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Impacts of Climatic Change on River Runoff in Northern Xinjiang of China over Last Fifty Years

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Abstract: The characteristics of climatic change and river runoff, as well as the response of river runoff to climatic change in the northern Xinjiang are analyzed on the basis of the hydrological and meteorological data over the last 50 years by the methods of Mann-Kendall nonparametric test and the nonlinear regression model. The results show that: 1) The temperature and the precipitation increased significantly in the whole northern Xinjiang, but the precipitation displayed no obvious change, or even a decreasing trend in the northern mountainous area of the northern Xinjiang. 2) River runoff varied in different regions in the northern Xinjiang. It significantly increased in the northern slope of the Tianshan Mountains and the north of the northern Xinjiang (p = 0.05), while slightly increased in the west of the northern Xinjiang. 3) North Atlantic Oscillation (NAO) affects river runoff by influencing temperature and precipitation. The NAO and precipitation had apparent significant correlations with the river runoff, but the temperature did not in the northern Xinjiang. Since the mid-1990s river runoff increase was mainly caused by the increasing temperature in the northern slope of the Tianshan Mountains and the north of the northern Xinjiang. Increased precipitation resulted in increased river runoff in the west of the northern Xinjiang.
Keywords: climatic change; river runoff; Mann-Kendall test; nonlinear regression model; NAO; northern Xinjiang

1 Introduction

It is world-widely acknowledged that global climate change is caused by growing atmospheric concentration of carbon and other trace gases (IPCC, 2001; 2007; Kamga, 2001). The fourth report of IPCC (2007) pointed out that the average temperature of the atmosphere and the ocean are both increasing globally. Since 1850, when global surface temperature was recorded by the instrument, the warmest periods included 11 years from 1995 to 2006 (IPCC, 2007). Water and watershed systems are highly sensitive to climate change (Gleick and Adams, 2000). Global warming and change in precipitation patterns caused by CO_2 emission and other human activities change the availability of water resources and in turn affect the natural ecosystems. One of the major consequences caused by climate change is the alternation of regional hydrological cycles and the subsequent changes in stream flow regimes (Xu, 2000). Water resources are the most important natural resources for social and economic development in arid and semiarid areas (Boehmer *et al*., 2000).

Xinjiang, located in the hinterland of the Euro-Asian continent, belongs to arid and semi-arid climate, where water is the basic and significant renewable resources for the existence and development of oasis (Han, 2001). With global warming, the climate of Xinjiang turns warmer significantly. Chen *et al*. (1991) analyzed changes of mean temperature in Northwest China and concluded that this region might be one of regions most sensitive to global warming. Some researches on climate and runoff for individual basins in arid regions have been conducted recently (Chen *et al*., 2006; Kader and Hiroshi, 2006; Zheng *et al*., 2006) and showed that over the past 50 years, climate changes have influenced river discharges, and there was a humid-warm trend in the climate of Xinjiang and North-

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west China (Shi *et al.*, 2003; Chen *et al.*, 2006).

Other studies concluded that there was an increase trend in river runoff in Xinjiang (Hao *et al.*, 2006; Wu *et al.*, 2006; Yang *et al.*, 2006). Rivers in the northern Xinjiang, mostly inland rivers, are the most essential and reliable water resources for productive activities and everyday life (Han, 2001). The change of water resources is crucially important to the economic development of the northern Xinjiang. Previous researches mainly focused on the relationship between climate and river runoff in the northern Xinjiang (Gong and Yuan, 2000; He *et al.*, 2003). However, there were few studies focusing on the response of river runoff to climate change in different regions.

This paper is designed to investigate the changes of climate and the factors influencing river runoff in different regions of the northern Xinjiang. Based on above, nonlinear response equations are formulated between river runoff and climate factors to analyze the response of river runoff to climatic warming since the mid-1990s.

2 Materials and Methods

2.1 Study area

Xinjiang′s topography is featured by three mountains flanking two basins, namely the Altay Mountains, the Junngar Basin, the Tianshan Mountains, the Tarim Basin and the Kunlun Mountains from the north to the south. It is a arid and temperate zone of continental climate. Aqueous vapor mainly comes from the west, northwest and north. The precipitation and surface runoff tend to decline from the northwest to the southeast. Xinjiang can be geographically divided into three regions: the northern region, the eastern region and the southern region. The northern Xinjiang (Fig. 1) is composed of the prefectures of Altay, Tacheng and Ili, Bortala Mongol Autonomous Prefecture, Urumqi City and Changji Hui Autonomous Prefecture, which is mostly under the influence of favonian circumfluence. At some mountains with higher altitudes, it is easier to head off vapor from the west, north and northwest, and finally form the center of glaciers. The precipitation is very rich in the higher mountains, where most surface water originates (Gong and Yuan, 2000; He *et al.*, 2003).

2.2 Data sources

In this paper, runoff data for 1959–2006 from 12 hydrological stations were used (Fig. 1), including three representative stations, i.e., Qunkule Station at the Burqin River in the north of the northern Xinjiang, Kafuqihai Station at the Teks River in the west of the northern Xinjiang and Kenswat Station at the Manas River in the northern slope of Tianshan Mountains. Due to the non-inhabitant nature of the study area, the runoff observed is basically the natural amount of runoff, with very little human disturbance. The gauged data from the hydrological stations may reflect the trend of the natural runoff change of the rivers. The collected hydrological data included average annual and average monthly river runoff. Meanwhile, monthly meteorological data at the hydrological stations were also collected to explore the causes for the change in the river runoff. Meanwhile, annual temperature and precipitation in 1961–2007 were also collected from 48 meteorological stations in the northern Xinjiang, and North Atlantic Oscillation (NAO) index data in 1961–2000 were used, which refer to standardization of the pressure gap at sea level per month between two locations of Gibraltar (36.1ºN, 5.4ºW) and Reykjavik (64.1ºN, 22.5ºW) (Hurrell, 2001).

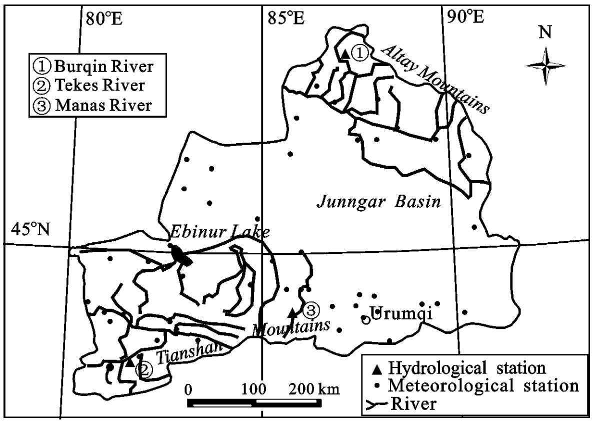


Fig. 1 Location of northern Xinjiang and distribution of hydrological and meteorological stations

2.3 Methods

2.3.1 Mann-Kendall test for monotonic trend

Mann-Kendall test is an effective and general measure for analyzing the trend of time series. This nonparametric test technique can be used in trend analyses in a time series without specifying whether the trend is linear or nonlinear if the independent variable is time (Hao *et al.*, 2007; Chen *et al.*, 2008; Xu *et al.*, 2008). We used the Mann-Kendall test to analyze the changing trend in the annual river runoff, temperature and precipitation in the northern Xinjiang during the past five decades.

In the Mann-Kendall test, the null hypothesis H_0 states that the data (x_1, x_2, …, x_n) are a sample of independent and identically distributed random variables. The alternative hypothesis H_1 of a two-sided test is that the distribution of x_j and x_i are not identical for all j and i. The test statistic (s) is given as follows:

$$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{1}$$

where x_j and x_i are the sequential data values, n is the length of the data set, and

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \tag{2}$$

For sample sizes larger than ten, the statistic s is nearly normally distributed, i.e., the statistic Z_c is a standard normal variable.

$$Z_c = \begin{cases} \dfrac{s+1}{\sqrt{Var(s)}}, & s < 0 \\ 0, & s = 0 \\ \dfrac{s+1}{\sqrt{Var(s)}}, & s < 0 \end{cases} \tag{3}$$

In the equation, the mean value and variance of the statistic s are as follows:

$$E(s) = 0 \tag{4}$$

$$Var(s) = \frac{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18} \tag{5}$$

where t is the extent of any given tie.

2.3.2 Mann-Kendall jump test of abrupt

The Mann-Kendall jump test is one of the most effective methods for testing abrupt time series changes (Hao *et al.*, 2007). We used this method to analyze the possible transition points of river runoff, temperature and precipitation.

For time series x_n (n is the length of the data set), the order series (s_k) is given as follows:

$$s_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3, \cdots, n) \tag{6}$$

In which

$$r_i = \begin{cases} +1, & x_i > x_j \\ 0, & x_i \le x_j \end{cases} \quad (j = 1, 2, \cdots, i) \tag{7}$$

where x_j and x_i are the sequential data values, and the statistic (UF_k) is defined as:

$$UF_k = \frac{[s_k - E(s_k)]}{\sqrt{Var(s_k)}} \quad (k = 1, 2, \cdots, n) \tag{8}$$

where $UF_1 = 0$, $E(s_k)$ and $Var(s_k)$ are the average value and variance of S_k, which can be calculated by following equations:

$$E(s_k) = \frac{n(n+1)}{4} \tag{9}$$

$$Var(s_k) = \frac{n(n-1)(2n+5)}{72} \tag{10}$$

For converse time series x_n, x_{n-1}, … x_1, the equations above are calculated again, meanwhile $UF_k = -UB_k$, k = n, n–1, …, 1, $UB_1 = 0$.

2.3.3 Nonlinear regression model

The mathematical model based on the multi-regression method was formulated between runoff and annual precipitation and average annual temperature, which are used to discuss the response of runoff to the climatic change. Considering the nonlinear relationship between water system and climate change, some methods were referred (Wang *et al.*, 2003) to establish the relationship between runoff and precipitation and temperature:

$$R = c \cdot P^{\alpha} \cdot T^{\beta}$$

where R is river runoff; P is precipitation; T is temperature; c, α, β are remaining verified coefficients.

3 Results and Analyses

3.1 Climatic change characteristics

3.1.1 Climatic changes in northern Xinjiang

The average annual temperature and annual precipitation from 1961 to 2007 are analyzed (Fig. 2). The average annual temperature had an increasing trend of 0.38℃/10yr (y = 0.3784x + 4.8416, R^2 = 0.9861), and had an accelerated increasing trend of 0.08℃/10yr (y = 0.0792x + 0.1994, R^2 = 0.9944) per decade in the northern Xinjiang. The annual precipitation had an increasing trend of 14.5 mm/10yr (y = 14.514x + 192.49, R^2 = 0.9108). The highest temperature and the lowest precipitation both appeared in 1997, which were 7.47℃ and 161.38 mm, respectively. The lowest temperature was 3.92℃ in 1969, and the highest precipitation was 324.59 mm in 1987.

The isograms of increasing precipitation (percentage) and increasing temperature (℃) in the northern Xinjiang

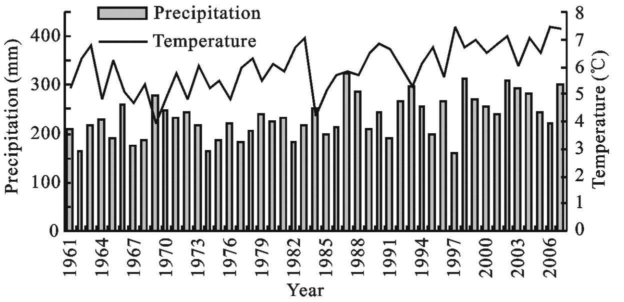


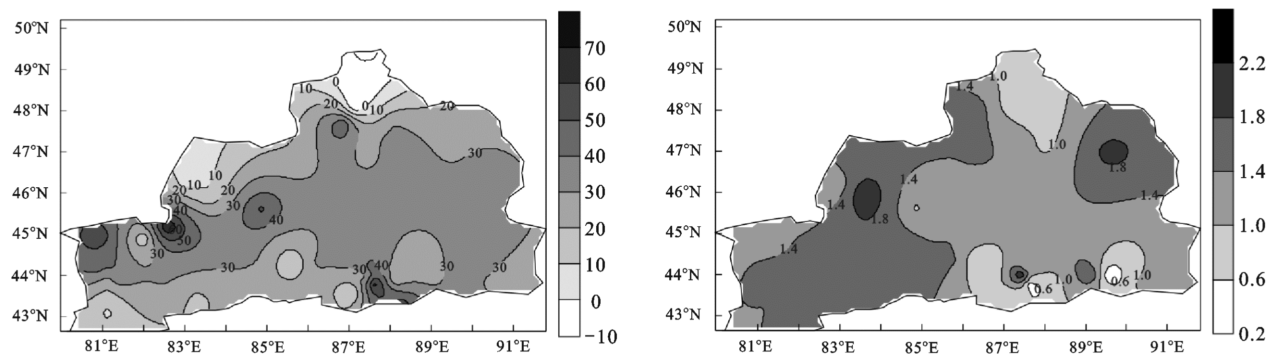
Fig. 2 Variations of average annual temperature and annual precipitation in the northern Xinjiang

are worked out by the following steps. The temperature and precipitation for 2001–2007 from 48 stations subtract those for 1961–1970 and the increment is analyzed by method of Kriging (Fig. 3). The isograms show that the temperature in most regions of the northern Xinjiang increased by 1℃ from the 1960s to the early 2000s (2001–2007). And the northeast and the west of the northern Xinjiang had the most significant increase in temperature. The west of the northern Xinjiang and the eastern region of the northern slope of the Tianshan Mountains had the most significant increase in precipitation.

Figure 4 indicates that the year 1994 is considered as a jump point of temperature from decrease to increase and the increasing tendency is significant at the 99% confidence level. UF curve indicates that the temperature had a decreasing trend in the 1960s and it had been increasing since the 1970s. The year 1987 is proved to be the jump point of precipitation from decrease to increase in the northern Xinjiang and the increasing tendency is significant at the 99% confidence level.

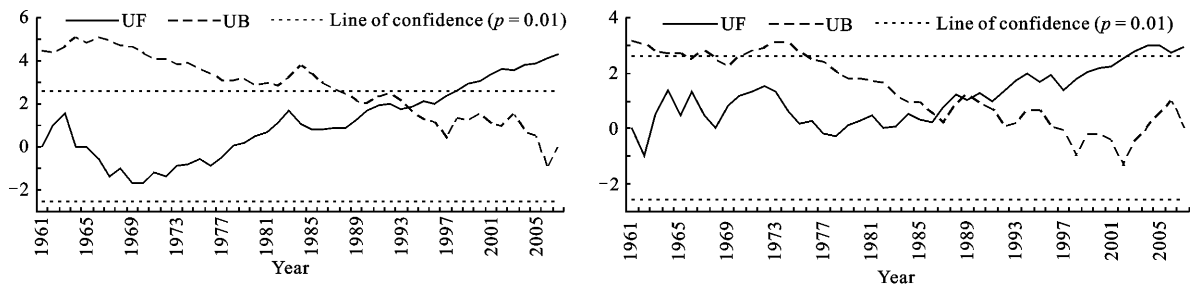
3.1.2 Climatic changes in different regions of northern Xinjiang

Climatic change is analyzed based on the annual precipitation and average annual temperature data from 1957 to 2006 in different regions of the northern Xinjiang (Fig. 5). In the northern region (Qunkule Station), temperature, increasing by 0.2℃/10yr ($y = 0.201x + 2.4637$, $R^2 = 0.5969$), had no significant changes from the mid-20th century to the 1990s, but increased by 0.5℃ in the past decade. In the western region (Kafuqihai Station) and the northern slope of the Tianshan Mountains (Kenswat Station), the temperature increased faster than that in the northern region. The average temperature of the early 21st century in the western region was 1.5℃ higher than that of the 1960s, with an



(a) (b)

Fig. 3 Isograms of percent of increasing precipitation (%) (a) and increasing temperature (mm) (b) in northern Xinjiang



(a) (b)

Fig. 4 Mann-Kendall jump test to abrupt of temperature (a) and precipitation (b) in northern Xinjiang

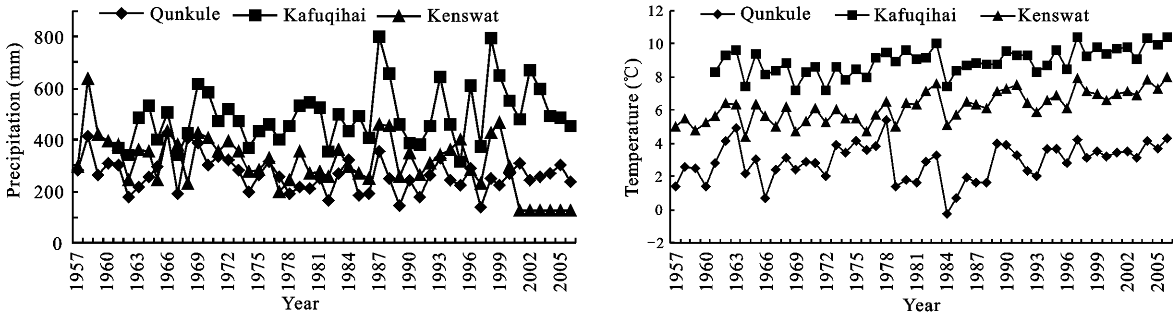


Fig. 5 Annual variation of temperature and precipitation in Qunkule, Kafuqihai and Kenswat stations

increasing trend of 0.37℃/10yr (y = 0.3711x + 7.9595, R^2 = 0.911). The average temperature of the early 21st century in the northern slope of the Tianshan Mountains was 1.6℃ higher than that of the 1960s, with an ascending tendency of 0.40℃/10yr (y = 0.403x + 5.036, R^2 = 0.9499), and was 0.5℃–0.7℃ higher than that in the 1990s. The precipitation of the 1960s in the northern region was 30 mm higher than that of the early 2000s. While the precipitation of the western region increased by 80 mm, and that of the northern slope of Tianshan Mountains only increased by 5 mm from the 1960s to the early 2000s.

The jump points of the temperature series are analyzed by the Mann-Kendall jump test based on the annual temperature data from 1957 to 2006 in the three stations of the northern Xinjiang (Fig. 6). The result shows that the distinct jump years of temperature changes as a result of climatic change in Kafuqihai (the western region), Kenswat (the northern slope of the Tianshan Mountains) and Qunkule (northern region) stations were 1996, 1992 and 2004, respectively. The UF curve shows that the western region and the northern slope of the Tianshan Mountains had more significant change than the northern region did. The UF curves show an ascending trend from 1976 in the western region and the northern slope of the Tianshan Mountains and from 1988 in the northern region. The temperature gradient was smaller in the northern region than the other regions, that is to say, the rate of temperature increasing was lower in the northern region. All of these show the differences in the regional climate change.

When jump tests are conducted on the precipitation series of Qunkule, Kafuqihai and Kenswat, significant changes do not occur. Trend test finds that Z_c values of Qunkule and Kenswat were minus (–1.7 and –0.05 respectively), showing a decreasing trend. The Z_c value of Kafuqihai was 1.84, showing an increasing tendency. But neither of them shows significant changes at the 95% confidence level. Compared with oases in the plain, all indicates that the precipitation change in the mountainous regions is relatively stable.

3.2 River runoff change characteristics

Through the analysis of the total river runoff of the northern Xinjiang based on the data from 12 hydrological stations and the runoff from three representative rivers, i.e., the Birqin River (Qunkule Station), the Tekes River (Kafuqihai Station), and the Manas River (Kenswat Station) (Fig. 7), three stages of runoff change in the past 50 years are found: the years with average water amount from the 1960s to the mid-1970s, the dry years from the end of the 1970s to the end of the 1980s, the water-ample years from the 1990s to the beginning of the 21 century. And the overall tendency of the river runoff change in the three rivers was rising. The average river runoff in the early

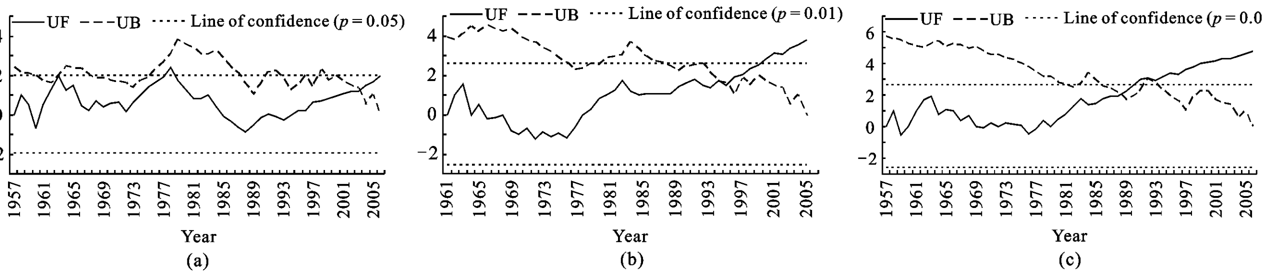


Fig. 6 Mann-Kendall jump test to abrupt of temperature in Qunkule (a), Kafuqihai (b) and Kenswat (c) stations

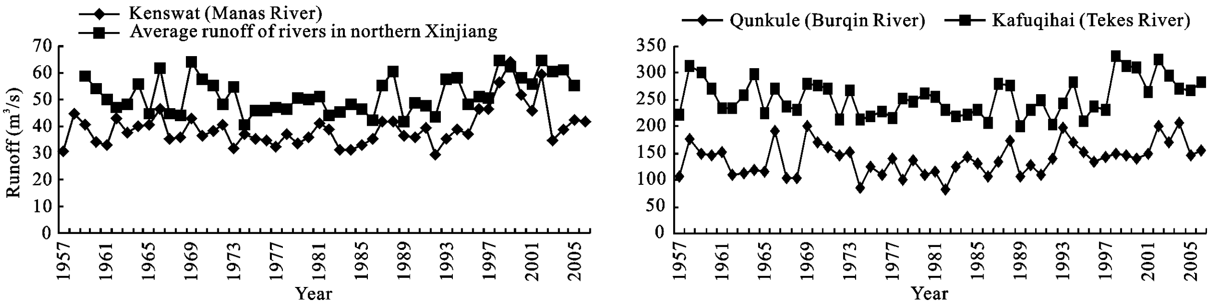


Fig. 7 Annual variation of river runoff in northern Xinjiang

2000s increased by 507×10^6 m^3 compared to that in the 1960s in the northern Xinjiang. The runoff of the Burqin River increased by 1.046×10^9 m^3 in the early 2000s; the runoff of the Teks River 945×10^6 m^3; and the runoff of Manas river 309×10^6 m^3 compared to those in the 1960s.

The results of the Mann-Kendall trend test shows that there are statistically increasing trends in the runoff changes of the Burqin River (Z_c = 1.96), the Teks River (Z_c = 0.8), the Manas River (Z_c = 2.14) and in the northern Xinjiang (Z_c = 1.89). Mann-Kendall jump test shows that the year 2000 and 1996 were the jump points of remarkable runoff changes from decrease to increase for the Burqin River and the Manas Rivers, the river runoff has no significant change in Tekes River and average river runoff in the northern Xinjiang (Fig. 8). The test results also indicate that the former phases of the Manas River (1957–1996) and the Burqin River (1957–2000) did not have statistically significant trends, but the latter ones did.

3.3 Correlations between river runoff and climate factors

3.3.1 Correlations between river runoff and temperature and precipitation

The relationships between annual runoff series and annual temperature series and annual precipitation series are analyzed by the method of Correlate-bipartite. The results show that annual river runoff of the whole northern Xinjiang, the Bruqin River and the Tekes River have significant correlations with precipitation, while the annual runoff of the Manas River have correlations with precipitation and temperature (Table 1).

3.3.2 Correlations between river runoff and SO and NAO

There is no significant correlation between annual runoff series and South Oscillation (SO). Southern Pacific

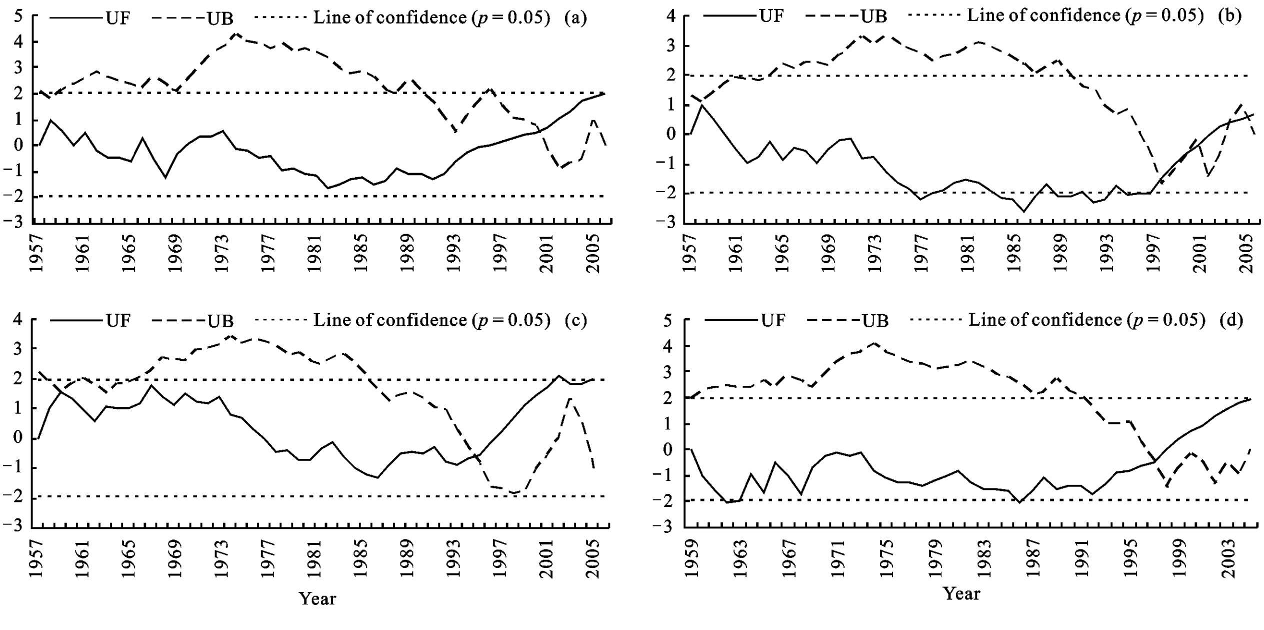


Fig. 8 Mann-kendall jump test to abrupt of river runoff in Qunkule (a), Kafuqihai (b), Kenswat (c) stations and average river runoff in northern Xinjiang (d)

Table 1 Correlation coefficients between river runoff and temperature, precipitation

	Temperature	Precipitation
Annual runoff of northern Xinjiang	–0.146	0.768**
Annual runoff of Burqin River (Qunkule)	0.108	0.486**
Annual runoff of Tekes River (Kafuqihai)	–0.113	0.681**
Annual runoff of Manas River (Kenswat)	0.377*	0.337*

Note: * significance at 95% confidence level, ** significance at 99% confidence level

Ocean Oscillation is distant from Xinjiang and, with mountains blocking in between, it does not influence the river runoff in the northern Xinjiang. The correlation analysis between annual runoff series with North Atlantic Oscillation (NAO) (Table 2) reveals that the runoff of the Manas River has negative correlation with the summer NAO, the runoff of the Tekes river and the Manas River with summer NAO (one year in advance) show negative correlation.

3.4 Response of river runoff to climate changes

The regression equations are formulated by choosing the climatic factors and river runoff whose correlation is significant at 99% confidence level. All the equations pass the F Test at the 99% confidence level, which proves the reliability of the equations as shown in Table 3. Figure 9 shows that the curve of measured value and simulated values are consistent with each other, which also proves the reliability of the equations. The time series data for annual river runoff, precipitation and the index of NAO fit the model. The simulated results (Table 3, Fig. 9) reveal that the difference between the measured and simulated values of the average runoff of the northern Xinjiang is very little, indicating that the simulated result is excellent. The simulated results of the Tekes River and the Manas River are good before the mid-1990s, but that of the Tekes River and the Manas River are not better after the mid-1990s. The mid-1990s is an important abrupt point of climatic change by Mann-Kendall jump test in the northern Xinjiang, from which the temperature has a significant increase and the river runoff increases. Increased temperature leads to a significant increase of river runoff in the north of the northern Xinjiang and the northern slope of the Tianshan Mountains, which influences the simulated results.

4 Discussion

The NAO has a strong climatic impact not only on North America/the Atlantic and European regions but also on almost the whole Northern Hemisphere domain (Hurrell *et al.*, 2003). Our analysis, which agrees with former researcher's conclusion (Nan *et al.*, 2006), indicates that NAO influences the runoff of the Manas river significantly, but the influence on the runoff of the western mountain area in the northern Xinjiang is lagged, and NAO (one year in advance) affects the runoff of the next year. It should be noted that NAO does not influence the river runoff directly but does by affecting temperature and precipitation, meanwhile in the summer of a low-value year of NAO, the temperature is on the high side (Li *et al.*, 2008). The NAO contributes most to the temperature variation in Northern Hemisphere (Hurrell, 1996; Hurrell and Van, 1997). In global climatic system, the increase of greenhouse gas influences global warming, which in turn leads to the variation of NAO, and they are interactive. This justifies the fact that the temperature of the northern slope of the Tianshan Moun-

Table 2 Correlation coefficients between river runoff and SO and NAO

	SO	NAO	Summer NAO	Summer NAO (one year in advance)
Annual runoff of Burqin River (Qunkule)	–0.039	0.085	–0.206	–0.229
Annual runoff of Tekes River (Kafuqihai)	0.155	–0.216	–0.340	–0.461**
Annual runoff of Manas River (Kenswat)	0.067	–0.448*	–0.566**	–0.471**

Note: * significance at 95% confidence level, ** significance at 99% confidence level

Table 3 Regression equations between river runoff and climatic factors in northern Xinjiang

River	Equation	R^2	F	Sig$F$
Average river runoff	$R = 10^{0.438}P^{0.539}$	0.57	56.50	0.0000
Qunkule (Burqin River)	$R = 10^{1.396}P^{0.309}$	0.32	7.60	0.0008
Kafuqihai (Tekes River)	$R = 10^{1.531}P^{0.35}N_{sa}{}^{-0.111}$	0.44	14.50	0.0000
Kenswat (Manas River)	$R = 10^{1.949}N_s{}^{-0.526}$	0.27	10.35	0.0030

Note: R denotes river runoff; P, precipitation; N_{sa}, Summer NAO (one year in advance); N_s, Summer NAO

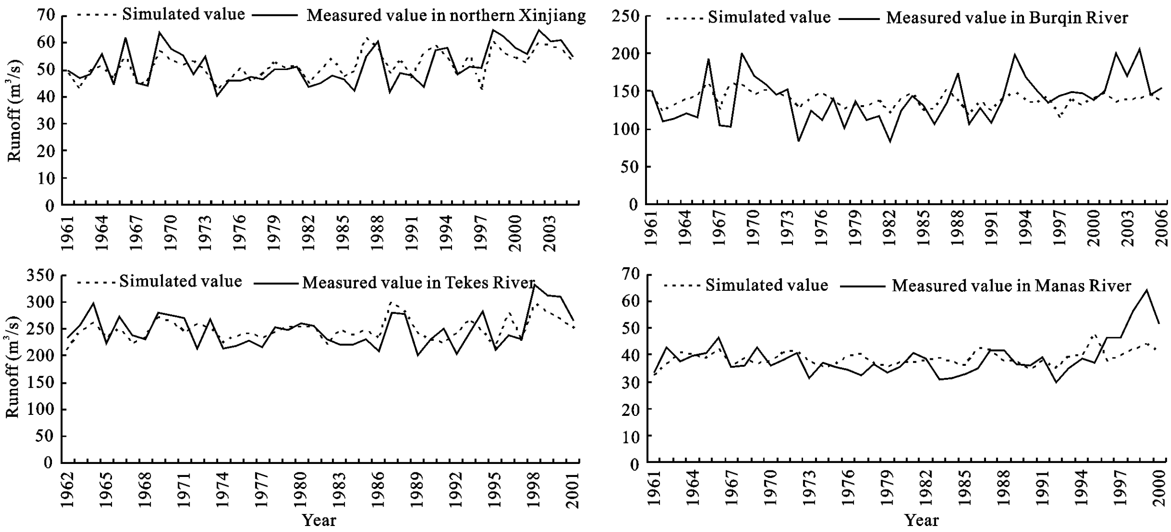


Fig. 9 Measured and simulated values of annual river runoff in northern Xinjiang

tains and the west of the northern Xinjiang increases-faster than that of the north of the northern Xinjiang, and that the increase rate of green house gases is coming down (IPCC, 2007), while the rate of temperature rise is still accelerating.

In general, the drier the climate, the greater the hydrological sensitivity to climate change (Chen *et al.*, 2006). Since the mid-1990s, the runoff-formation area along the Burqin River has shown prominent temperature ascent, the main water source and supply of the Burqin River is seasonal snow melting. The trend test of the annual series of monthly runoff shows that the runoff in May and June monotonically increases (Z_c values are 2.91 and 2.86 for each and is significant at 99% confidence level). Higher temperature leads to the increase of melting snow, and as a result, the runoff in May and June occupies 47% of the annual runoff, which in turn increases the annual runoff. It can also be found that the runoff of the Manas river from December to March monotonically increase, against trend test of the monthly runoff annual series (Z_c values are 3.08, 2.46, 3.10 and 2.90 for each and was significant at 99% confidence level), the runoff from April to November is generally rising but not significantly (Z_c values are 1.45, 1.15, 1.21, 1.42, 1.00, 1.27, 1.53, 1.92 for each month). The water source and supply of the Manas River are mainly from the glacier-snow melting, the higher temperature since the mid-1990s leads to the increase of runoff. The runoff of the Tekes River is generally rising but not significantly every month in annual variation (Z_c value is between 0.5 and 1.6), more rain may restrain glacier melting in summer (Zeng and Wang, 2004), river runoff has no significant increase with increased precipitation and significantly increased temperature.

5 Conclusions

The global climate changes have a significant impact on climate in the northern Xinjiang. The temperature rised most prominently in the northeast and west parts of the northern Xinjiang; the precipitation rised most prominently in the west of the northern Xinjiang and the east of the northern slope of the Tianshan Mountains. The temperature in the northern Xinjiang has increased significantly since the mid-1990s, the average annual temperature of the 21 century increased by 0.5–0.7℃, and as a result, the speed of rising also accelerates. The precipitation increased significantly at the end of the 1980s except the mountain areas, in fact the precipitation decreased in the northern mountains of the northern Xinjiang.

North Atlantic Oscillation (NAO), which affects river runoff by influencing temperature and precipitation. The NAO and precipitation have apparent significant correlations with the river runoff, but the temperature does not in the northern Xinjiang. Then since the mid-1990s river runoff increases are mainly caused by the increasing temperature in the northern slope of the Tianshan Mountains and the north of northern Xinjiang. Increased precipitation results in increased river runoff in the west region of the northern Xinjiang.

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