SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

December 2011 Vol.54 No.12: 1812–1821
doi: 10.1007/s11430-011-4333-8

Spatiotemporal precipitation variations in the arid Central Asia in the context of global warming

CHEN FaHu[1*], HUANG Wei[1], JIN LiYa[1], CHEN JianHui[1] & WANG JinSong[2]

[1]*MOE Key Laboratory of West China's Environmental System, Lanzhou University, Lanzhou 730000, China;*
[2]*Key Open Laboratory of Arid Climate Change and Disaster Reduction, China Meteorological Administration, Lanzhou 730020, China*

Received December 10, 2010; accepted August 30, 2011

This study analyzed the temporal precipitation variations in the arid Central Asia (ACA) and their regional differences during 1930–2009 using monthly gridded precipitation from the Climatic Research Unit (CRU). Our results showed that the annual precipitation in this westerly circulation dominated arid region is generally increasing during the past 80 years, with an apparent increasing trend (0.7 mm/10 a) in winter. The precipitation variations in ACA also differ regionally, which can be divided into five distinct subregions (I West Kazakhstan region, II East Kazakhstan region, III Central Asia Plains region, IV Kyrgyzstan region, and V Iran Plateau region). The annual precipitation falls fairly even on all seasons in the two northern subregions (regions I and II, approximately north of 45°N), whereas the annual precipitation is falling mainly on winter and spring (accounting for up to 80% of the annual total precipitation) in the three southern subregions. The annual precipitation is increasing on all subregions except the southwestern ACA (subregion V) during the past 80 years. A significant increase in precipitation appeared in subregions I and III. The long-term trends in annual precipitation in all subregions are determined mainly by trends in winter precipitation. Additionally, the precipitation in ACA has significant interannual variations. The 2–3-year cycle is identified in all subregions, while the 5–6-year cycle is also found in the three southern subregions. Besides the inter-annual variations, there were 3–4 episodic precipitation variations in all subregions, with the latest episodic change that started in the mid- to late 1970s. The precipitations in most of the study regions are fast increasing since the late 1970s. Overall, the responses of ACA precipitation to global warming are complicated. The variations of westerly circulation are likely the major factors that influence the precipitation variations in the study region.

arid Central Asia, annual and seasonal precipitation, changing tendency, regional difference

Citation: Chen F H, Huang W, Jin L Y, et al. Spatiotemporal precipitation variations in the arid Central Asia in the context of global warming. Sci China Earth Sci, 2011, 54: 1812–1821, doi: 10.1007/s11430-011-4333-8

There is a general consensus that the 20th century is the warmest during the past thousand years and the recent 30 years is the warmest in the 20th century [1–3]. The warming has caused a tremendous impact on global and regional water resources and precipitation. However, the responses of regional precipitation and water resources to global warming differ regionally [4]. For example, Ma et al. [5] reported that the variations of precipitation and humidity in each continent are considerably different during the past 50 years. The Eurasia is generally drying due to decreasing precipitation. By analyzing the precipitation variations over nine major arid regions in the global land area during 1900–1994, Hulme [6] found that the relationships between temperature warming and precipitation variations differ on different arid regions. In general, the precipitations in the arid regions are decreasing, while the global average precipitation is increasing [6]. The Arid Central Asia (ACA) is one of the largest arid regions at the middle latitudes. The ACA, the major part of the arid Central Asia, ranges from approxi-

*Corresponding author (email: fhchen@lzu.edu.cn)

mately 35°–53°N, and stretching from Caspian Sea to the western China border. This region covers Kazakhstan, Kirghizstan, Tajikistan, Turkmenistan, Uzbekistan, northern Iran and Afghanistan. The precipitation variations are suggested to be controlled by westerly circulation and North Atlantic Oscillation [7, 8]. The annual precipitation falls mainly in winter and spring, which is distinctly different from that in the middle latitude Eastern Asia influenced by summer monsoon circulation with major rainfall in summer. Our previous studies suggested that the humidity (precipitation) variations in ACA are opposite to those of the summer monsoon dominated East China during the Holocene and the last 1000 years [9–11], suggesting that there is a westerly circulation dominated climate regime in the mid-latitude Asia [12]. This "westerly-dominated climate regime" describes the opposite precipitation/humidity changes between the arid Central Asia and the summer monsoon dominated regions [12].

Because of the global warming, the air temperature in ACA is also increaseing (0.18°C per decade) during the last 100 years [13]. The change in temperature in this region, however, is of greater magnitudes than other regions in China and is approximately twice the rate of temperature increase in the Northern Hemisphere [13]. The climate in arid northwestern China, especially the Xinjiang region, has changed from warm-dry to warm-wet regime since the middle 1980s [14], which is also supported by the fact that precipitation and soil moisture increased in the recent 50 years [15–17]. The monsoon dominated northern China and east northwestern China, however, are becoming warmer and drier in the recent 50 years [17–19]. The tree-ring reconstructed drought index in east Tianshan Mountains (located in arid northwestern China) and Helan Mountain (located in the Asian summer monsoon boundary) also supports the observed opposite humidity changes between the arid and monsoon regions in the recent 50 years [20, 21]. Additionally, Wang et al. [22] analyzed the variations of humid index in the mid-latitude Asia from Caspian Sea to East China. They identify a generally warm and dry tendency during the past 100 years, with most noticeable warm and dry trends appeared in the Asian summer monsoon boundary regions. The changes in temperature, precipitation, land use, and land cover, as well as regional climate changes, in certain areas of the Central Asia are studied using observations and climate models (e.g. [23]). However, the ACA is a strongly heterogeneous area, comprising both the high mountains and its surrounding low lands. Related to the complexity in terrain is the inhomogeneous climates and in particular, the precipitation across the ACA. Snow cover, forest, grassland, oasis, and desert are dominant landscapes in these regions. The precipitation is scarce over the vast inland basins, while the precipitation over the mountainous regions is quite higher, which is also the major water resources that supply the water usage in the arid region. Therefore, understanding the variations of precipitation and the related water resources in the context of global warming is of paramount importance for the regional agriculture and economy. However, there are no previous studies that analyzed the precipitation variations and their regional differences specifically for the ACA. The physical mechanisms that influence the precipitation variations remain unexplained. This study evaluated the annual and seasonal precipitation variations and their regional differences in ACA during 1930–2009. The physical mechanisms that influence the precipitation variations are also discussed.

1 Data and method

1.1 Data

The data used in this study are the high spatial resolution gridded (0.5° × 0.5°) monthly precipitation data during 1901–2009, obtained from the Climate Research Unit, University of East Anglia (http://www.cru.uea.ac.uk). This dataset represents an advance over other datasets because the homogeneities of the observed precipitation in individual weather stations have been checked and adjusted by various statistical methods before constructing the girded dataset [24]. The dataset also has higher spatial resolution and longer temporal coverage than other available products. This dataset has been widely used to investigate climate changes and variations regionally and globally (e.g. [5, 25–27]). This study focuses on the arid area of the Central Asia (35.25°–52.75°N, and between 46.25°E to the west border of China, see the shaded region of Figure 1). Before using the CRU data, we evaluate the quality of the data by checking the available observations that were used to construct the gridded data. Our examination showed that there were very few observations available in the study regions before 1930s. In areas around the Caspian Sea, there were no observations during the 1920s. Therefore, this study only analyzed the precipitation during 1930–2009 because of the unreliable data before 1930.

1.2 Empirical orthogonal function and rotated empirical orthogonal function

The empirical orthogonal function (EOF) decomposes the climate data from different locations into a set of orthogonal spatial patterns (EOF modes) along with a set of associated un-correlated temporal variations (principal components). A few EOF modes may account for the majority of the total variances included in the original climate data [28]. Therefore, the EOF is a powerful method for dimensionality reduction and pattern extraction. However, the EOF modes tend to reveal structures over most of the study domain and with a significant magnitude, which may not be able to distinguish the localized pattern we are interested in. The rotated EOF (REOF) is thus introduced to overcome those weaknesses [29]. The major advantage of REOF

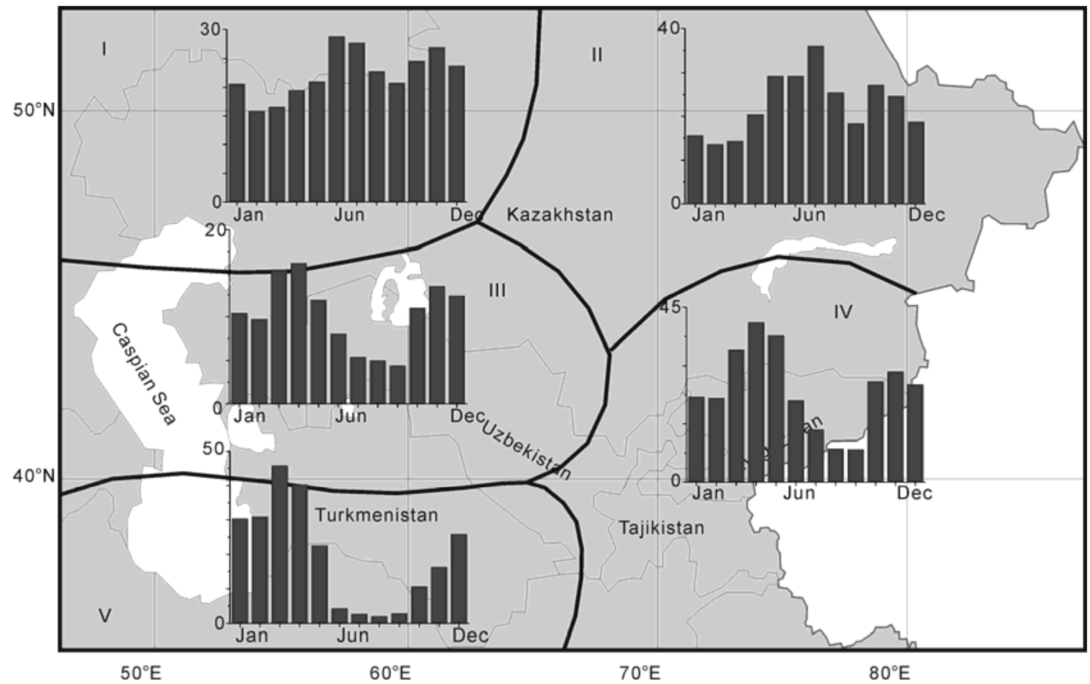

Figure 1 The ACA and five subregions. Histograms show the monthly average precipitation (mm/month) in each subregion during 1961–1990.

compared to the standard EOF is that it can accurately describe localized structures of the meteorological fields by rotating the expansion coordinates. In this study, REOF analysis is used to investigate the spatial features in precipitation variations in ACA.

1.3 Piecewise linear fitting

Finding the overall linear trend is a common method in studying the changes in climate variables. However, fitting the linear trend only has a relevant meaning because it smoothes out the low frequency variations within the long climate time series. To reveal the low frequency behaviors in the precipitation data, the newly developed piecewise linear fitting method, named Piecewise linear fitting [30], is used. This method objectively computes the trend changing points in the climate time series. In particular, the method assumes that there are 1–12 breakpoints in the analyzed precipitation series. For each of these cases the method computes the best fitted trend in each segment of the analyzed precipitation series. This procedure obtains all the partial solutions with fewer break points and allows us to build a series of the sum of the square residuals of the best fit with one, two, and up to a maximum of twelve breakpoints. At the end, the solution that minimizes the residual sum of square is chosen, and the trend in each segment is estimated.

1.4 Multi-tape method and wavelet analysis

The multi-tape spectral analysis (MTM, [31]) is used to analyze the cycles in precipitation in ACA. The MTM provides a novel means for spectral estimation of a time series containing nonlinear and strong short noises. This method has been widely applied to problems in climate signal analysis, including analyses of temperature and precipitation data. Additionally, the Mexico hat wavelet is also used in this study. Compared to conventional Fourier analysis and MTM, the wavelet analysis is able to decompose a time series into time-frequency spaces, which help determine both the dominant cycles of the analyzed time series and how those cycles vary in time [29].

2 Results

2.1 Changes in area averaged precipitation

To understand the temporal precipitation variations in ACA as the whole, the average annual and seasonal precipitations are calculated over the entire domain. The annual and seasonal precipitations are all increasing during the past 80 years (Table 1). The annual precipitation is increasing at a rate of 1.2 mm/10 a. The increasing trend is the strongest in

Table 1 Linear trends of precipitation in different periods in ACA[a)]

	1930 to mid-1970s	Late 1970s to 2009	1930–2009
Annual	3.8*	1.3	1.2
Spring	2.6*	0.2	0.1
Summer	0.7	2.1	0.2
Autumn	0.6	–0.8	0.3
Winter	0.3	–0.4	0.7*

a) * indicates that the trend is significant at 95% confidence level. The unit is mm/10 a.

winter, with a rate of 0.7 mm/10 a (significant at 95% confidence level), followed by autumn (0.3 mm/10 a), summer (0.2 mm/10 a), and spring (0.1 mm/10 a). The piecewise linear trend fitting results suggested that the precipitation variations differ seasonally. During 1930–1970, the spring precipitation is significantly increasing at a rate of 2.6 mm/10 a, while the summer precipitation is increasing since the late 1970s. Superimposed on the long-term trends are interannual variations and extreme wet/dry fluctuations. Some extreme dry years recorded in the observations (e.g. 1943– 1945 and 1974–1975) are also recorded by tree ring chronologies (e.g. [20, 32–34]).

2.2 Subregions of the annual precipitation in the ACA

To better understand the regional characters of the precipitation variations, we used the REOF method to divide the study area into several subregions. The first 10 loading EOF modes explain 70.9% of the total variance of the annual precipitation (Table 2). According to North et al. [35], the remaining EOF modes are random noises and should be ignored. The first two EOF modes explained 25.3% and 12.9% of the total precipitation variations. These two modes describe the difference of precipitation variations between the north and south, and west and east of the study region, respectively. To reveal the localized precipitation pattern, the first 10 EOF modes were subjected to an REOF expansion. After rotation, the accumulated percent variance of the first 5 rotated loading vectors explained 46.5% of the total variance, which can well describe the regional features of the precipitation variations. By taking 0.5 as a threshold value for the rotated loading vectors in the REOF, we divided the entire region into five subregions (Figure 1). Details of the five subregions are listed below.

Subregion I, termed the West Kazakhstan region. The topography in this region is characterized by vast plains, low lands and hills. The precipitation is relatively high in the south. The average annual precipitation in the region is 261 mm. The precipitation falls fairly even on all seasons, with two small peaks in June and November (Figure 1).

Subregion II, termed the East Kazakhstan region. This region includes central and northeastern Kazakhstan, with high mountains and low lands. The average annual precipitation in the region is 269 mm. Though the summer precipitation is slightly more than other seasons, the annual precipitation falls fairly even on all seasons.

Subregion III, termed the Central Asia Plains regions. This region comprises Caspian Sea, southwestern Kazakhstan, Uzbekistan, and Turkmenistan. This desert region is very dry with very low annual precipitation (125 mm). Majority of the annual precipitation (59.8%) occurs in winter and spring, with very little precipitation in summer.

Table 2 The total precipitation variances that are accounted for by the EOF and REOF modes

Number	1	2	3	4	5	6	7	8	9	10	Σ
EOFs	25.3	12.9	8.7	5.7	4.2	3.7	3.1	2.9	2.3	2.1	70.9
REOFs	11.3	10.8	8.3	8.1	8.0	7.3	5.4	4.7	4.1	2.9	70.9
Increment	−14.0	−2.1	−0.4	2.4	3.8	3.6	2.3	1.8	1.8	0.8	0

Subregion IV, termed the Kirghizstan region. This region is located in west Tianshan mountainous regions and the Pamir Plateau and comprises Kirghizstan, Tajikistan, and southeastern Kazakhstan. The average annual precipitation is 289 mm, with peak precipitation in April. Major precipitation occurs in winter and spring and accounts for 63% of the annual total precipitation.

Subregion V, termed Iran Plateau region. This region comprises northern Iran, southern Turkmenistan, and northern Afghanistan. The average annual precipitation is 232 mm, with 81.9% of the annual precipitation occurring in winter and spring and nearly no precipitation in summer.

2.3 Periodic variations in annual precipitation

The annual and seasonal precipitations in each subregion are computed by averaging the precipitation on all the grid points in the region during the past 80 years. Strong interannual precipitation variations are identified in all the subregions as well as the entire study region by MTM method (Figure 2). There is a significant (at 95% confidence level) 2–3-year cycle in annual precipitation of the entire study region and subregions I, II, III, and V. The 2–3-year cycle in subregion IV is slightly weaker but it is still significant at 90% confidence level. The 2–3-year cycle is also identified in seasonal precipitation data. Additionally, a significant 5–6-year cycle is found in annual precipitation of the entire study region and the three south subregions III, IV and V. To examine how those cycles vary in time, the wavelet analysis is used. Our examination showed that the 5–6-year cycle is evident in annual precipitation of the entire region during the past 80 years, except for the 1930s and 1980s. The 2–3-year cycle is evident in annual precipitation from subregions I, II, III and V since the 1930s, consistent with the MTM results in Figure 2. Dominant 5–6-year cycle is observed in annual precipitation in subregion IV during the past 80 years.

2.4 Linear trends in precipitation and their regional differences

The annual precipitation is increasing in all subregions except region V, which shows a weak decreasing trend. The trends of increasing precipitation in the four subregions I, II, III, and IV are 3.9, 0.7, 1.9, and 2.0 mm/10 a, respectively. Among them, the precipitations in subregions I and III are significantly increasing at 95% confidence level. Compared to other subregions, the magnitude of increasing precipitation trend in subregion I is the highest. Though the total precipitation in subregion III is the lowest, the relative precipitation increment is the highest, which led to significant

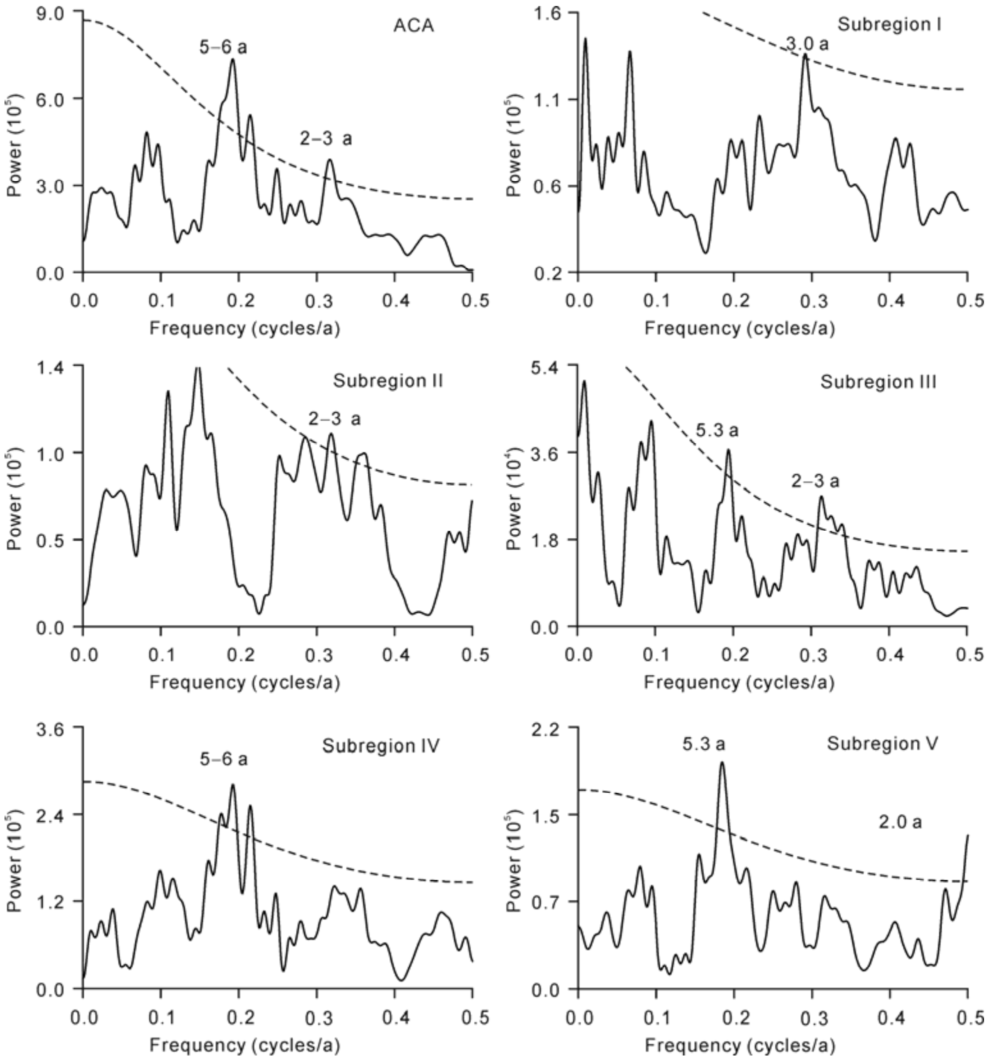

Figure 2 The MTM power spectrum of the annual precipitation in the ACA and its five subregions during the past 80 years. Dashed lines indicate the cycles are significant at 95% confidence level.

increasing trend during the past 80 years. Additionally, the precipitation increment in region IV is also high. Increasing precipitation may provide more water supplies for the agriculture in the oasis areas in the ACA.

The piecewise trend fitting showed that it is generally wet in the 1960s followed by a dry 1970s in the ACA and the four subregions I, II, III, and IV with increasing precipitation. Superimposed on the linear trends in precipitation are significant interannual variations in those four subregions. A 2–3-year cycle is dominant in subregions I, II, and III, while a 5–6-year cycle is dominant in subregion IV. The variations of precipitation in subregion V are different from the other 4 subregions. No obvious trend is identified in this region. The precipitation is fluctuated mainly with a 2–3 cycle around the mean condition. This subregion is generally dry in the 1940s and 1950s but wet in the 1970s, clearly different from the other four regions. Since the late 1970s, the precipitation variations are rather different among the five subregions. The annual precipitation is increasing step-by-step in subregions III and IV, but slowly decreasing in subregion V. The precipitations in subregions I and II, however, are first increasing rapidly followed by slowly decreasing.

The seasonal precipitations in subregions I and II show similar variations. The increment of annual precipitation in subregion I during the past 80 years is caused mainly by increasing precipitation in winter and spring. The trends are, respectively, 1.5 and 0.9 mm/10 a in the two seasons. The piecewise linear fitting showed that the precipitation variations in this region were increased in all seasons from 1930 to the early 1960s. The winter precipitation significantly increased at a rate of 4.7 mm/10 a in this interval. From the early 1960s to the late 1970s, the precipitation decreased in all seasons with most significant decreased in spring (–12.5 mm/10 a). From the late 1970s to the early 1990s, the precipitation again increased in all seasons with most noticeable increase observed in spring (4.2 mm/10 a). Since the early 1990s, the precipitation in all seasons has been slowly decreasing. In subregions II, the annual precipitation increased weakly during the past 80 years (Figure 3). The increasing trend is also caused mainly by increasing precipitation in winter (Figure 4). Similar episodic trends were detected in this subregion as in subregion I.

The seasonal precipitations in subregions III and IV also show similar variations. In subregion III, the annual precipitation has significantly increased during the past 80 years. The winter and autumn precipitation has significantly increased but the winter precipitation contributes more to the

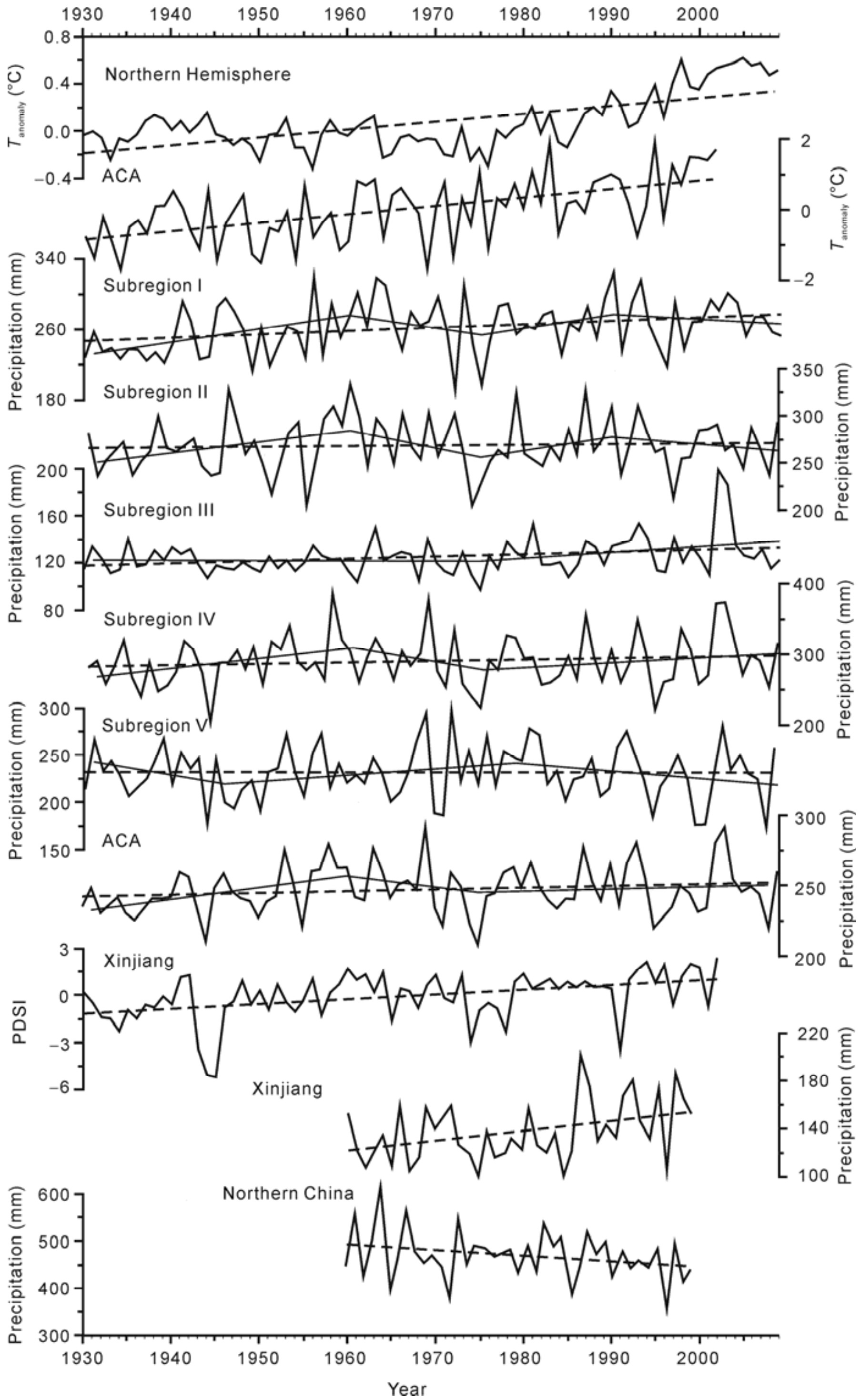

Figure 3 The temporal variations of annual precipitation in the ACA and its subregions during the past 80 years. For comparison, the temporal variations in precipitation in Xinjiang, northern China [37], the PDSI in Xinjiang [20] as well as the air temperatures in the Northern Hemisphere [36] and the arid Central Asia [13] are also shown in this figure. The dashed lines indicate the overall linear trend during the past 80 years and the solid lines indicate the piecewise fitting trend.

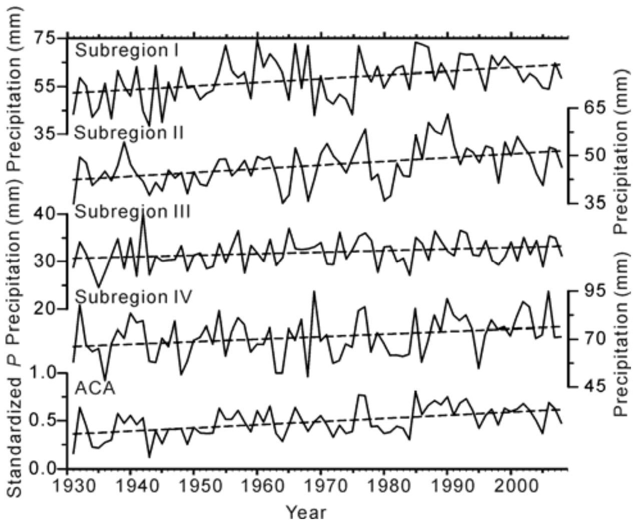

Figure 4 Variations (solid line) and trends (dashed line) in winter precipitation in ACA and its subregions I–V during the past 80 years.

increment of annual precipitation because mean autumn precipitation is relatively small. The spring and summer precipitations show apparent episodic trends, which override the overall linear trend. Persistent summer droughts are observed in the 1940s and 1970s. The precipitation in all seasons has increased step-by-step since the mid-1970s. Therefore, the annual precipitation increment is contributed by increasing precipitation in all seasons in the past 30 years in this region. Similar to subregion III, the annual precipitation in subregion IV also increased during the past 80 years, with majority of the increment caused by increasing winter precipitation. However, the precipitation increment after the mid-1970s is caused mainly by significant increasing precipitation in winter in this region, which is slightly different from subregion III.

Compared to other subregions, the precipitation variations in subregion V show distinct regional characters. The annual precipitation decreased from 1931 to the late 1940s, and then increased until the late 1970s, followed by a slow but stepwise decrease. The episodic changes are nearly out-of-phase to that of subregions III and IV. The overall decreasing annual precipitation is caused mainly by decreasing precipitation in winter and spring. No significant trends are detected, however, on annual and seasonal precipitations. The episodic precipitation changes also differ seasonally. The winter and spring precipitations show opposite trend from the 1930s to the early 1960s followed by similar decreasing trends since the 1970s. The differences in winter and spring precipitation trends are likely caused by the north-south shift of the westerlies. The summer precipitation is generally small but increased rapidly in the past 20 years. The autumn precipitation shows no detectable trend but with large magnitude of interannual variations. In summary, the annual precipitation in subregion V shows a weak decreasing trend superimposed with a significant 2–3-year cycle. The winter and spring precipitation decreased while the summer precipitation rapidly increased during the past 30–40 years.

The above results showed that the annual precipitation in subregions I–IV is increasing with majority of the increments occurred in winter. The subregion V, however, shows weak decreasing precipitation (Figure 5(a)). In the following, the winter precipitation in subregions I–IV is averaged to describe the overall precipitation changes in ACA (Figure 4) because variations in annual precipitation are caused mainly by changes in winter precipitation. The subregion V is excluded because it is not the traditional arid area in the Central Asia. In particular, the winter precipitation in subregion I–IV was normalized first and then averaged to form the averaged winter precipitation in the ACA. Figure 4 shows that the averaged winter precipitation in ACA significantly increased during the past 80 years. This suggested that, albeit the annual precipitations variations are different regionally (Figure 5), the winter precipitation, which contributes most to the annual total precipitation, is consistently increasing.

3 Discussion

This study analyzed the precipitation variations and their regional differences in ACA during 1930–2009. Our results showed that the precipitation in much of the ACA had increased during the past 80 years, except the southwestern portion of the study region (Figures 3 and 5). Those results are generally consistent with the dry/wet changes in Xinjiang, a neighboring arid region east of the study region. Previous studies showed that the climate in Xinjiang shifted from warm dry to warm wet regime in the 1980s [14]. The precipitation and humidity in this region are increasing [18, 19]. Following these changes, the inland lake areas are expanding, and some dried-up lakes are again refilled with water and changing into lakes [38, 39]. The tree-ring reconstructed PDSI also suggested that the soil moisture had increased during the past 100 years in Tianshan Mountains [20]. Because the arid Xinjiang is bordering the ACA, the increasing precipitation in both regions suggested that the precipitation variations in the two neighboring arid regions at the middle latitudes are controlled by a common set of forcings. It also suggested that it is better to understand the precipitation variations and their physical processes in both regions together from a larger regional perspective. The increasing precipitation in both regions, however, is opposite to the precipitation changes in the mid-latitude Asian summer monsoon region. The Asian summer monsoon is generally weakening during the past 100 years [40–42] and the humidity in the Asian summer monsoon boundary is decreasing [21]. Observations show that west northwestern China is becoming wetter and northern China is becoming dryer in the recent 50 years [19]. Rapid decreasing

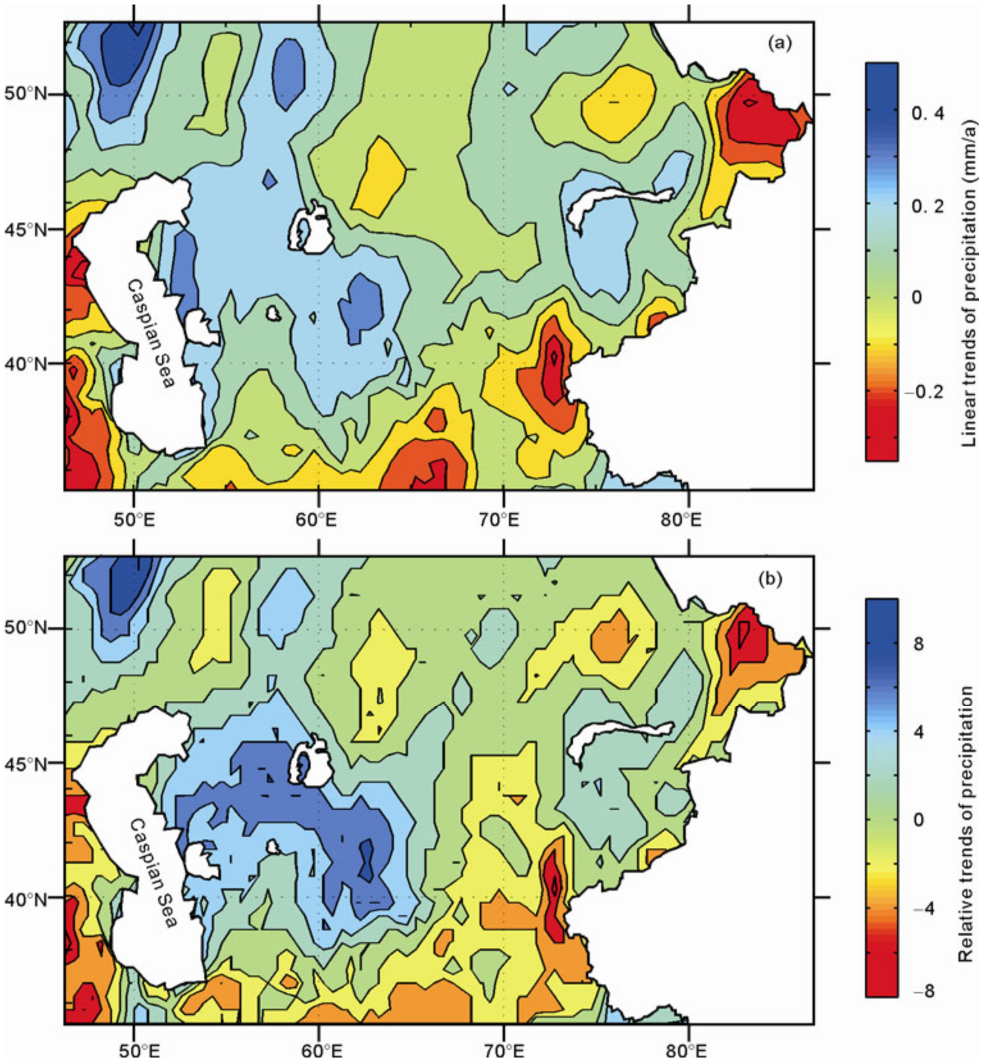

Figure 5 Absolute precipitation in the ACA during 1930–2009 (a) and relative precipitation changes during 1980–2009 relative to 1930–2009 (b). The unit is mm/100 a.

precipitation appeared in the monsoon boundary [18, 37] (see also Figure 3). The opposite precipitation changes in mid-latitude Arid Central Asia and the monsoon dominated regions suggested these 'westerly-dominate climate regime' that operated during the Holocene [9, 11, 12] also existed on shorter time scales.

Central Asia is rapidly warming during the past 100 years following the global warming. The warming, however, is far higher than the averaged warming rate over the Northern Hemisphere [13, 36]. Compared to regional temperature, the responses of regional precipitation to global warming is complicated (Figure 5). The rapid warming in the Northern Hemisphere from the 1920s to the 1940s is not observed in the Central Asia [13], likely because this warming was not a global phenomenon [43–45]. Accordingly, the precipitation in ACA has essentially no responses to this hemispheric warming. The rapid warming since the 1970s is observed both in Central Asia and in the Northern Hemispheric temperatures [13]. In response to this rapid warming, the precipitation in the major arid area of ACA (subregions III and IV) is increasing rapidly and fluctuated with greater magnitudes. The precipitation in southwest ACA (subregion V), however, is weakly decreasing. This suggested that the responses of precipitation in ACA to global warming differ regionally (Figure 5). The increasing precipitation in subregions III and IV and decreasing precipitation in subregion V are likely caused by north shift of the subtropical high and westerly jet. The global warming causes the subtropical high to move northward, which leads to a large scale subsidence of air mass in the Iran Plateau that suppresses the rainfall development. Observations also showed that the precipitation in northern Iran is decreasing following the global warming [46], consistent with our results in subregion V. The precipitation variations in subregions I and II (first rapidly increasing and then stepwise decreasing, see Figure 3) are likely related to variations of Siberia High and

Arctic Oscillation.

The annual precipitation in the major arid area of the ACA falls mainly in winter and spring. The increments of the annual precipitation during the past 80 years are also caused mainly by increasing winter precipitation (Figures 1 and 3). Therefore, the changes in locations and intensity of Siberia High likely played an important role on the variations of precipitation in the study regions, which deserves further investigation. Besides the changes in atmospheric circulations, other factors may also influence the precipitation variations in Central Asia. For example, Su and Wang [15] found that the increasing humidity in northwestern China in the 1980s is closely associated with the shift of ENSO from a cold to warm phase at the same time. The changes of evaporation in upwind lakes (e.g. Caspian Sea and Aral Sea) and the shrinks of those large lakes may also influence the water cycle and precipitation in ACA. Additionally, the heterogeneous terrain and vegetation, as well as the local aerosols, may also play some role on the precipitation changes in the study region. Modeling study [47] suggested that the drought in ACA in early Holocene was caused by weaker and northern displacement of the westerly jet and reduced evaporation in upwind inland lakes (e.g. Caspian Sea) and the North Atlantic Ocean. Therefore, the strength of the westerlies and the associated changes of water vapor at the middle latitudes are likely the major factors that influence the precipitation variations in ACA. More detail studies are needed to understand the responses of those factors to global warming, and the impact of those factors on increasing precipitation as well as their regional differences and mechanisms.

The precipitation in ACA has significant interannual variations, which are superimposed on the long-term trends. Significant 5–6-year and 2–3-year cycles are detected in precipitation in ACA (Figure 2). The 2–3-year cycle is dominant in all subregions, while the 5–6-year cycle is also evident in subregions III–V. The 2–3-year cycle is an important interannual climate signal in the atmosphere and was identified on various climate variables in the troposphere (e.g. [48–52]). This cycle was also identified in mid-latitude westerly circulation [53] and the precipitation in the Asian summer monsoon boundary regions [54]. Therefore, the 2–3-year cycle is likely the dominant interannual signal in atmospheric circulation and precipitation in the mid-latitude Asia, and certainly deserves further studies.

4 Conclusions

The average annual and seasonal precipitation in the entire ACA is increasing during the past 80 years. The largest increasing occurred in winter. The increasing precipitation in ACA is opposite to that of the summer monsoon dominated regions in China, suggesting that the "westerly-dominant climate regime" [12] also existed on shorter time scales.

The variations of precipitation in ACA also differ regionally, and can be divided into five subregions. The annual precipitation falls evenly on each season in the west (subregion I) and East Kazakhstan (subregion II) regions. The precipitation in the Central Asia Plains region (subregion III), Kirghizstan region (subregion IV), and Iran Plateau (subregion V) falls mainly during winter and spring. During the past 80 years, the precipitation is increasing in all subregions except subregion V.

The precipitation in ACA has significant interannual variations. The 2–3-year cycle is dominant in precipitation in all subregions, while the 5–6-year cycle is also significant in the three south subregions (III, IV, and V).

It is generally wet around the 1960s and generally dry around the 1970s in all subregions. However, the changes in precipitation since the late 1970s differ regionally. The precipitation in subregions III and IV has been persistently increasing since the late 1970s, which is likely related to the long-term changes in the westerly circulation at the middle latitudes. The precipitation in subregions I and II is first rapidly increasing and then slowly declining, which is likely related to the variations of Siberia High and Arctic Oscillation. The precipitation in subregion V is slowly but step-by-step decreasing, which is likely related to the northward shift of westerly jet stream and subtropical high. The mechanisms that caused the precipitation variations in ACA need further investigation.

We thank the three anonymous reviewers for their constructive comments, which have led to improvement of this manuscript. We also thank Dr. A. R. Tome for providing the codes used for piecewise linear fitting, and Drs. K. Fang, Y. Lu, H. Wang, Z. Ma, and S. Feng for their help and suggestions at different stages of this study. This work was supported by National Basic Research Program of China (Grant No. 2010CB950202), National Natural Science Foundation of China (Grant Nos. 40971056 and 41021091), and Fundamental Research Funds for the Central Universities (Grant No. LZUJBKY-2009-82).

1 IPCC. Summary for Policymakers of Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007. 4–6
2 Mann M E. Climate over the past two millennia. Annu Rev Earth Planet Sci, 2007, 35: 111–136
3 Mann M E, Zhang Z H, Hughes M K, et al. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. Proc Natl Acad Sci USA, 2008, 105: 13252–13257
4 Dai A G, Trenberth K E, Karl T R. Global variations in droughts and wet spells: 1900–1995. Geophys Res Lett, 1998, 25: 3367–3370
5 Ma Z G, Fu C B. Global aridification in the second half of the 20th century and its relationship to large-scale climate background. Sci China Ser D-Earth Sci, 2007, 50: 776–788
6 Hulme M. Recent climatic change in the world's drylands. Geophys Res Lett, 1996, 23: 61–64
7 Rogers J C, Van L H. The seesaw in winter temperatures between Greenland and northern Europe. Part II: Some oceanic and atmospheric effects in middle and high latitudes. Mon Weather Rev, 1979, 107: 509–519
8 Aizen E M, Aizen V B, Melack J M, et al. Precipitation and at-

mospheric circulation patterns at mid-latitudes of Asia. Int J Climatol, 2001, 21: 535–556
9 Chen F H, Yu Z C, Yang M L, et al. Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian monsoon history. Quat Sci Rev, 2008, 27: 351–364
10 Zhao Y, Yu Z C, Chen F H, et al. Vegetation response to Holocene climate change in monsoon-influenced region of China. Earth-Sci Rev, 2009, 97: 242–256
11 Chen F H, Chen J H, Holmes J, et al. Moisture changes over the last millennium in arid central Asia: A review, synthesis and comparison with monsoon region. Quat Sci Rev, 2010, 29: 1055–1068
12 Chen F H, Chen J H, Huang W. A discussion on the westerly-dominated climate model in mid-latitude Asia during the modern interglacial period (in Chinese). Earth Sci Front, 2009, 16: 023–032
13 Chen F H, Wang J S, Jin L Y, et al. Rapid warming in mid-latitude central Asia for the past 100 years. Front Earth Sci Chin, 2009, 3: 42–50
14 Shi Y F, Shen Y P, Kang E, et al. Recent and future climate change in northwest China. Clim Change, 2007, 80: 379–393
15 Su M F, Wang H J. Relationship and its instability of ENSO–Chinese variations in droughts and wet spells. Sci China Ser D-Earth Sci, 2007, 50: 145–152
16 Jiang D B, Su M F, Wei R Q, et al. Variation and projection of drought and wet conditions in Xinjiang (in Chinese). Chin J Atmos Sci, 2009, 33: 90–98
17 Feng S, Nadarajah S, Hu Q. Modeling annual extreme precipitation in China using generalized extreme value distribution. J Meteorol Soc Jpn, 2007, 85: 599–613
18 Jin L Y, Fu J L, Chen F H. Spatial differences of precipitation over northwest China during the last 44 years and its response to global warming (in Chinese). Sci Geogr Sin, 2005, 25: 567–572
19 Ma Z G, Fu C B. Some evidence of drying trend over northern China from 1951 to 2004. Chin Sci Bull, 2006, 51: 2913–2925
20 Li J B, Gou X H, Cook E R, et al. Tree-ring based drought reconstruction for the central Tien Shan area in northwest China. Geophys Res Lett, 2006, 33: L07715
21 Li J B, Chen F H, Cook E R, et al. Drought reconstruction for north central China from tree rings: The value of the Palmer drought severity index. Int J Climatol, 2007, 27: 903–909
22 Wang J S, Chen F H, Jin L Y, et al. Characteristics of the dry/wet trend over arid central Asia over the past 100 years. Clim Res, 2010, 41: 51–59
23 Lioubimtseva E, Cole R, Adams J M, et al. Impacts of climate and land-cover changes in arid lands of central Asia. J Arid Environ, 2005, 62: 285–308
24 Mitchell T D, Jones P D. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol, 2005, 25: 693–712
25 Wen X Y, Wang S W, Zhu J H, et al. An overview of China climate change over the 20th century using UK UEA/CRU high resolution grid data (in Chinese). Chin J Atmos Sci, 2006, 30: 894–904
26 Neukom R, Prieto M R, Moyano R, et al. An extended network of documentary data from south America and its potential for quantitative precipitation reconstructions back to the 16th century. Geophys Res Lett, 2009, 36: L12703
27 Xu H M, Taylor R G, Kingston D G, et al. Hydrological modeling of river Xiangxi using SWAT2005: A comparison of model parameterizations using station and gridded meteorological observations. Quat Int, 2010, 226: 54–59
28 Lorenz E N. Empirical orthogonal function and statistical weather prediction. Scientific Report No. 1 Statist Forecasting Project, Dept. Meteor., MIT, Boston, 1956
29 Wei F Y. Modern Climat Statistical Diagnosis and Forecasting Technique (in Chinese). Beijing: China Meteorological Press, 2007
30 Tomé A R, Miranda P M A. Piecewise linear fitting and trend changing points of climate parameters. Geophys Res Lett, 2004, 31: L02207
31 Thomson D J. Spectrum estimation and harmonic analysis. Proc IEEE, 1982, 70: 1055–1096
32 Li J B, Cook E R, Chen F H, et al. An extreme drought event in the central Tien Shan area in the year 1945. J Arid Environ, 2010, 74: 1225–1231
33 Yuan Y J, Jin L Y, Shao X M, et al. Variations of the spring precipitation day numbers reconstructed from tree rings in the Urumqi River drainage, Tianshan Mts. over the last 370 years. Chin Sci Bull, 2003, 48: 1507–1510
34 Wei W S, Yuan Y J, Yu S L, et al. Climate change in recent 235 years and trend prediction in Tianshan mountainous area (in Chinese). J Desert Res, 2008, 28: 803–808
35 North G R, Bell T L, Cahalan R F, et al. Sampling errors in the estimation of empirical orthogonal function. Mon Weather Rev, 1982, 110: 699–706
36 Brohan P, Kennedy J J, Harris I, et al. Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. J Geophys Res, 2006, 111: D12106
37 Qian W H, Qin A. Precipitation division and climate shift in China from 1960 to 2000. Theor Appl Climatol, 2008, 93: 1–17
38 Hu R J, Jiang F Q, Wang Y J, et al. A study on signals and effects of climatic pattern change from warm-dry to warm-wet in Xinjiang (in Chinese). Arid Land Geogr, 2002, 25: 194–200
39 Guo N, Zhang J, Liang Y. Climate change indicated by the recent change of inland lakes in northwest China (in Chinese). J Glaciol Geocryol, 2003, 25: 124–127
40 Li J P, Zeng Q C. A new monsoon index and the geographical distribution of the global monsoons. Adv Atmos Sci, 2003, 20: 299–302
41 Wang B, Ding Q H. Changes in global monsoon precipitation over the past 56 years. Geophys Res Lett, 2006, 33: L06711
42 Ding Y H, Wang Z Y, Sun Y. Inter-decadal variation of the summer precipitation in east China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. Int J Climatol, 2008, 28: 1139–1161
43 Zeng Z M, Yan Z W, Ye D Z. Two global warming events in the 20th century (in Chinese). Clim Environ Res, 2003, 8: 319–330
44 Li L J, Wang B, Zhou T J. Impacts of external forcing on the 20th century global warming. Chin Sci Bull, 2007, 52: 3148–3154
45 Wang J S, Chen F H, Jin L Y, et al. The response to two global warming periods in the 20th century over the arid central Asia (in Chinese). J Glaciol Geocryol, 2008, 30: 224–233
46 Raziei T, Bordi I, Pereira L S. A precipitation-based regionalization for western Iran and regional drought variability. Hydrol Earth Syst Sci, 2008, 12: 1309–1321
47 Jin L Y, Chen F H, Morrill C, et al. Causes of early Holocene desertification in arid Central Asia. Clim Dyn, 2011, doi: 10.1007/s00382-011-1081-1
48 Trenberth K E, Shin W T K. Quasi-Biennial fluctuations in sea level pressure over the Northern Hemisphere. Mon Weather Rev, 1984, 112: 761–777
49 Rasmusson E M, Wang X, Ropelewski C F. The biennial component of ENSO variability. J Mar Syst, 1990, 1: 71–96
50 Li C Y, Long Z X. Study on Subtropical High activity over the western Pacific and QBO in the stratosphere (in Chinese). Chin J Atmos Sci, 1997, 21: 670–678
51 Sathiyamoorthy V, Mohanakumar K. Characteristics of tropospheric biennial oscillation and its possible association with the stratospheric QBO. Geophys Res Lett, 2000, 27: 669–672
52 Ding Y G, Yu J H, Shi N. Quasi-Biennial Oscillation variability in interannual variance of the global surface temperature during the last 100-year period (in Chinese). Chin J Atmos Sci, 2001, 25: 89–102
53 Wang S W. A preliminary study on the characteristics and evolution of mean monthly circulation, I. Zonal Index (in Chinese). Acta Meteorol Sin, 1963, 33: 361–374
54 Wang C H, Cui Y. A study of the stability of the precipitation cycle over northwest China in the past 50 years (in Chinese). Adv Earth Sci, 2006, 21: 576–584