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Runoff Responses to Climate Change in Arid Region of Northwestern China During 1960–2010

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Abstract: Based on runoff, air temperature, and precipitation data from 1960 to 2010, the effects of climate change on water resources in the arid region of the northwestern China were investigated. The long-term trends of hydroclimatic variables were studied by using both Mann-Kendall test and distributed-free cumulative sum (CUSUM) chart test. Results indicate that the mean annual air temperature increases significantly from 1960 to 2010. The annual precipitation exhibits an increasing trend, especially in the south slope of the Tianshan Mountains and the North Uygur Autonomous Region of Xinjiang in the study period. Step changes occur in 1988 in the mean annual air temperature time series and in 1991 in the precipitation time series. The runoff in different basins shows different trends, i.e., significantly increasing in the Kaidu River, the Aksu River and the Shule River, and decreasing in the Shiyang River. Correlation analysis reveals that the runoff in the North Xinjiang (i.e., the Weigan River, the Heihe River, and the Shiyang River) has a strong positive relationship with rainfall, while that in the south slope of the Tianshan Mountains, the middle section of the north slope of the Tianshan Mountains and the Shule River has a strong positive relationship with air temperature. The trends of runoff have strong negative correlations with glacier coverage and the proportion of glacier water in runoff. From the late 1980s, the climate has become warm and wet in the arid region of the northwestern China. The change in runoff is interacted with air temperature, precipitation and glacier coverage. The results show that streamflow in the arid region of the northwestern China is sensitive to climate change, which can be used as a reference for regional water resource assessment and management.

Keywords: hydroclimatic variables; climate change; step change; water resources; arid region

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1 Introduction

Water resources play the most important role in the sustainable development of society and economy in arid region, and they determine the evolution of ecological environment in the arid regions, including the two contrary processes of oasis formation and desertification (Boehmer *et al.*, 2000; Chen *et al.*, 2007). Increased concentration of greenhouse gases in the atmosphere leads to higher air temperature, and higher air temperature will in turn intensify the hydrological cycle with more evaporation and more precipitation, which will alter the river system (Cunderlik and Simonovic, 2005). Estimating the possible effects of climatic change on water recourses is particularly important for the researches aimed at supporting the sustainable management and long-term planning of water resources. It is especially important in the arid region where the supply of water resources is a major constraint for social development and ecological protection.

The effects of climate change on hydrology have been studied by many researchers in different regions.

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Probst and Tardy (1987) found that global runoff from major rivers have increased about 3% during 1910–1975. Labat *et al.* (2004) suggested that the global runoff increases by 4% when the global air temperature rises by 1℃. The research result of Teng *et al.* (2012) showed that the runoff will decline in Southeast and far Southwest Austria, and that of Gupta *et al.* (2011) showed that there is a decline in the future climatic runoff in most of river basins of India compared to normal climatic runoff. In the arid region of the northwestern China, both mean annual air temperature and precipitation experienced an increasing trend, while annual runoff demonstrated a mixed trend of increasing (the upstream region) and decreasing (the downstream region) in the Tarim River Basin during the past 50 years (Xu *et al.*, 2004; Chen *et al.*, 2007; Xu Z X *et al.*, 2010). The annual runoff form three tributaries as well as the mainstream in the Shiyang River Basin exhibited statistically significant decreasing trends (Li *et al.*, 2008). The annual runoff of the Toutun River had been in a monotonic decreasing trend during 1956–2003 following the decrease in precipitation and increase in air temperature (Li *et al.*, 2007). For the Ili River, Sun *et al.* (2010) found that the air temperature increased significantly form 1961–2007 during the summer, autumn and winter months, while the precipitation increased significantly during the summer and winter months in the Ili River Basin. The investigation of North Uygur Autonomous Region of Xinjiang also showed that the air temperature increased significantly in the whole northern Xinjiang and river runoff varied in different regions (Yang *et al.*, 2010). There were also some studies for other basins, such as the Heihe River (Wang and Meng, 2007) and the Aksu River (Xu *et al.*, 2011). In these studies, it could be found that the hydrological responses to climate change show a mixed pattern in the arid region of the northwestern China. Although most of the stations experienced an increase in air temperature, precipitation and surface runoff, the decrease in runoff could also be found in some areas, such as the Shiyang River, the Toutun River and the downstream of the Tarim River. However, previous studies were conducted in a single small basin with low-quality hydroclimatic dataset, which make it difficult to draw general conclusions for study area.

In this paper, to further understand the spatial distribution of the trends in the hydrometeorological variable, we divide the arid region into 28 basins according to Water Resource Partition Map of China. The long-term trends of the air temperature, precipitation and runoff time series are detected both at individual station and basin scale. In addition, the sensitivities of runoff to climate change are investigated at basin scale. The purposes of this study are to detect the trends of major hydroclimatic variables at annual and seasonal scales, and reveal association between climate change and the variability of hydrological process response.

2 Materials and Methods

2.1 Study area

In China, arid region accounts for approximately 30% of total land area, and it is mainly distributed in the northwestern China. The arid region of the northwestern China (34°–50°N, 73°–108°E) includes Uygur Autonomous Region of Xinjiang, Gansu Province, the western Inner Mongolia, the northern Hui Autonomous Region of Ningxia and the northern Qinghai Province. In this arid region, almost all the endorheic drainage basins are located in the western Helan Mountains in Ningxia and the western Wushao Mountain in Gansu Province, covering an area of 2.53×10^6 km^2. These endorheic drainage basins are Tarim Basin, Qaidam Basin, Badain Jaran Desert, Tengger Desert, and other endorheic drainage basins in the northern Xinjiang, the desert region of Alxa Banner in the western Inner Mongolia, and the Gobi desert of Hexi Corridor in Gansu Province (Liu *et al.*, 2010). Dominated by continental arid conditions and little effects of East Asian Monsoon, this arid region is under the control of the typical inner-continental land masses climate, with a wide temperature range, low precipitation and low humidity. In order to describe the spatial distribution of hydroclimatic indices clearly, in the present study, the arid region was divided into three parts (North Xinjiang, South Xinjiang, and Hexi Corridor), and each part was also divided into several basins (Fig. 1). Each basin is an independent unit based on catchment characteristics, and most of the basins have a closed, independent and self-balanced hydrological system.

2.2 Data

Monthly and yearly temperature and precipitation data covering the study area were provided by National Cli-

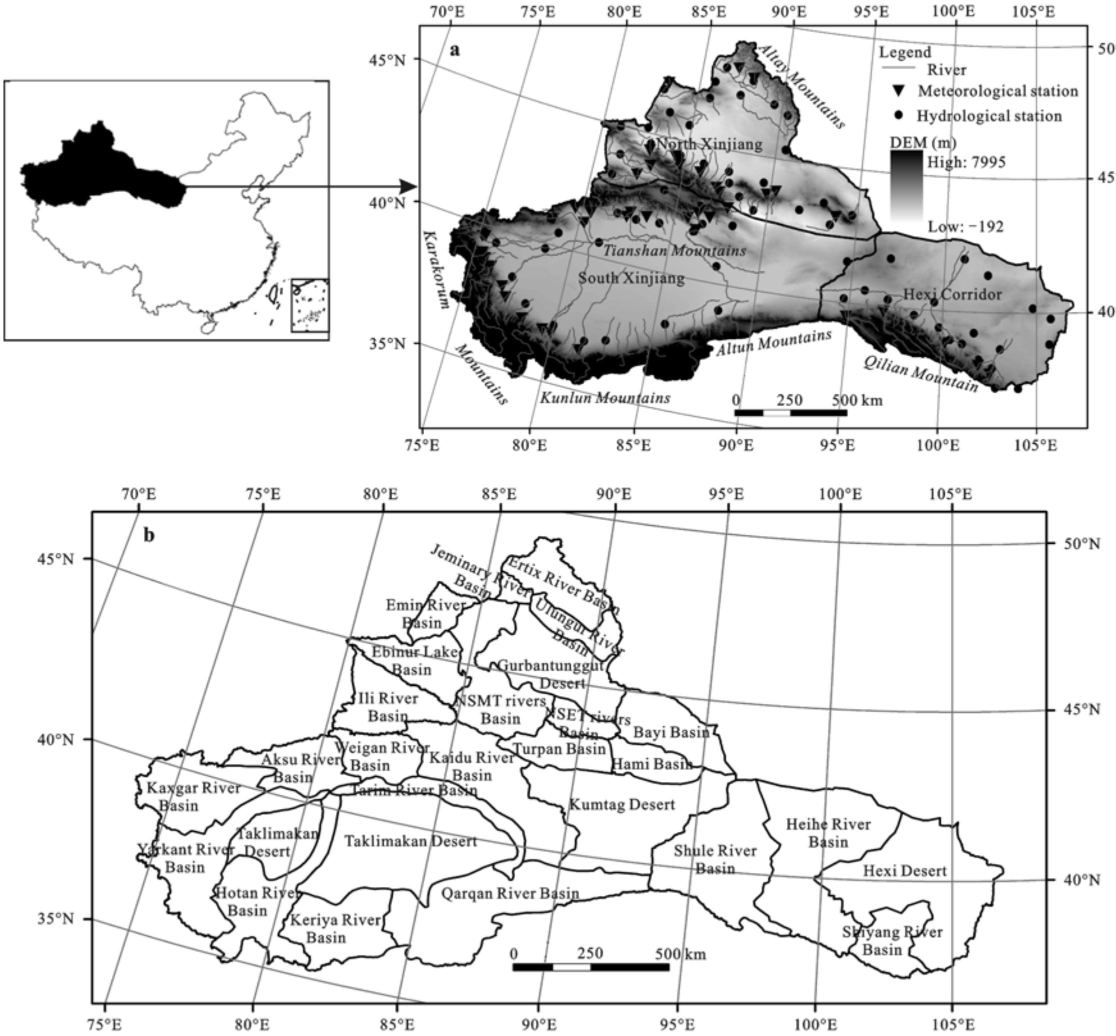

Fig. 1 Distribution of meteorological station, hydrological station, hydrological basin (a) and drainage basin (b) (NSMT rivers: the rivers in the middle section of the north slope of the Tianshan Mountains; NSET rivers: the rivers in the eastern section of the north slope of the Tianshan Mountains)

mate Center (NCC) of China Meteorological Administration (CMA). For this area, 84 stations passed the internal homogeneity check of the China National Meteorological Center (CNMC), including the moving t test (Peterson *et al.*, 1998), standard normal homogeneity test (Alexandersson, 1986), and departure accumulating method (Buishand, 1982). Stations installed after 1960 or that with data gaps were excluded. As a result, 76 meteorological stations for 51 years (January 1960 to February 2011) were selected.

Another dataset, including monthly and yearly air temperature, precipitation and runoff, were provided by Hydrological Bureau of Xinjiang region and Gansu Province. In this study, the data covering the period from 1965 to 2003 among the 122 hydrological stations were selected. However, we only used 65 hydrological stations for precipitation analysis, 46 stations for air temperature analysis and 52 stations for runoff analysis due to many missing data in other stations. Interpolations were applied since most hydrological stations lacked data covering the period during 2004–2010. Linear regression equation was employed to analyze the relationship between the hydrological series and climate series from nearby meteorological stations. Couples with R-square above the level of 0.3843 (0.01 significant level) were deemed efficient for this extend. Homogeneity test was also applied to these interpolated climate series, and all of the extended climate series passed this test.

After the initial processes mentioned above, we developed 141 stations for precipitation analysis, 121 stations for air temperature analysis and 52 stations for runoff analysis. Air temperature and precipitation series cover the period from 1960 to 2010. For the runoff time series, 26 stations cover the period of 1960–2009, and the others cover the period of 1960–2003. In addition, the runoff series were not extended while the trends were calculated based on the original data. All hydrological stations are mountain-pass stations, and most of them are unaffected by human activities. Table 1 shows the period of the record and the details of representative river gauge and basin characteristics

2.3 Methods

Hypothesis testing for the long trend of climate change is helpful to understand the inherent mechanism of hydrological process. In this paper, two types of general trend are considered: one is the monotonic trend, and the other is the step change (Zhao *et al*., 2008). In order to investigate the season changes of hydroclimatic variables, seasonal sub-series (spring (from March to May), summer (from June to August), autumn (from September to November) and winter (from December to next February)) was used at each station and basin. The arithmetic mean of air temperature and precipitation at all stations was regarded as the integrated climate series in the drainage basin to carry out the monotonic trend test. In this study, Mann-Kendall test and distribution-free cumulative sum chart (CUSUM) test were employed to detect possible trend in climate change and streamflow. The Mann-Kendall test, widely used in many researches (Mann, 1945; Kendall, 1975; Xu Z X *et al*., 2010; Tao *et al*., 2011), was applied to detect a monotonic trend in a time series. In addition, distribution-free CUSUM test (McGilchrist and Woodyer, 1975; Chiew and McMahon, 1993) was also used to analyze the step change of hydroclimatic variables. This non-parametric rank-based method is to test whether the means in two parts in a series are different with respect to an unknown time of change. Given a time series data ($X_1, X_2, X_3, \ldots, X_n$), the statistic is defined as:

$$V_k = \sum_{i=1}^{k} \operatorname{sgn}(X_i - X_{\text{median}}) \qquad (k = 1, 2, \cdots, n) \tag{1}$$

Table 1 General characteristics of representative river basins and hydrologuical stations included in analysis

Region	Basin	Basin area (km^2)	Hydrological station	Latitude (N)	Longitude (E)	Period of record
North Xinjiang	Ertix River	48782	Qunkule	87°07′48″	48°06′00″	1957–2003
			Altai	87°47′60″	42°49′48″	1957–2003
	Emin River	20806	Kalanguer	83°13′12″	47°00′00″	1958–2003
	Ebinur Lake Drainage	49812	Jiangjunmiao	84°43′12″	44°05′00″	1956–2009
	Ili River	56953	Kafuqihai	82°30′00″	43°22′12″	1957–2003
			Wulasitai	83°07′48″	43°47′60″	1958–2003
	NSMT rivers	81433	Kensiwaite	85°57′00″	43°58′12″	1956–2006
	NSET rivers	17707	Kaikenhe	89°49′48″	43°36′00″	1957–2003
South Xinjiang	Aksu River	48827	Xiehela	79°37′12″	41°34'′12″	1956–2010
			Shaliguilanke	78°35′60″	40°57′00″	1957–2010
	Weigan River	38163	Heizi Reservoir	82°25′48″	41°43′48″	1960–2006
	Kaidu River	105205	Dashankou	85°43′48″	42°13′12″	1956–2010
	Kaxgar River	75542	Kalabeili	75°12′00″	39°32′60″	1958–2003
			Keleke	75°22′48″	38°47′60″	1959–2002
	Yarkant River	84427	Kaqun	76°54′00″	37°58′48″	1954–2010
	Hotan River	77198	Wuluwati	79°25'′48″	36°52′12″	1956–2010
			Tongguziluoke	79°55′12″	36°49′12″	1956–2010
	Keriya River	66355	Lulmaimtlgan	81°28′12″	36°28′12″	1957–2003
	Turpan Basin	36398	Alagou	81°19′12″	40°31′48″	1957–2003
	Hami Basin	40677	Toudaogou	93°47′60″	43°07′48″	1954–2006
Hexi Corridor	Shule Rive	124471	Changmabao	96°50′60″	39°49′12″	1953–2009
	Heihe River	68767	Yinluoxia	100°10′48″	38°47′60″	1945–2009
	Shiyang River	41586	Zhamushi	102°34′12″	37°42′00″	1952–2009

where sgn(X) = 1 ($X > 0$); sgn(X) = 0 ($X = 0$); sgn(X) = −1 ($X < 0$); X_{median} is the median value of the X_i data set.

The distribution of V_k follows the Kolmogorov-Smirnov two-sample statistic (KS = $(2/n)\max|V_k|$) with the critical values of $\max|V_k|$ given by: $\alpha = 0.10\ \ 1.22\sqrt{n}$; $\alpha = 0.05\ \ 1.36\sqrt{n}$; $\alpha = 0.01\ \ 1.63\sqrt{n}$.

A negative value of V_k indicates that the latter part of the record has a higher mean than the earlier part and vice versa, and the $\max|V_k|$ indicates the most likely mean jump year.

In addition, the relationship between hydrological and meteorological variables was explored by using Pearson product-moment correlation. The correlations calculated were tested for statistically validity at the 95% significance level.

3 Results and Analyses

3.1 Precipitation

3.1.1 Spatio-temporal distribution of monotonic trends

Table 2 shows the statistical characteristics and trends of the precipitation and air temperature for the study area. Annual precipitation shows a significant positive trend (8.01 mm/decade). On seasonal basis, statistically significant positive trends ($P < 0.05$) of precipitation can be detected for all seasons except for spring, with winter experienced the most significant increase. In term of annual precipitation, 56% of stations exhibit significant increasing trends at the 0.05 significance level.

Table 2 Results of Mann-Kendall test for annual and seasonal precipitation and temperature

	Precipitation (mm/decade)	Temperature (℃/decade)
Annual	8.01^{**} (172.38)	0.35^{**} (7.20)
Spring	1.78 (43.93)	0.24^{*} (9.18)
Summer	2.55^{*} (78.48)	0.26^{**} (17.75)
Autumn	1.72^{**} (35.50)	0.41^{**} (7.40)
Winter	1.73^{**} (13.80)	0.39^{**} (–8.83)

Notes: data in the parenthesis are the mean of the study area; *, ** delineate the significance at 0.05 and 0.01 significance level, respectively

The spatial trends of the annual and season precipitation at individual station and basin scale are shown in Fig. 2 and Fig. 3. In spring, summer, autumn and winter, the percentages of the total number of stations exhibiting significant increasing trends ($P < 0.05$) are 6%, 18%, 19%, and 36%, respectively (Fig. 2). For annual precipitation, the stations in North Xinjiang, the middle and west of the south slope of the Tianshan Mountains show most significant increasing trends (Fig. 2a); the basins of the Ebinur Lake Drainage, in the northern North Xinjiang (the Ulungur River, the Jeminay River, the Ertix River), and in the south slope of the Tianshan Mountains (the Weigan River, the Aksu River, the Kaidu River) exhibit significant increasing trends at the significant level of 0.01 (Fig. 3a).

Seasonally, vast majority of the stations in spring have no significant trends (Fig. 2b); only the basins of the Qarqan River, the Kumtag Desert, the Hami Basin and the Ulungur River show statistically significant trends at the 0.05 significant level. In summer, 18% of stations demonstrate significantly increasing trends at the 0.05 significant level, especially the stations around the Tianshan Mountains and stations in the western South Xinjiang (Fig. 2c); the Kaidu River exhibit significant increase trend at the 0.01 significant level (Fig. 3c). Precipitation in autumn have significantly increasing trend ($P < 0.01$) in the Aksu River and the Bayi Basin (Fig. 3d). For the changes of the precipitation in winter, the stations dominated by significant increase trends are mostly located in North Xinjiang (Fig. 2e); the basins of North Xinjiang (except for the Ili River and the Ulungur River), the Kaidu River and the Kumtag Desert exhibited the most statistically variations (Fig. 3e).

It can be found that the precipitation in the study area dominated by increasing trends, especially the stations in North Xinjiang and the south slope of the Tianshan Mountains. The increase in the precipitation is related to larger-scale circulation currents. The results of previous studies showed that water vapor from the Indian Ocean and the western Pacific has increased in recent years, which might bring abundant rainfall for the arid region (Xu L *et al.*, 2010). However, the mixed pattern in the precipitation indicated that this change was a complex process affected by both the regional atmospheric circulation and the local environment.

3.1.2 Step change for each basin and study area

Cumulative sum (CUSUM) charts of annual and seasonal precipitation for the study area are shown in Fig. 4. Step change for the precipitation was identified, with the annual precipitation in 1991 at the 0.01 significance level. The annual precipitation before 1991 is 163 mm;

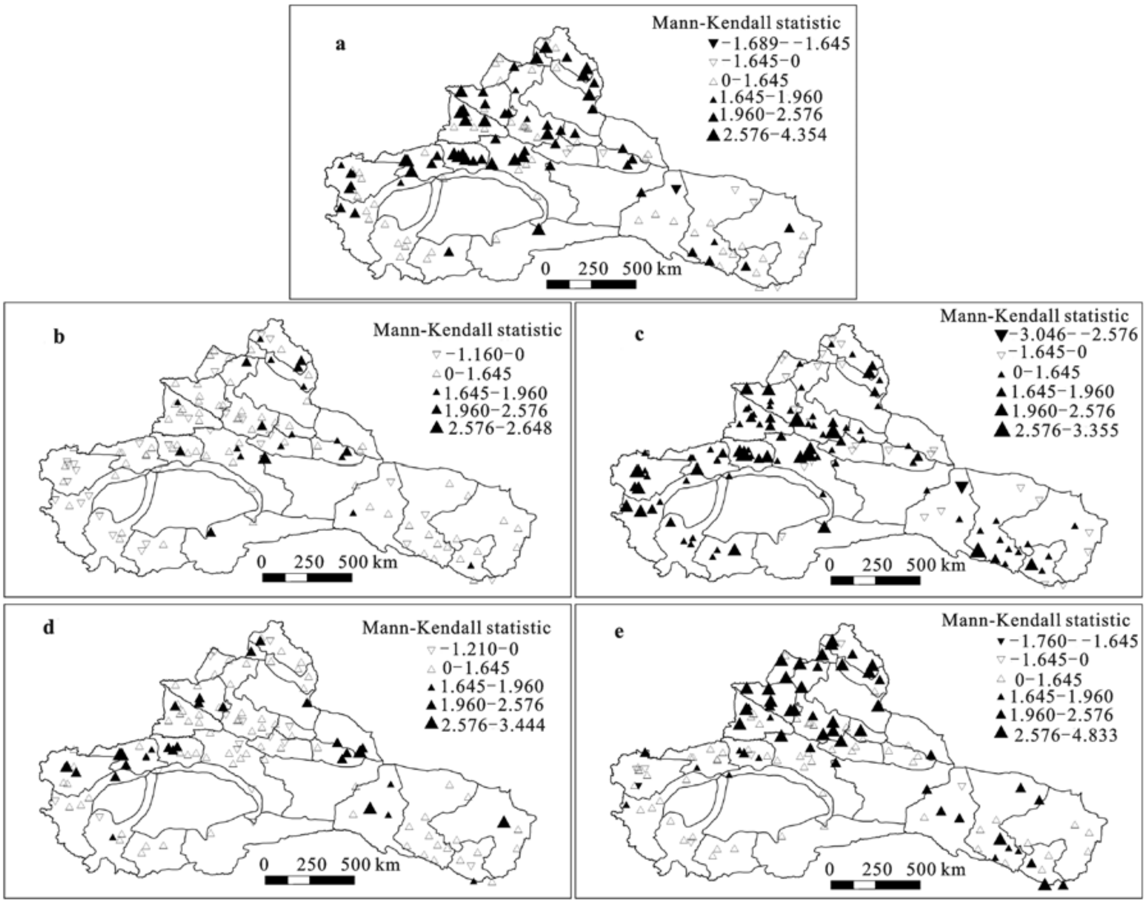

Fig. 2 Distribution of Mann-Kendall trends of annual and seasonal precipitation at individual station: a) annual; b) spring; c) summer; d) autumn; e) winter. Black solid triangle denotes significantly increasing and decreasing trend (MK statistic: Z = 1.645, P = 0.10; Z = 1.960, P = 0.05; Z = 2.576, P = 0.01)

and that after 1991 is 188 mm. Step changes also are observed in individual basin. About 12 basins have step change in 1986 at the significance level of 0.05, three basins in 1970, 1980 and 1991, respectively. On a seasonal basis), the change points can also be detected for all seasons. The change points are identified as 1986, 1990, 1997 and 1985 in spring, summer, autumn and winter, respectively, and the precipitation in later time series is higher than that in earlier series. The step changes of individual basin at a seasonal scale show a mix pattern, and seldom basins observe step change in the same year.

3.2 Air temperature

3.2.1 Spatio-temporal distribution of monotonic trends

The regional MK trends for annual and seasonal air temperature are listed in Table 2. For air temperature, significantly increasing trends are dominated in the whole year and in all seasons. Autumn shows the most significant change, and the regional trend magnitude is 0.41℃/decade.

Figure 5 and Fig. 6 show the spatial distribution pattern of the temporal trends of the air temperature at individual station and basin scale. For the annual air temperature, about 97% of the stations have a significantly increasing trend (P < 0.05); all the basins show statistically significant increase (P < 0.01), especially for the Qarqan River, the Bayi Basin and the Heihe River (Fig. 6a). About 61% and 73% of the stations have statistically significantly increasing trends in spring and winter, respectively (Fig. 5b, Fig. 5e); the spatial distribution of trends in spring also have the similar pattern as the trends in winter, with the stations located in the South Xinjiang and the Hexi Corridor having larger trend magnitudes (Fig. 6b, Fig. 6e). For air temperature in summer, 80% of the stations exhibit statistically significant trends (Fig. 5c); all the basins except

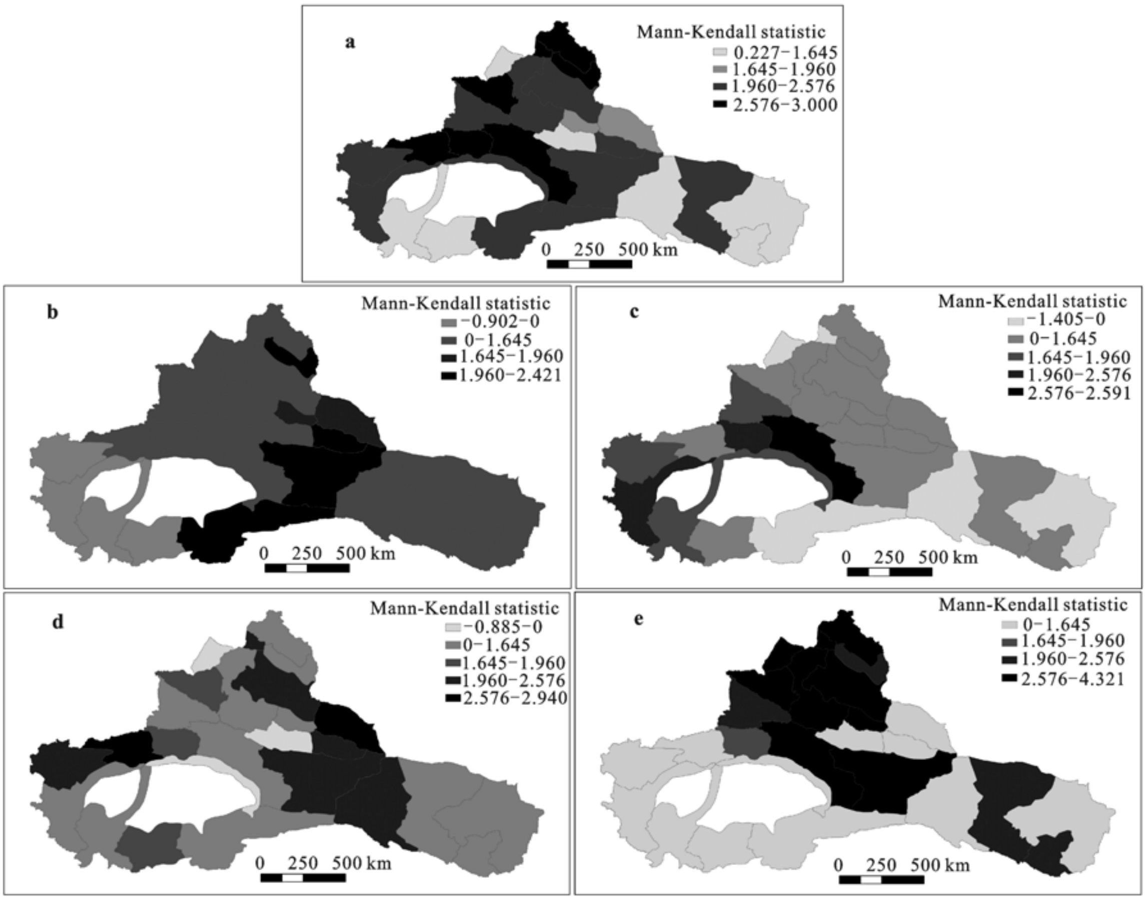

Fig. 3 Regional trends of precipitation at basin scale: a) annual; b) spring; c) summer; d) autumn; e) winter (MK statistic: $Z = 1.645$, $P = 0.10$; $Z = 1.960$, $P = 0.05$; $Z = 2.576$, $P = 0.01$; Taklimakan Desert: No data)

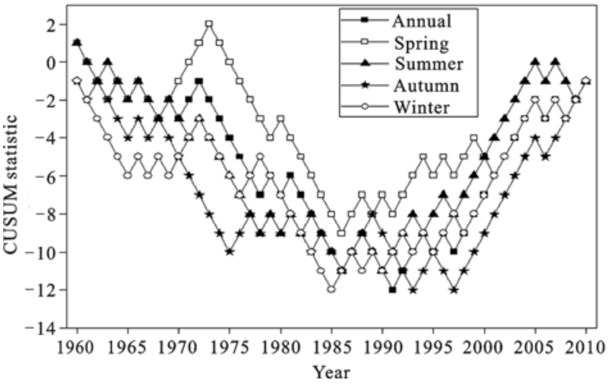

Fig. 4 Cumulative sum (CUSUM) charts for annual and seasonal precipitation

for rivers in the eastern section of the north slope of the Tianshan Mountains (NSET rivers), the Weigan River and the Yarkant River show significant changes at the 0.05 significant level (Fig. 6c). Similarly, in autumn approximately 95% of the stations demonstrate statistically increasing trends (Fig. 5d); the basins of the Hotan River and the Aksu River exhibit most significant changes comparing with other basins (Fig. 6d). Therefore, it can be concluded that the air temperature has increased significantly, which results in a warmer climate in the arid region of the northwestern China.

3.2.2 Step change for each basin and study area

Step change probably occurred in 1988 ($P < 0.01$) for regional annual air temperature (Fig. 7), but no similar results can be found at seasonal scale. The step changes of 1998, 1996, 1987 and 1985 ($P < 0.05$) are detected for spring, summer, autumn and winter for the whole region, respectively. As for the basin scale, step change occurred in 1988 for 17 basins, and in 1996 for 10 basins in terms of annual air temperature. The step changes at seasonal scale are found in 1998 for spring (15 basins), 1996 for summer (21 basins), 1986 for autumn (15 basins) and 1985 for winter (19 basins), respectively. So the years of step change at basin scale are in accordance with the results at whole regional scale, for example, step changes of the annual air temperature all observed in 1988.

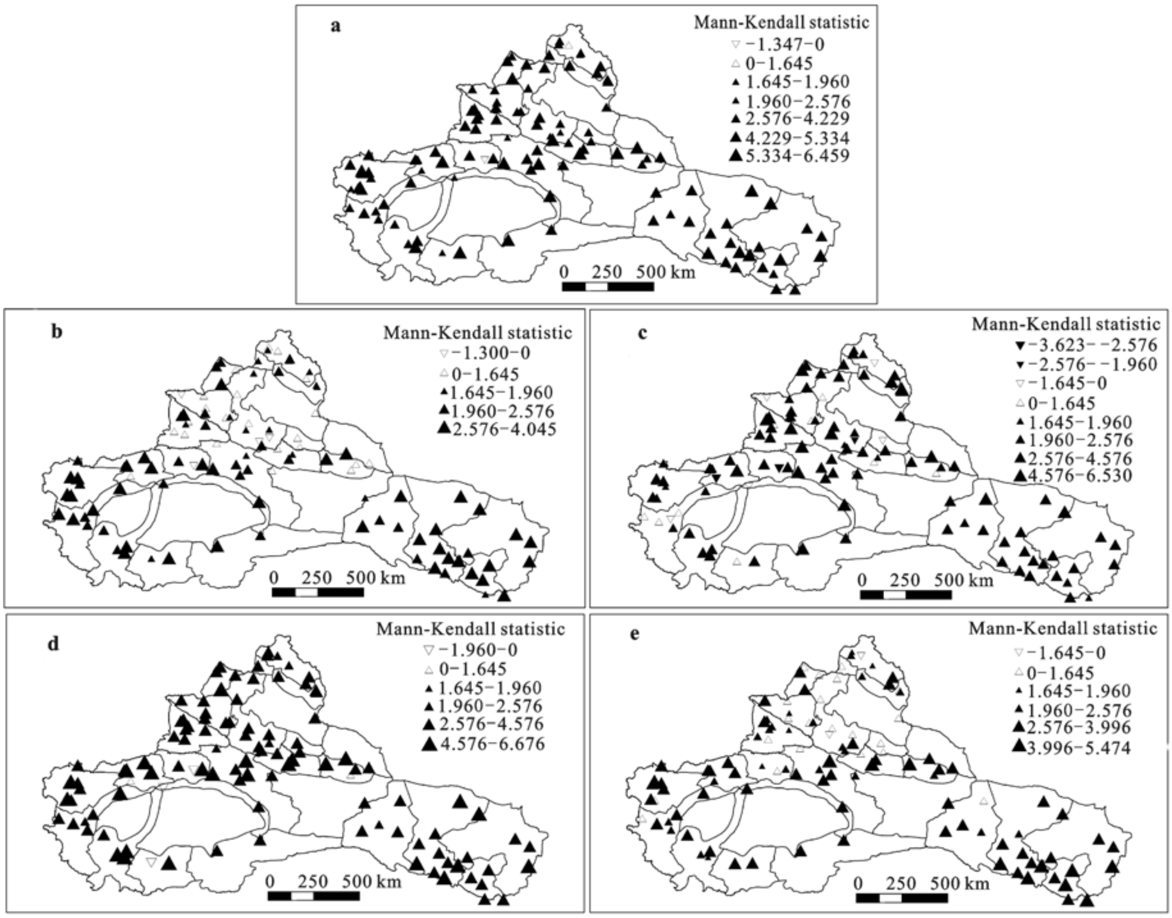

Fig. 5 Distribution of Mann-Kendall trends of air temperature at individual station: a) annual; b) spring; c) summer; d) autumn; e) winter. Black solid triangle denotes significantly increasing and decreasing trend (MK statistic: $Z = 1.645$, $P = 0.10$; $Z = 1.960$, $P = 0.05$; $Z = 2.576$, $P = 0.01$)

3.3 Runoff

Figure 8 illustrates the overall spatial distribution of statistically significant trends for annual and seasonal runoff. Most of hydrological stations show increase trends. Annual runoff increases significantly at the stations around the the Tianshan Mountains, especially for the basins of the Aksu River, the Kaidu River, the NSET rivers and the Shule River. Some stations located in the Weigan River, the Kaxgar River and the Yarkant River also display significantly increasing trends ($P < 0.05$). Significanly decreasing trends are observed in the Shiyang River.

Runoff in spring has a significantly increasing trend ($P < 0.10$) at 14 stations which are distributed sparsely and evenly in the study area. In summer, increasing trends can be found at 12 stations, mostly located in the southern slope of the Tianshan Mountains (the Aksu River, the Weigan River, the Kaidu River) and the Shule River. Thirteen stations in autumn have significant positive trends in study area ($P < 0.10$), and these stations are mainly distributed at the south slope of the Tianshan Mountains (i.e., the Aksu River, the Weigan River, the Kaidu River), and in the Shule River and the Hotan River basins. In winter, the trends of the runoff exhibit a mix pattern, with 16 stations showing significantly increasing trends and 4 stations decreasing trends. It is very interesting that all the stations in the Yarkant River Basin and the Hotan River Basin show significantly increasing trends in winter. Therefore, the runoff generally demonstrates positive trends in the study area, especially the rivers located in the south slope of the Tianshan Mountains.

Step changes of the runoff were calculated at individual station. Although most stations fail to achieve statistical significance, the step changes at the signifycance level of 0.05 are observed at the stations of Yingxiongqiao (1988 (step-change year), rivers in the middle section of the north slope of the Tianshan Moun-

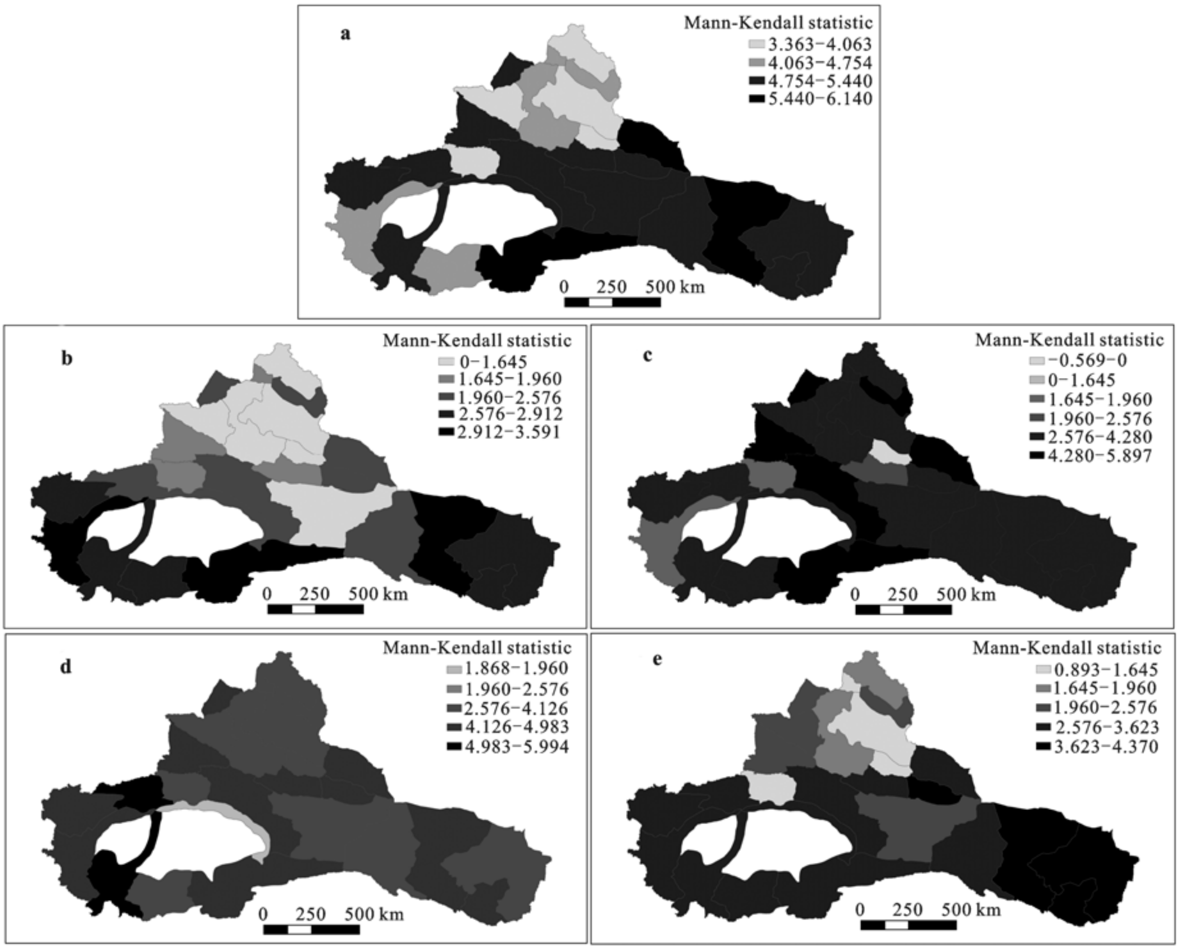

Fig. 6 Regional trends of air temperature at basin scale: a) annual; b) spring; c) summer; d) autumn; e) winter (MK statistic: $Z = 1.645$, $P = 0.10$; $Z = 1.960$, $P = 0.05$; $Z = 2.576$, $P = 0.01$; Taklimakan Desert: No data)

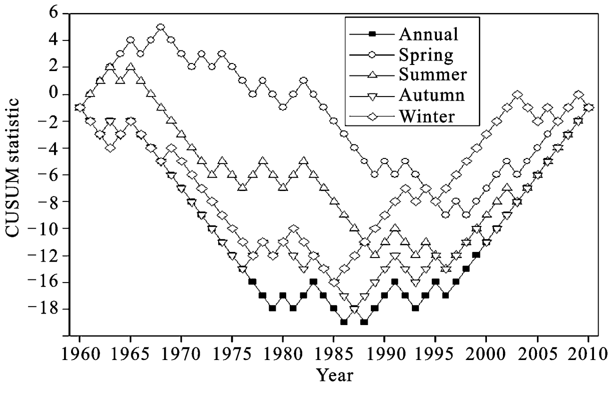

Fig. 7 Cumulative sum (CUSUM) charts for annual and seasonal air temperature

tains (NSMT rivers) (basin)), Kensiwate (1995, NSMT rivers), Alagou (1988, Turpan Basin) in the North Xinjiang, and the step changes are also found at the stations of Langang (1986, the Weigan River), Heizhi (1986, the Weigan River), Shaliguilank (1993, the Aksu River), Xiehela (1993, the Aksu River), Xidaqiao (1993, the Aksu River), Huangshuigou (1995, the Kaidu River), and Dashankou (1995, the Kaidu River) in the South Xinjiang. Step changes of Yinluoxia (the Heihe River), Dangchengwan (the Shule River), Changmabao (the Shule River) and Zhamushi (the Shiyang River), respectively, are observed in 1979, 1981 and 1997, 1990 in the Hexi Corridor. So the step changes of runoff exhibit a complicated pattern, with different hydrological stations displaying different step change points, and the step changes for most stations are observed between 1985 and 1995.

From the analysis above, it can be concluded that in many regions of North Xinjiang, such as the Ertix River, the Emin River, the Ebinur Lake Drainage, both air temperature and precipitation showed an increasing trends, while annual runoff has no significant change. In the Hotan River Basin, the annual runoff does not exhibit significantly change along with the increase of air temperature. For some rivers in the north and south slopes of the Tianshan Mountains, for example, the rivers in the middle section of the north slope of the Tianshan Mountains (NSMT rivers), the Aksu River, the Weigan River and the Kaidu River, the runoff demonstrate a significant increase associated with a significant increase of air temperature and precipitation. The climate transition is found in the late 1980s and the early 1990s. Step change of the runoff is identical with the climate variables. However, some basins also showed posteriority, for example, step change of climatic variables in the Aksu River is found in 1986, while the runoff is found in 1993. Due to the complex terrains and atmospheric circulation structures of the northwest arid areas, the hydrological effects caused by meteorological variables might be different in different basins.

3.4 Correlation between runoff and meteorological variables

Correlations between runoff and precipitation at basin scale were analyzed. From Fig. 9a, it can be seen that the runoff presents strong correlation with the annual precipitation. For the Kaidu River, the Weigan River, the Heihe River, the Shiyang River, and the stations in the North Xinjiang, the correlation coefficients are extremely significant ($P < 0.05$).

In spring, the runoff is significantly correlated with the precipitation in the Kaidu River, the NSMT Rivers, the Heihe River and the Shiyang River (Fig. 9b). In summer, the runoff has significant correlation with the precipitation in the Kaidu River, the NSMT rivers, the Heihe River, the Shiyang River, the Weigan River and the Extix River (Fig. 9c). Similarly, in autumn, the precipitation also has significant influence on the runoff in the Heihe River, the Shiyang River and the NSMT rivers (Fig. 9d). In winter, less significant relationships are found between the runoff and the precipitation compared with other seasons (Fig. 9e).

Correlations between runoff and air temperature at basin scale are shown in Fig. 10. The annual air temperature also has significant positive influence on streamflow, especially the stations in the south slope of

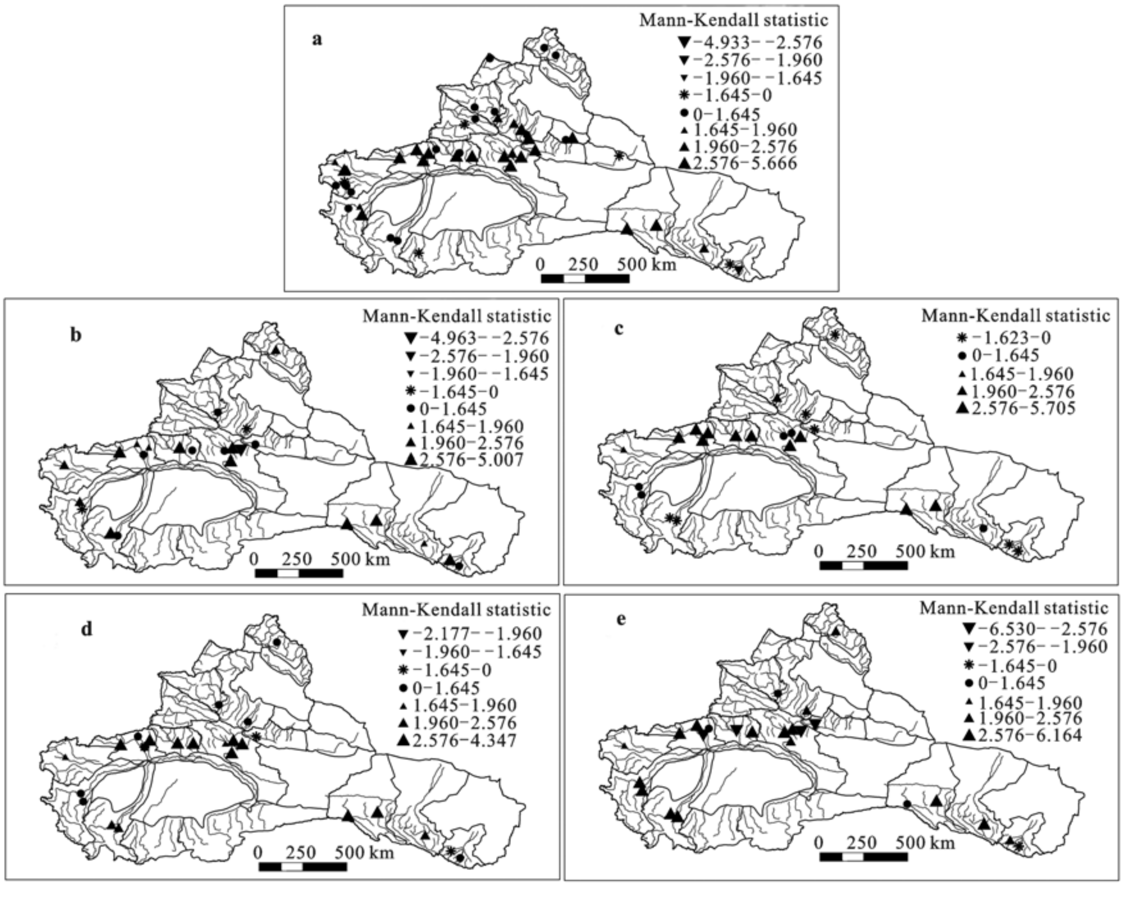

Fig. 8 Spatial distribution of trends of runoff at individual station: a) annual; b) spring; c) summer; d) autumn; e) winter. Black solid triangle denote significantly increasing and decreasing trend (MK statistic: $Z = 1.645$, $P = 0.10$; $Z = 1.960$, $P = 0.05$; $Z = 2.576$, $P = 0.01$)

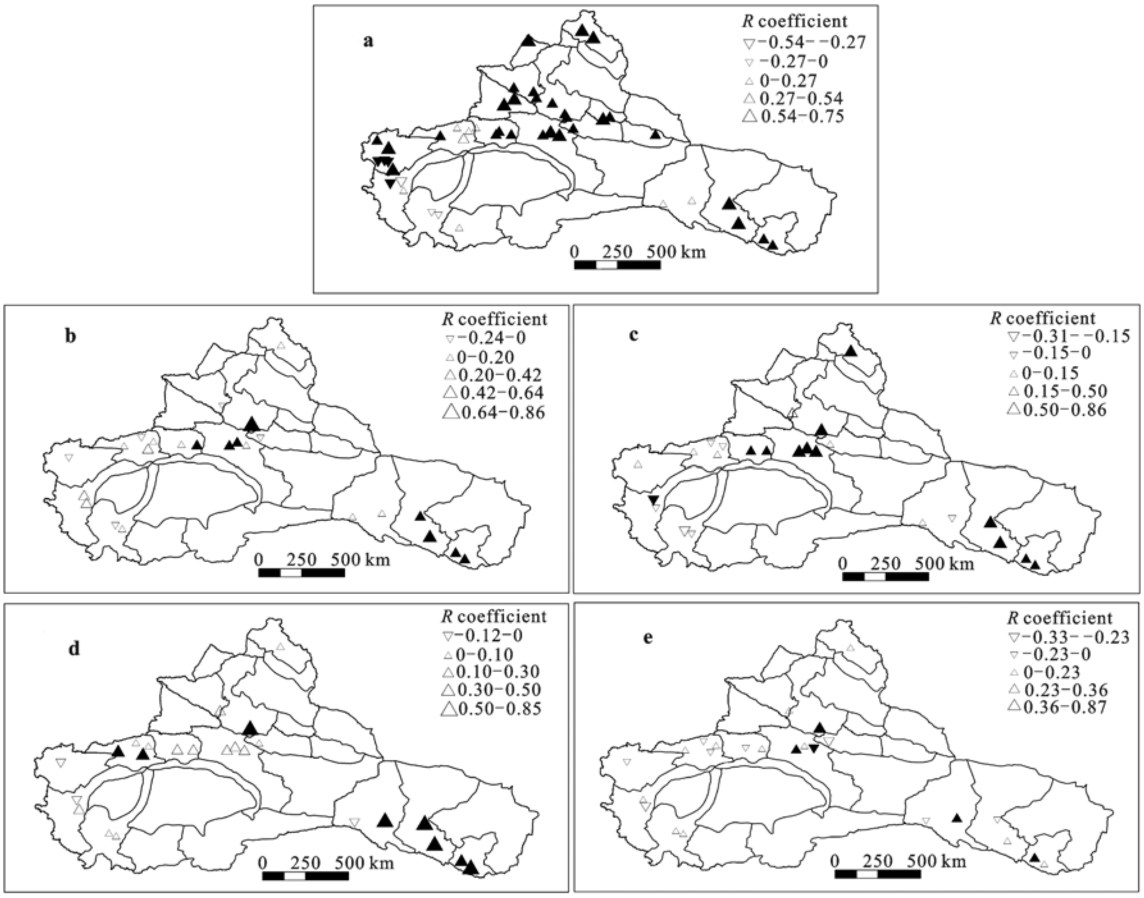

Fig. 9 Correlation between runoff and precipitation at basin scale: a) annual; b) spring; c) summer; d) autumn; e) winter. Positive/negative coefficients are shown as up/down triangles, and filled symbols represent statistically significant correlation (significant at the 0.05 level). The size of the triangles is proportional to the magnitude of the trends

the Tianshan Mountains (the Kaidu River, the Weigan River and the Aksu River), the Yarkant River, the NSMT rivers and the Shule River, while negative influence in the NSET Rivers and the Ertix River (Fig. 10a).

In spring, the correlation coefficients between the temperature and the runoff differ significantly, with 7 stations exhibiting strong positive correlation and 2 stations negative correlation (Fig. 10b). In summer, runoff of 10 stations has strong positive correlation with the air temperature, especially for the basins of the Aksu River and the Shule River (Fig. 10c). In autumn, the stations with significant positive coefficients are mainly distributed in the south slope of the Tianshan Mountains (the Aksu River, the Weigan River and the Kaidu River) (Fig. 10d). In winter, significant correlation coefficients are also found in the south slope of the Tianshan Mountains (Fig. 10e).

The remarkable thing is that the annual runoff in the Aksu River, the Yarkant River, the Shule River have significant positive correlation coefficients with the annual temperature, but no significant relationships with the annual precipitation, which manifests that the main supply source of the runoff in these areas is glacier melt water. The Kaidu River and the Weigan River are affected significantly by both the annual temperature and the annual precipitation, revealing that the runoff in these areas is supplied by both glacier and rainwater. The changes of the runoff in the Ertix River are consistent with those of the annual precipitation, but inconsistent with those of the annual temperature, indicating rainwater is the main supply for this river.

The proportions of glacier water in the runoff from headtwater are shown in Fig. 11. Effects of the glacier coverage and the proportion of the glacier water on the trends of the runoff are also evaluated by using a linear regression method. The trends of the runoff exhibit a strong negative correlation with the glacier coverage and the proportion of the glacier water in runoff. The

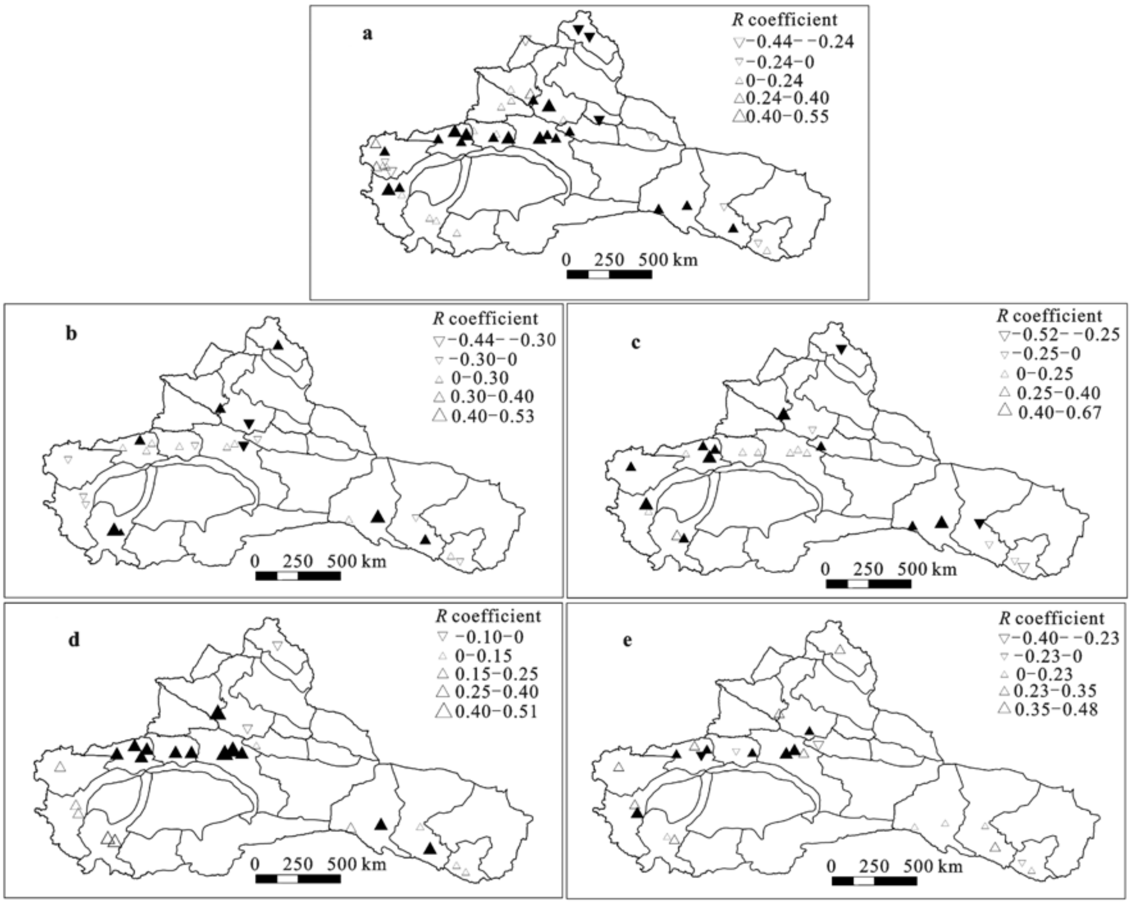

Fig. 10 Correlation between runoff and air temperature at basin scale: a) annual; b) spring; c) summer; d) autumn; e) winter. Positive/negative coefficients are shown as up/down triangles, and filled symbols represent statistically significant correlation (significant at the 0.05 level). The size of the triangles is proportional to the magnitude of the trends

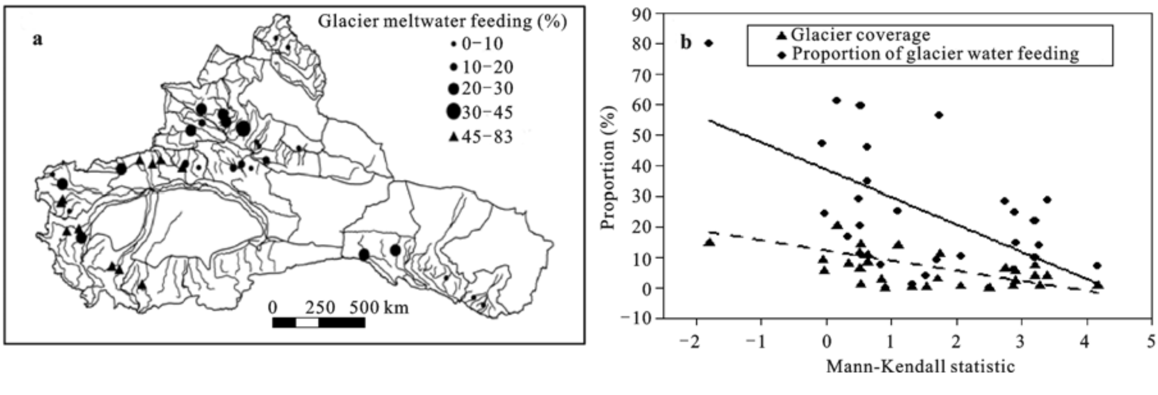

Fig. 11 Proportion distribution of glacier water feeding at mountain pass station (a) and relationship between trends of runoff and glacier coverage and proportion of glacier water in runoff (b) (the data of glacier coverage and proportion of glacier water in runoff derived from Zhou (1999))

runoff seems to decrease when the glacier coverage increases. Significant negative relationship is detected for trends between the glacier coverage and runoff, which is significant at the level of 0.01 (Equation 2).

$$y = -2.1618x + 9.3435 \quad (R^2 = 0.3042,\ P = 0.003) \qquad (2)$$

where y denotes the trends of the runoff; x denotes the glacier coverage. Relationship between the trends of the runoff and the proportion of the glacier water in runoff can be obtained by using the following equation:

$$y = -0.0365x + 2.3974 \ (R^2 = 0.3252, \ P = 0.002) \quad (3)$$

where y denotes the trends of the runoff; x denotes the proportion of the glacier water in the runoff. The determination coefficient of the model is significant at significance level of 0.01. From Equation (3), the point that the runoff will decrease when the proportion of glacier water increases can be extracted.

4 Discussion

In this study, it can be seen that the effects of the air temperature on the runoff are complex. The runoff has a significant positive correlation with the temperature due to the increase in glacier melt, and significant negative correlation with air temperature due to increased evapotranspiration. In the context of increasing precipitation and temperature, the runoff from headwater exhibits an increase at most of the hydrological stations, however, the streamflow along the mainstream of the river decreases. The main reason for drastically decline of the mainstream runoff is human activities. For example, approximately 86% of the total water use is for irrigation at the Shiyang River Baisn (Li *et al.*, 2008). In the Tarim River Basin, the irrigated areas has been expanded from about 3480 km^2 in the 1950s to 12570 km^2 in the 2000s, and the consumption of water has increased from 5.0×10^9 m^3 to 15.5×10^9 m^3 accordingly in the same periods (Ye *et al.*, 2006; Xu Z X *et al.*, 2010). The number of artificial reservoirs increased from 2 to 11 and water storage capacity from 0.098×10^9 m^3 in 1950 to 1.070×10^9 m^3 in 1995 in the Tarim River Basin (Feng *et al.*, 2001; Hao *et al.*, 2008). Therefore, it can be concluded that the increasing runoff can not alleviate the water shortage because of the human excessive water consumption.

Glacier runoff is the major contributor to water resources that are used to support the sustainable development of the environment, industry and agriculture in the arid regions (Yao *et al.*, 2004). From the analysis above, the areas affected by precipitation are the rivers in North Xinjiang, the Weigan River, the Kaidu River, the Heihe River and the Shiyang River, where the precipitation is relatively abundant. Seasonal snow melt water is the main recharge source to the runoff in the arid regions, so for the rivers in South Xinjiang, such as the Hotan River, the Yarkant River, the southern Kaxgar River, and the Keriya River, and there are not significant positive correlations between rainfall and runoff.

But for the air temperature, the effects on the runoff are multiple: 1) For the rivers feeded by the glacier, such as the Yarkant River and the Aksu River, the temperature has positive effects on streamflow, and the increase of the temperature will lead to increased runoff. However, these positive effects are not significant in the basins of the Hotan River, the southern Kaxgar River, and the Keriya River. The reasons probably are that the glaciers in these areas are located at high mountains (snow line above 5000 m) and the interannual variability of precipitation and temperature in high mountains are much smaller than that in the low mountains. 2) Warming also increases the runoff of the Kaidu River, the Shule River and the NSMT rivers due to abundant glacier in these basins (glacier water feeding from 15% to 45%). The Ili River also have abundant glacier, but the increased runoff by effects of air temperature is not obvious. That is because that the glacial melt water in the Ili River is transformed into the groundwater (the proportion exceeding 30%) due to high vegetation coverage in this area. 3) In the Ertix River, the temperature and runoff have a significant negative relationship because of the little glacier coverage in Altai Mountains (glacier water feeding less than 2%). The increase in the temperature only leads to the increase in evaporation, which will cause the reduction in the runoff. The trends of the runoff seem to decrease when the glacier coverage and the proportion of glacier water feeding in the runoff increased because of smaller glacier being more sensitive to climate warming than the larger ones (Ye *et al.*, 2001). With climatic warming, small glaciers are at the risk of being strongly impacted. It is predicted that the smaller glaciers (area < 1 km^2) on the northern slope of the Tianshan Mountains will likely disappear within the next 20–40 years (Li *et al.*, 2010). The runoff increases with the reduction of the glacier, but when the glacier area is shrinking to a certain scale, the glacier runoff will experience transformation from the increase to the decrease. As the glacier area atrophy, the glacial runoff area will shrink and the glacier runoff will abate, which will cause serious effects on the ecological system of the arid regions. Therefore, there is considerable uncertainty whether the future runoff will continue to increase or not, but glacial ablation should be concerned to us.

The climate in the study area changes from the warming-drying trend to the warming-wetting trend. However, due to the peculiar geographical location and the climatic conditions, the arid climatic environment in the region can not be qualitatively changed by a short-term precipitation increase, especially for the endorheic drainage basins (Tao *et al*., 2011). As the meteorological data and hydrological stations used in the 28 basins are quite sparsely and irregularly distributed among the arid region, and also most of them are located in the lower altitude or near the artificial Oasis with scarce stations in the high mountain area. So, further study should take more stations and longer time series of data.

5 Conclusions

There are observed trends in annual and seasonal air temperature, precipitation and runoff series in the arid region of the northwestern China which are analyzed by dividing the study area into 28 sub-regions (basins). Some conclusions are draw as follows:

(1) Regional annual precipitation exhibits significantly increase, with most stations showing significant changes in winter. In contrast to the air temperature, the significance of the changes in precipitation during 1960–2010 is low. The basins showing significant changes are mainly distributed in the northern North Xinjiang (the Ulungur River, the Jeminary River, and the Ertix River) and the south slope of the Tianshan Mountains (the Weigan River, the Aksu River and the Kaidu River). Step change can be detected for regional annual precipitation around in 1991, which indicates that the weather has become wet since 1990s in the arid region of the northwestern China.

(2) The air temperature has few spatial differences, with the stations dominated by significantly increasing trends for the study area. For annual air temperature, all the basins exhibit significant increase at the significant level of 0.01, but the basins in the North Xinjiang present less increasing trends than the basins in the South Xinjiang and the Hexi Corridor. Similar distribution of trends can be observed in spring and winter. Step changes probably occur in 1988 for annual air temperature for the study area. The climate during 1989–2010 become warm compared with the period of 1960–1988.

(3) Affected by the changes of the precipitation and the air temperature, the runoff increases significantly at the stations around the Tianshan Mountains, especially the stations in the south slope of the Tianshan Mountains, the NSET rivers and the Shule River. Few rivers are observed with decreasing trends, and only the Shiyang River showed significant negative trends. Step changes are detected in few stations for runoff series, and the years with step change also show non-uniform in the arid sub-regions.

(4) Significant relationships can be found between runoff, precipitation and air temperature, but the effects of climate variables vary from basin to basin. The runoff has stronger correlation with the precipitation in the basins where the precipitation is relatively abundant, such as the Kaidu River, the Weigan River, the Heihe River, the Shiyang River and the rivers in North Xinjiang. Air temperature has a significant positive influence on annual runoff in these basins where abundant glacier exists, such as the south slope of the Tianshan Mountains (the Kaidu River, the Weigan River and the Aksu River), the Yarkant River, the NSMT Rivers, and the Shule River. The changes of the runoff are based on complicated interactions between climatic variables (temperature and precipitation) and regional conditions (glacier coverage).

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