant roles in the climate of the ASA region

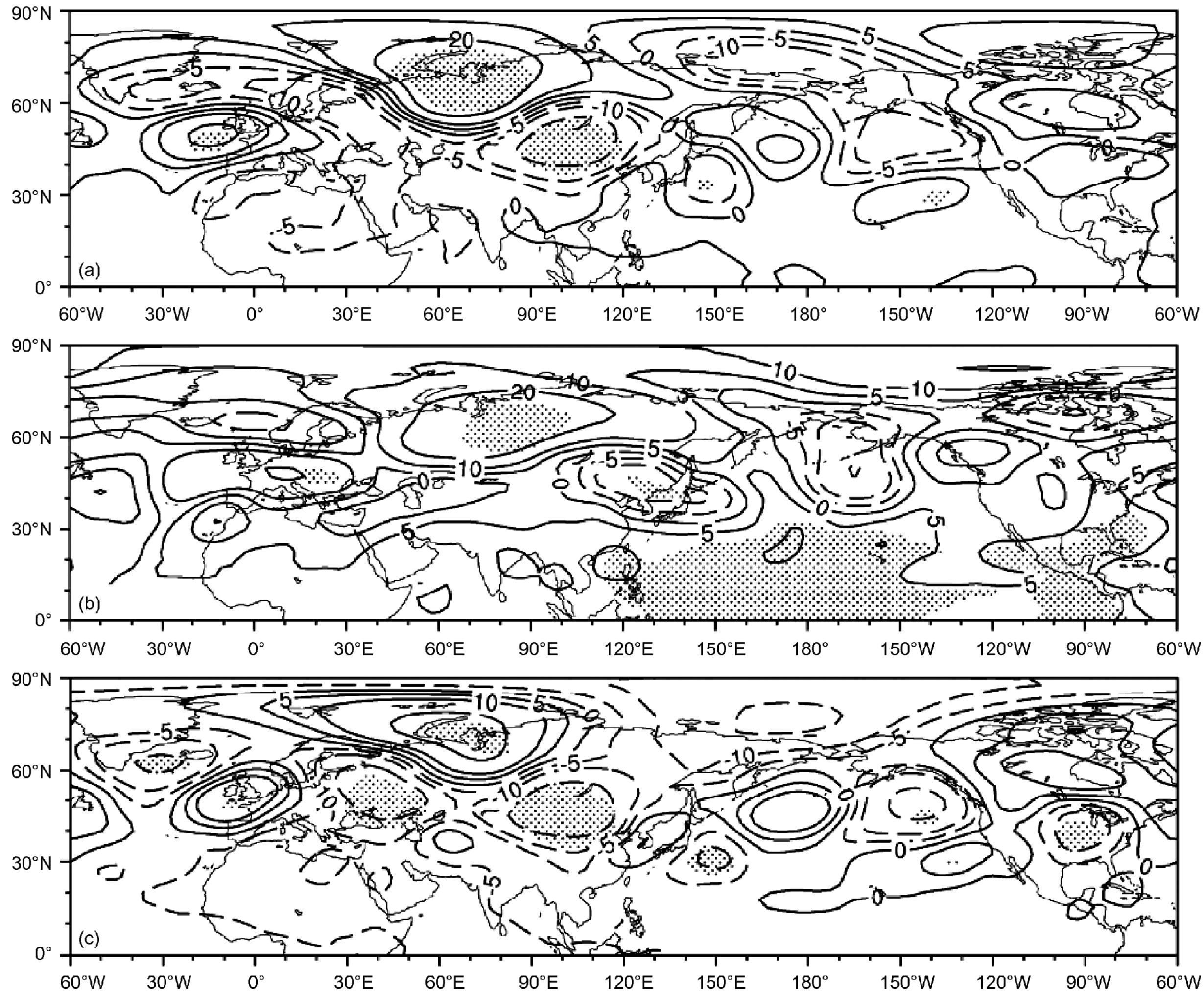

Figure 9 Composition of zonal wind field (unit: m s^{-1}) at 200 hPa geopotential height in years with positive precipitation anomalies relative to that in negative years (a) over the ASA region, (b) west of 100°E, and (c) east of 100°E (dotted areas are significant at the 95% confidence level).

of CEA. Against the background of global warming, the East Asian summer monsoon exhibits a weakening trend, inducing drought in the East Asian monsoon edge belts of the ASA region of East Asia. The South Asian summer monsoon exhibits an enhanced trend followed by weakened, which is in agreement with the water vapor transport along two paths (east and west) to the ASA regions of Asia. When the Plateau summer monsoon increases (decreases), the summer precipitation from the Tarim Basin to the east of the Tibetan Plateau and to the middle and lower reaches of the Yangtze River increases (decreases), while the summer precipitation in North China and Mongolia decreases (increases). A stronger (weaker) zonal circulation of the westerly belt leads to more (less) precipitation in the arid regions of the CEA. Changes in the zonal circulation of the westerly circulation may be the main factor responsible for the precipitation changes in the arid region of Central Asia. In addition, the meridional airflows, including blocking, the EU teleconnection pattern, the Silk Road pattern, and the meridional migration of the Asian jet stream, significantly influence the climate of the ASA region of CEA.

A large number of studies focusing on the influences of the monsoon system and westerly circulation on the climate in the ASA region of CEA have been performed and some advances have been made. However, most of these studies focused on a small area and there have been few reports considering the ASA region of CEA as a whole. Moreover, the results obtained in different studies are seldom consistent, and it is worthwhile to investigate these phenomena through analysis of observational data, dynamic theory, and numerical simulations. At present, the relationship between atmospheric circulation and the climate of the ASA region of CEA has mostly been evaluated using statistical methods. In the future, the underlying physical mechanisms need to be investigated in more detail, especially through numerical simulations. In addition, previous studies have mainly focused on the direct effects of the westerly circulations and monsoon systems on the regional climate, whereas understanding of the interaction between these two phenomena remains insufficient. For example, alteration of the circula-

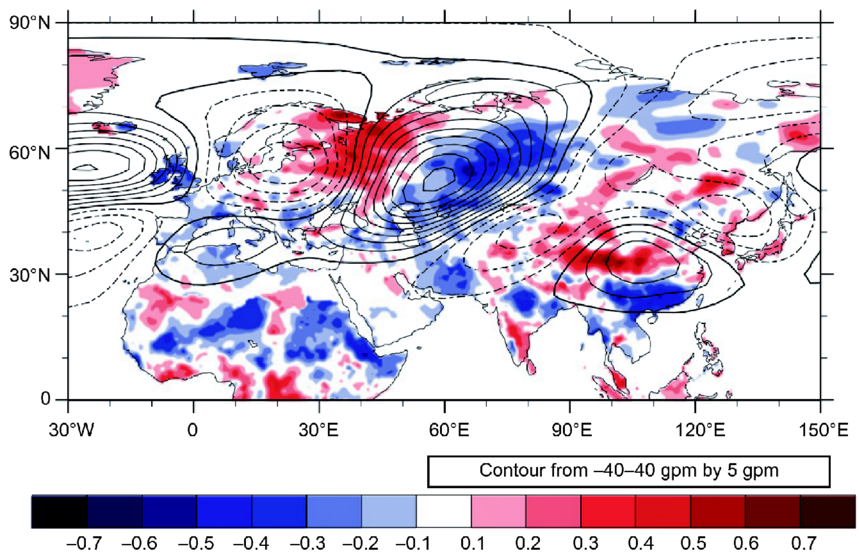

Figure 10 Correlation coefficients obtained by empirical orthogonal function analysis on July V200 and land precipitation (PREC/L) anomalies (by shading), and the regressions of 200 hPa geopotential height (unit: gpm) to the corresponding principal components (by contours) (Chen and Huang, 2012).

tion structure caused by changes in the South Asian monsoon may affect water vapor transport to the ASA region of Northwest China by the westerly belt through causing the westerly belt to swing. Simultaneously, owing to the addition of the thermal and mechanical forcing from the Tibetan Plateau, the westerly circulation swing and retreat of the monsoon will be more complicated. Therefore, in the future, it will be necessary to elucidate the mechanisms responsible for the effects of the monsoon systems and westerly circulation on the climate of the ASA region of CEA; meanwhile, the influence of interactions between the monsoon systems and westerly circulation on the climate in this region and quantification of their relative contributions should also be ascertained.

Acknowledgements *This work was supported by the National Natural Science Foundation of China (Grant Nos. 41475095, 91737101 & 91744311)*

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(Responsible editor: Renhe ZHANG)