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Variations of temperature and precipitation of snowmelt period and its effect on runoff in the mountainous areas of Northwest China

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Abstract: Water resources in the arid land of Northwest China mainly derive from snow and glacier melt water in mountainous areas. So the study on onset, cessation, length, temperature and precipitation of snowmelt period is of great significance for allocating limited water resources reasonably and taking scientific water resources management measures. Using daily mean temperature and precipitation from 8 mountainous weather stations over the period 1960−2010 in the arid land of Northwest China, this paper analyzes climate change of snowmelt period and its spatial variations and explores the sensitivity of runoff to length, temperature and precipitation of snowmelt period. The results show that mean onset of snowmelt period has shifted 15.33 days earlier while mean ending date has moved 9.19 days later. Onset of snowmelt period in southern Tianshan Mountains moved 20.01 days earlier while that in northern Qilian Mountains moved only 10.16 days earlier. Mean precipitation and air temperature increased by 47.3 mm and 0.857℃ in the mountainous areas of Northwest China, respectively. The precipitation of snowmelt period increased the fastest, which is observed in southern Tianshan Mountains, up to 65 mm, and the precipitation and temperature in northern Kunlun Mountains increased the slowest, an increase of 25 mm and 0.617℃, respectively, while the temperature in northern Qilian Mountains increased the fastest, increasing by 1.05℃. The annual runoff is also sensitive to the variations of precipitation and temperature of snowmelt period, because variation of precipitation induces annual runoff change by 7.69% while change of snowmelt period temperature results in annual runoff change by 14.15%.

Keywords: snowmelt period; temperature; precipitation; runoff; mountainous areas of Northwest China

1 Introduction

Snowmelt runoff is an important source of fresh water in many parts of the world (Lowry *et*

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al., 2010; Lyon *et al*., 2010; Stewart *et al*., 2004). It is estimated that about 1/6 of the world's population use water from snowmelt runoff (Hock *et al*., 2006). With global warming, snowmelt runoff has attracted considerable attention (Fritze *et al*., 2011; Fucik *et al*., 2012; Langlois *et al*., 2005; Lilbaek and Pomeroy, 2008; Sui *et al*., 2010; Tahir *et al*., 2011). Snowmelt runoff is mainly affected by meteorological elements in snowmelt period, such as snowmelt period temperature and length and so on, which have impact on annual runoff and water seasonal distribution (Beebee and Manga, 2004). The earlier the onset of snowmelt period arrives, the earlier the runoff comes into the river, which increases water evaporation and causes water resources waste (Burns *et al*., 2007); snowmelt runoff increases in spring while that in summer will reduce accordingly, which results in water decrease during the peak period of irrigation and is not conducive to the growth of crops. Meanwhile, due to limited reservoir storage capacity, water storage earlier in the reservoir may lead to flooding under large amount of water circumstance while water storage later may result in water resources waste (Stewart *et al*., 2004). Therefore, the variation of the snowmelt period has a significant influence on making out water resources management strategy (Butt and Bilal, 2011).

Many scholars revealed a lengthening of snowmelt period in past decades. Clow (2010) found that snowmelt period in Colorado moved 2–3 weeks earlier in the past 29 years (1978–2007); snowmelt period in eastern North America shifted about one week earlier (Hodgkins and Dudley, 2006); snowmelt periods in Lancang River, Yellow River and Yangtze River were about 10 days earlier (Lu *et al*., 2009). However, previous research seldom involves snowmelt period change in the arid land of Northwest China.

Located in the hinterland of the Eurasian continent, the arid land of Northwest China occupies the vast area between the western Helan Mountain-Zaocys Ridge line and northern Kunlun Mountains (Figure 1). It covers about 2.5 million km^2, accounting for over 1/4 of China's total. The area is rich in solar energy resources owing to long sunshine duration and strong radiation. However, the area is arid, ecologically fragile with a shortage of water resources, widespread desertification, and sparse vegetation. Mean annual rainfall is less than 400 mm, reducing gradually from east to west.

The scarcity of water resources has become a key factor to prevent socio-economic and ecological environment from sustainable development. The water resources in the study area are mainly from snow and glacier melt water and precipitation in mountains. According to field investigation in recent years, many water managers didn't know snowmelt period advanced clearly and often miss the best impoundment period in spring, which results in water resources shortage in summer. Therefore, the study on snowmelt period change is of great significance for probing into water resources change under the influence of climate change and working out reasonable water resources management measures in the arid land of Northwest China.

2 Data and methods

2.1 Data

This paper uses daily mean temperature data from 8 mountain weather stations (Bayinbuluke, Tuergate, Tashikuergan, Menyuan, Qilian, Tuole, Wushaoling and Yeniugou) in the mountainous areas of Northwest China from January 1, 1960 to December 31, 2010 (Figure 1).

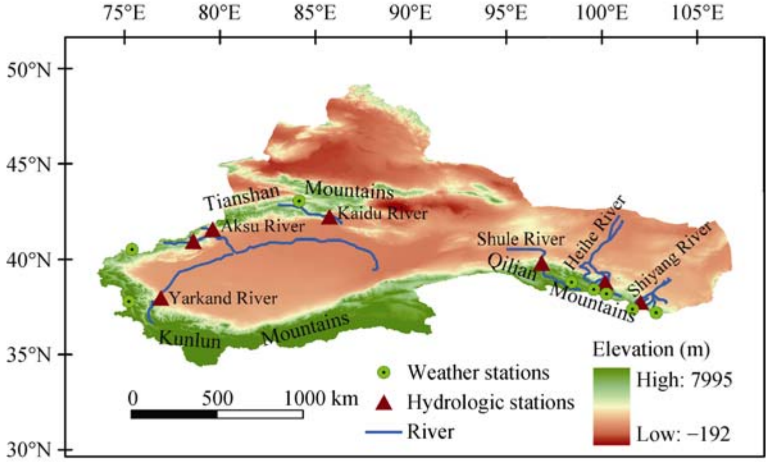

Figure 1 Location of the arid land of Northwest China and distributions of rivers, weather and hydrological stations

Immerzeel *et al*. (2010) defined the area above an elevation of 2000 m as main water supply area in Asia. This study uses weather stations at mean elevation of 3054 m, which have good representativeness and can reflect the characteristics of climate change in mountains clearly. For daily data, if one day has missing data, the average value of its neighboring days is used to replace the missing data, and no missing data of 2 consecutive days or more has occuredd, so the data has high reliability.

Annual runoffs of the 6 rivers are analyzed from 1960 to 2008 by adopting data from 7 mountain-pass hydrological stations (Kaqun, Xiehela, Shaliguilanke, Dashankou, Yingluoxia, Zamus and Changmabao). Meanwhile, the study area is divided into three sub-regions, i.e., southern Tianshan Mountains, northern Kunlun Mountains and northern Qilian Mountains. Detailed information of hydrological stations and rivers are shown in Figure 1.

Daily runoff data are from two mountain-pass hydrological stations for snowmelt period (June to October) during 1960−2007 in southern Tianshan Mountains and northern Kunlun Mountains. Therefore, we analyze the change of date of maximum daily runoff for snowmelt period of each decade in southern Tianshan Mountains and northern Kunlun Mountains. We are not able to include northern Qilian Mountains in the analysis due to lack of data.

These 8 weather stations data are selected from the National Meteorological Administration of China. The runoff data in each river are derived from local hydrologic bureau.

2.2 Methods

As is known, once the temperature is higher than 0℃, snow will melt. We refer to the calculation method of growing season (Peterson and Folland, 2000; Jiang *et al*., 2011). In this study, onset and cessation of snowmelt period are defined as the period from the beginning date, specified to be the last appearance of 5 consecutive days from April to June with the daily average temperature lower than 0℃ to the starting date, defined to be the first appearance of 5 consecutive days from August to October with the daily average temperature < 5℃ to the ending date of the snowmelt period. The length of snowmelt period was the difference between cessation and onset. In fact, glacier will melt in snowmelt period to a certain extent, but it is very difficult to determine glacier melting time. Thus, for the sake of convenience we use snowmelt period to represent glacier and snow melt period.

The sensitivity coefficients are utilized to present the sensitivity of hydrological elements to the changes in meteorological elements in the process of the effect of climate change on hydrological system (Zheng *et al.*, 2009; Ma *et al.*, 2010). This paper adopts the sensitivity analysis method proposed by Zheng *et al.* (2009) to explore the sensitivity of annual runoff to the length and temperature of snowmelt period. The formula is as follows:

$$\varepsilon = \frac{\overline{X}}{\overline{Q}} \frac{\sum (X_i - \overline{X})(Q_i - \overline{Q})}{\sum (X_i - \overline{X})^2} \tag{1}$$

where X_i denotes the meteorological element, Q_i denotes the annual runoff, ε is the sensitivity coefficient, $\overline{X}$ and $\overline{Q}$ are mean values of runoff and meteorological element over years, respectively. The physical meaning of ε is that meteorological element changed by 1% can induce runoff to change by ε%.

To quantitatively identify runoff change caused by length, temperature and precipitation changes of snowmelt period in the past 50 years, the following formula is used to calculate the change rate of runoff:

$$\phi = \frac{\Delta x}{\overline{X}} \times 100 \times \varepsilon \tag{2}$$

where ϕ is runoff change rate (%) caused by meteorological element X (snowmelt period temperature or precipitation); Δx is the change of meteorological element X.

Previous studies found that a step change point in the mean temperature of ANC basically occurred in 1987 (Chen and Xu, 2005; Zhang *et al.*, 2011), thus Δx refers to the change amount of the meteorological elements (X) (compared the period 1988−2010 with the period 1960−1987); $\overline{X}$ is mean value of meteorological element from 1960 to 1987; ε is the sensitivity coefficient of annual runoff to meteorological element X.

Linear regression and Mann-Kendall test methods are employed to analyze the changing trends and the regional differences of mountainous snowmelt periods during 1960−2010.

3 Results

3.1 Onset

During 1960−2010, mean onset of snowmelt period in the mountainous areas of Northwest China ranging from May 1 to May 31 (Figure 2a) shows an downward trend and linear tendency is −3.005d/10a ($P < 0.001$, under the Mann-Kendall test), which indicates that mountains snowmelt period has moved earlier gradually. In the past 50 years, onset of snowmelt period has shifted 15.33 days earlier.

Results from the linear regression show that in the past 50 years (Figures 2b-d), linear tendencies of onset in southern Tianshan Mountains, northern Kunlun Mountains and Qilian Mountains exhibited downward trends. All of the trends are statistically significant ($P<0.05$, under the Mann-Kendall test). Onset of snowmelt period in southern Tianshan Mountains moves 20.01 days earlier and that in northern Kunlun Mountains shifts 15.80 days earlier while that in northern Qilian Mountains moves only 10.16 days earlier.

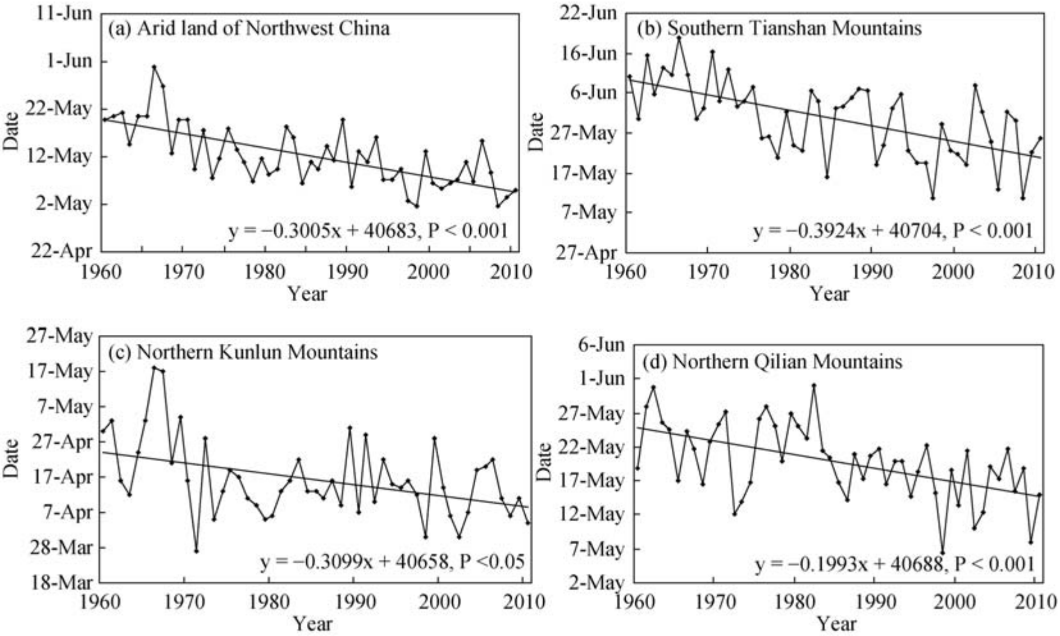

Figure 2 Time series of onset of snowmelt period and its linear trend in entire Northwest China (a), southern Tianshan Mountains (b), northern Kunlun Mountains (c), and northern Qilian Mountains (d) from 1960 to 2010

3.2 Cessation

From 1960−2010, mean cessation of snowmelt period in the mountainous areas of Northwest China, ranging from September 13 to October 2, exhibits an increasing trend with an average of 1.801 days/10a at $P < 0.001$ significance level, which indicates cessation of mountain snowmelt period moved later. In recent 51 years, the average of cessation of the mountains snowmelt period has shifted 9.19 days later (Figure 3a).

Figures 3b-d show the temporal variations of linear tendencies of cessation of snowmelt period over different areas in Northwest China for the period 1960−2010. It can be seen that all subregions of the study area have positive tendency in cessation of the snowmelt period. The cessations of snowmelt period in northern Qilian Mountains and northern Kunlun Mountains have relatively high positive tendencies and are significant at $P < 0.01$ level, and low positive tendency is observed in southern Tianshan Mountains and is not significant.

Regionally, cessations of snowmelt period in northern Qilian Mountains and northern Kunlun Mountains moved 10.48 days and 10.26 days later while that in southern Tianshan Mountains shifted only 6.81 days later.

3.3 Length

During 1960−2010, mean length of the snowmelt period ranges from 113 days to 153 days in the mountainous areas of Northwest China, with a regional average length of 131.76 days (Figure 4a). From linear tendency, the length of snowmelt period exhibits an upward trend with an increasing rate of 4.806 days/10a and its increasing trend is significant at $P < 0.001$ level. In recent 51 years, the mean length of the snowmelt period in the study area has

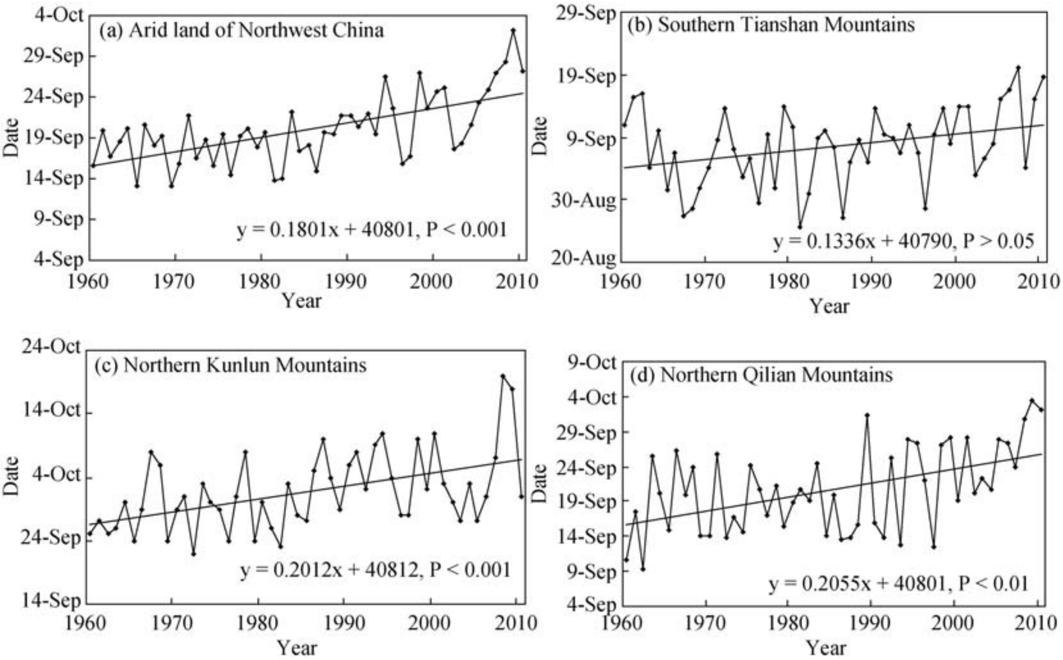

Figure 3 Time series of cessations of snowmelt period and its linear trend in entire Northwest China (a), southern Tianshan Mountains (b), northern Kunlun Mountains (c), and northern Qilian Mountains (d) from 1960 to 2010

increased by 24.5 days.

The lengths in different areas show increasing trends and all increasing trends reach significant levels (*P* <0.001), but the change range varies from region to region. The two regions, southern Tianshan Mountains and northern Kunlun Mountains, have high positive tendencies, and relatively low positive tendency is observed in northern Qilian Mountains (Figures 4b-d).

Regionally, the length of snowmelt period increased the fastest in southern Tianshan Mountains, up to 26.83 days, followed by that in northern Kunlun Mountains, increasing by 26.06 days, while that in northern Qilian Mountains increased the shortest, increasing by 20.65 days.

3.4 Temperature

3.4.1 Mean temperature

During 1960–2010, mean air temperature of snowmelt period in the mountainous areas of Northwest China exhibits an upward trend with the increasing rate of 0.168℃/10a and its increasing trend is significant at *P* < 0.001 level (Figure 5a). In recent 51 years, air temperature of snowmelt period has increased by 0.857℃, higher than the average of the entire globe (Brohan *et al.*, 2006; IPCC, 2007) for the same period.

Figures 5b-d show the temporal variations of linear tendencies of the temperature of snowmelt period over different regions for the period 1960–2010. It can be seen that all parts of the mountainous areas of Northwest China have positive tendency in temperature of snowmelt period. The northern Qilian Mountains have relatively high positive tendency, and

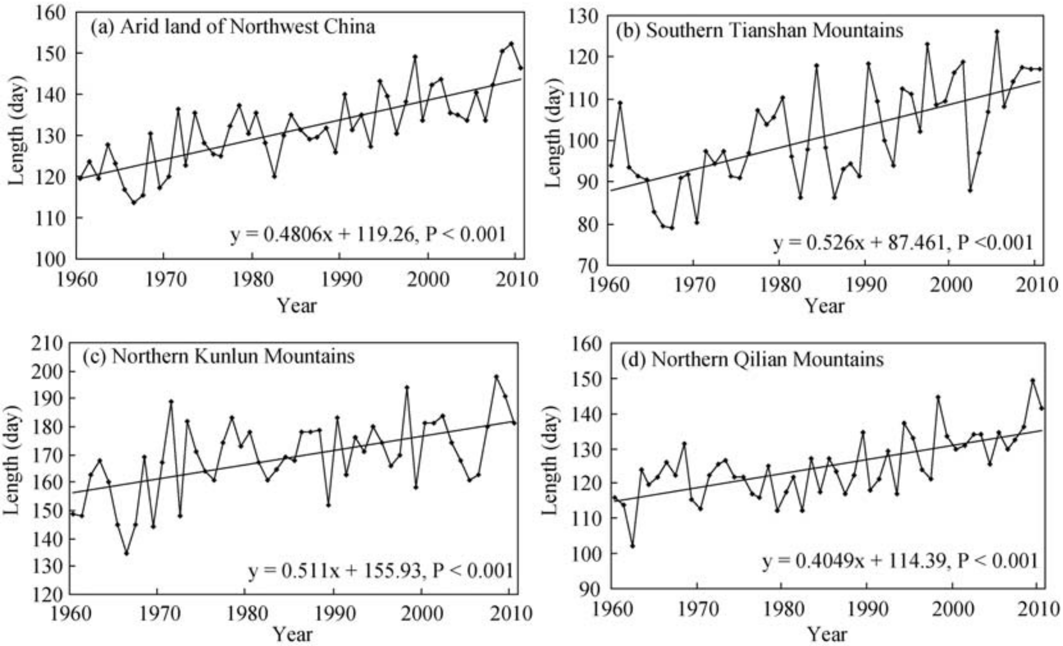

Figure 4 Time series of length of snowmelt period and its linear trend for entire Northwest China (a), southern Tianshan Mountains (b), northern Kunlun Mountains (c), and northern Qilian Mountains (d) from 1960 to 2010

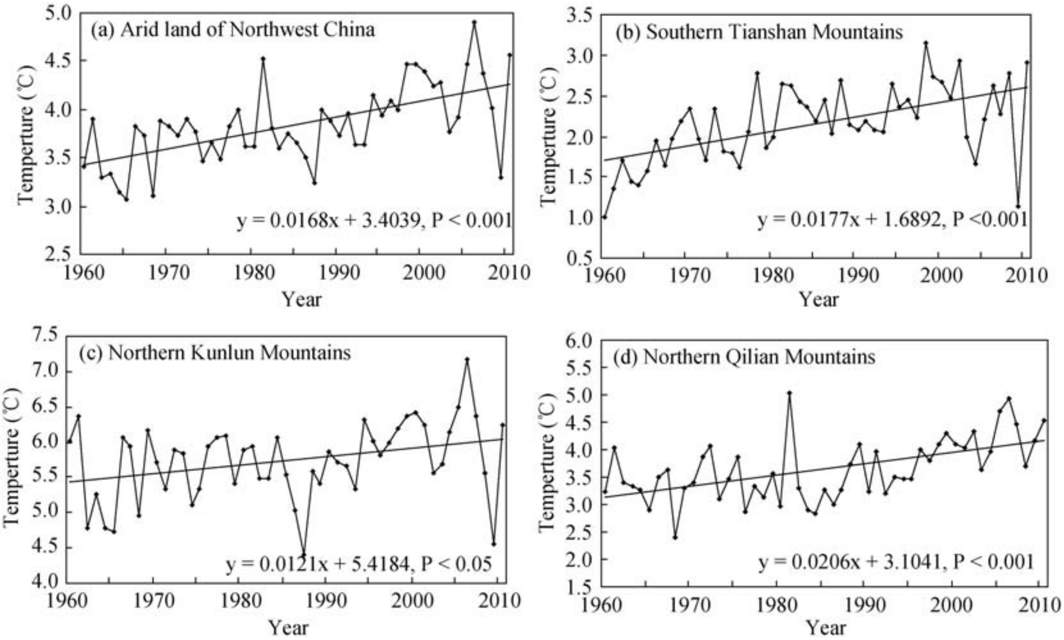

Figure 5 Time series of temperature of snowmelt period and its linear trend for entire Northwest China (a), southern Tianshan Mountains (b), northern Kunlun Mountains (c), and northern Qilian Mountains (d) from 1960 to 2010

low positive tendencies are observed in southern Tianshan Mountains and northern Kunlun Mountains. However, all of these trends are statistically significant ($P < 0.05$, under the Mann-Kendall test).

Regionally, the temperature of snowmelt period in northern Qilian Mountains increases the fastest, increasing by 1.05℃, followed by that in southern Tianshan Mountains, increasing by 0.903℃, and that in northern Kunlun Mountains increased the slowest, increasing by only 0.617℃.

3.4.2 Maximum daily temperature

Taking Aksu River and Yarkand River as objects, this paper analyzes the date change of the maximum daily mean temperature in different decades (9-day moving average). For the period 1960–2000, the date of the maximum daily temperature in Aksu River moves 22 days earlier (Figure 6). Compared with that in the 1990s, the date is delayed for 5 days for the period 2000–2010, which is basically consistent with that in the 1980s. The maximum daily temperature in Yarkand River occurs 10 days ahead in the 1960s–1980s while the date has been delayed for the period 1990–2010, however, the date for the period 2000–2010 is basically consistent with that in the 1960s.

Overall, the dates of the maximum daily temperature in the mountainous areas appear earlier in the 1970s and 1980s while the date has been delayed in the last decade.

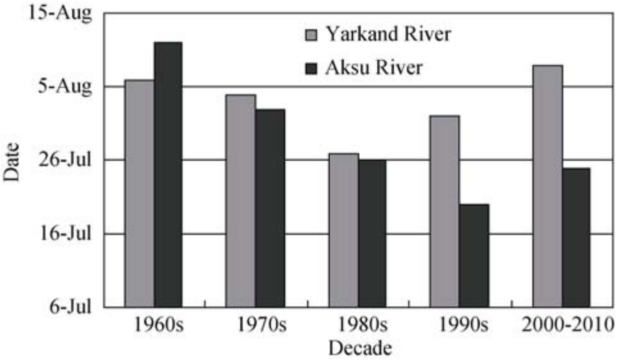

Figure 6 The date of maxima daily temperature (9-day moving mean) in each decade over Aksu River and Yarkand River

3.5 Precipitation

In the past 50 years, the mean precipitation of snowmelt period shows an increasing trend in the study area, and the linear trend is 9.27 mm/10a at $P < 0.001$ level of significance test (Figure 7a). The increase rates in precipitation in southern Tianshan and northern Qilian Mountains are higher with 12.75 mm/10a and 10.12 mm/10a, respectively, and reach the significance level ($P < 0.05$); that in northern Kunlun Mountains is lower with 4.92 mm/10a and does not reach significant level (Figures 7b-d).

3.6 Runoff

3.6.1 Maximum daily runoff

In order to reflect the date change of the maximum daily runoff clearly, this paper takes daily runoff in Aksu River and Yarkand River as objects owing to the limited daily runoff data, and then explores the dates of the maximum daily runoff in different decades (9-day moving average), as shown in Figure 8.

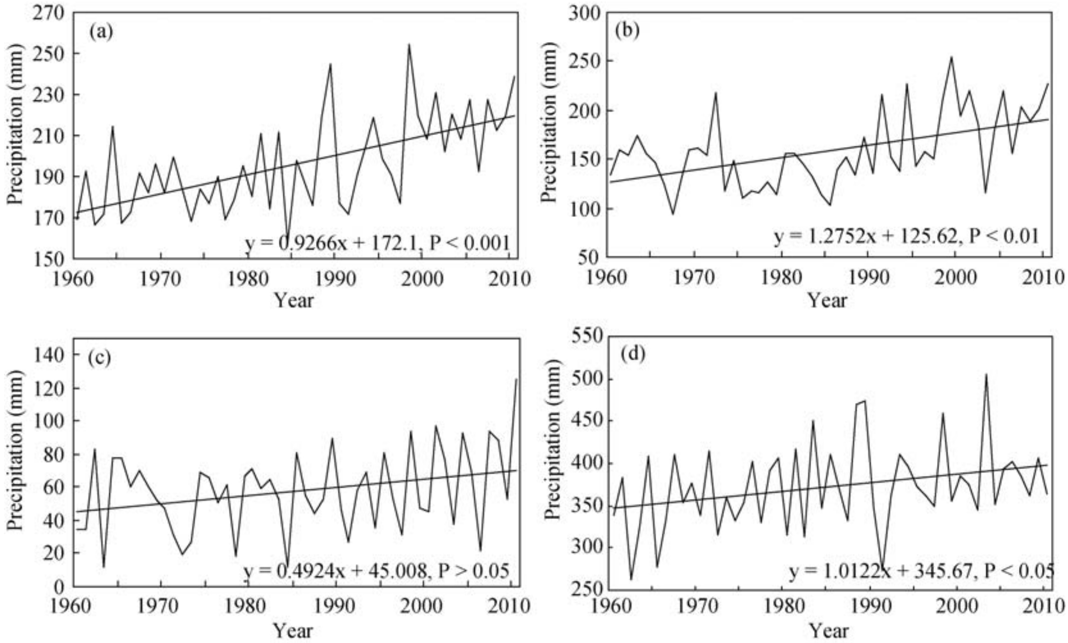

Figure 7 Time series of precipitation of the snowmelt period and its linear trend for entire Northwest China (a), southern Tianshan Mountains (b), northern Kunlun Mountains (c), and northern Qilian Mountains (d) from 1960 to 2010

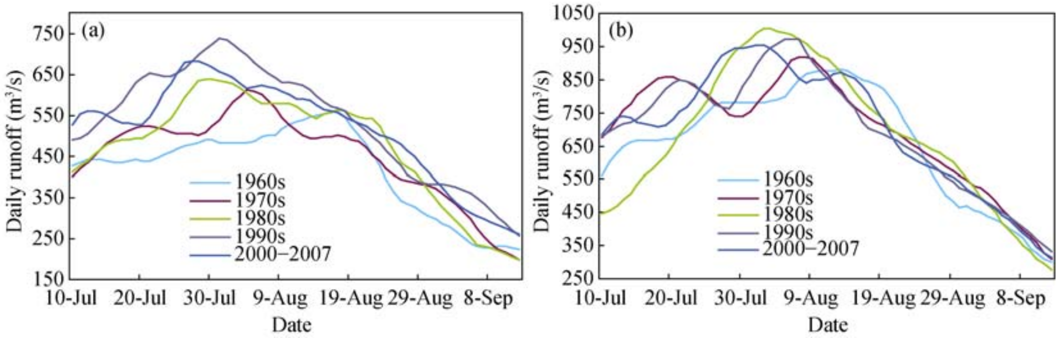

Figure 8 Time series of daily runoff (9-day moving mean) for snowmelt period in each decade over Aksu River (a) and Yarkand River (b)

In the 1960s, the maximum daily runoff in Aksu River occurs on August 17; however, it occurs on August 4 in the 1970s, earlier than in the 1960s; and then the dates of the maximum daily runoff in the 1980s, 1990s and 2000–2007 are basically consistent and appear on July 30, July 31 and July 28, respectively (Figure 8a). This indicates that the date of the maximum daily runoff in the 1970s–1980s has advanced by about 18 days while the date of the maximum daily runoff in 1980–2007 is basically stable and occurs on about July 30.

In the 1960s, 1970s, 1980s, 1990s and 2000–2007, the dates of the maximum daily runoff in Yarkand River occur on August 13, August 8, August 2, August 6 and August 1, respectively (Figure 8b). It can be seen that the dates of the maximum daily runoff in Yarkand River are basically consistent with those in Aksu River. The dates in the 1970s–1980s shift earlier in Yarkand River, but earlier date length (about 10 days) was less than that in Aksu

River; and after the 1980s, the dates remain stable in Yarkand River.

3.6.2 Annual runoff

During 1960–2008, runoff in the mountainous areas of Northwest China shows an upward trend with a mean increasing rate of 10.66×10^8 $m^3/10a$ and its trend is significant at $P <$ 0.001 level (Figure 9a).

Regionally, the maximum increasing rate of runoff reaches to 6.29×10^8 $m^3/10a$ in southern Tianshan Mountains while the minimum increasing rate of runoff is only 1.48×10^8 $m^3/10a$ in northern Qilian Mountains; meanwhile, the increasing rate of runoff in northern Kunlun Mountains comes the second, being 2.89×10^8 $m^3/10a$ (Figures 9b-d). Therefore, the increasing rates in different regions are different, which is related to not only regional climate changes but also the impact of human activities (Liu *et al*., 2011; Xu, 2011; Hu *et al*., 2012; Zhang *et al*., 2012).

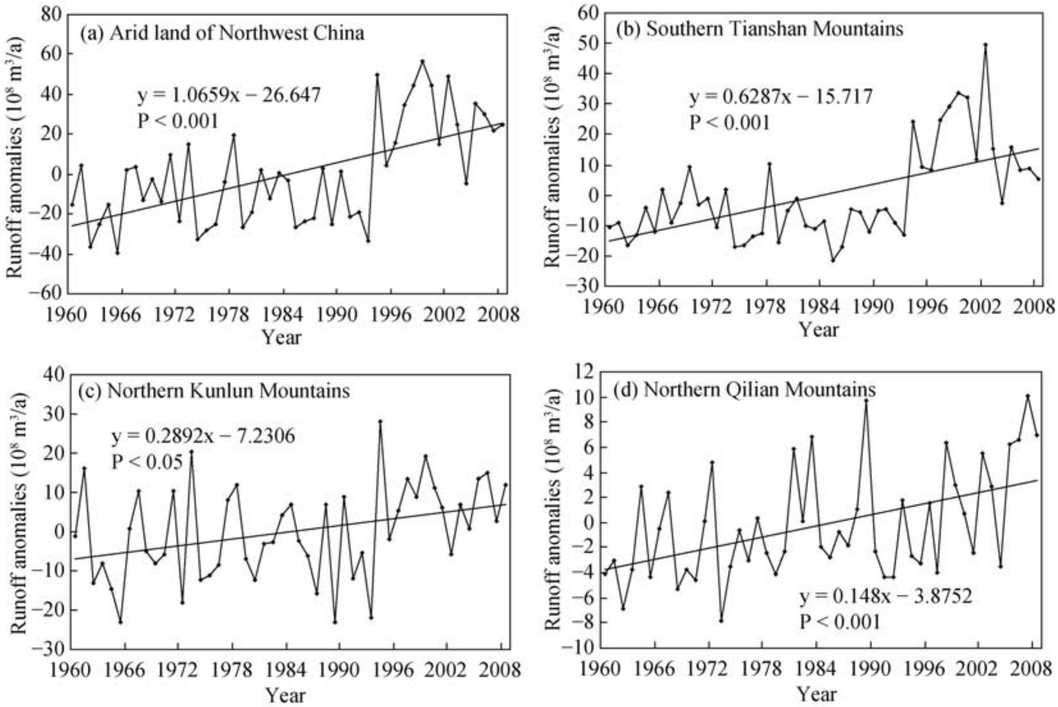

Figure 9 Time series of annual runoff and its linear trend in entire Northwest China (a), southern Tianshan Mountains (b), northern Kunlun Mountains (c), and northern Qilian Mountains (d) from 1960 to 2010

3.7 Sensitivity

3.7.1 Sensitivity coefficients of annual runoff to length and temperature

To clarify the sensitivity of runoff to climate changes, this study calculates the sensitivity coefficients of annual runoff to length and mean temperature of snowmelt period. Figure 9 shows that the sensitivity coefficients of annual runoff to snowmelt period length and temperature are 0.497 and 1.114 in the mountainous areas of Northwest China, that is to say, length of snowmelt period changed by 1% can induce annual runoff to change by 0.497% while temperature of snowmelt period changed by 1% can cause annual runoff to change by

1.114%, which also indicates the sensitivity of annual runoff to temperature of snowmelt period is greater than that to snowmelt period length.

The sensitivities of annual runoff to snowmelt period length and temperature varies from region to region (Figure 10). The sensitivity of annual runoff to snowmelt period length in northern Qilian Mountains is the highest, with the coefficient of 1.292, followed by that in northern Kunlun Mountains, with a coefficient of 0.696, and that in southern Tianshan Mountains is the lowest, with a coefficient of only 0.47. Meanwhile, temperature of snowmelt period changed by 1% can induce runoffs to change by 1.266%, 0.647% and 0.406%, respectively, in northern Kunlun Mountains, in northern Qilian Mountains and northern Tianshan Mountains. The results show that the sensitivity of annual runoff to temperature is the highest in northern Kunlun Mountains, that is because the runoff recharge proportion from glacier melt water occupies larger (more than 55%) in this region than that in the other regions (about 10%–35%) (Shi *et al.*, 2005; Chen, 2010).

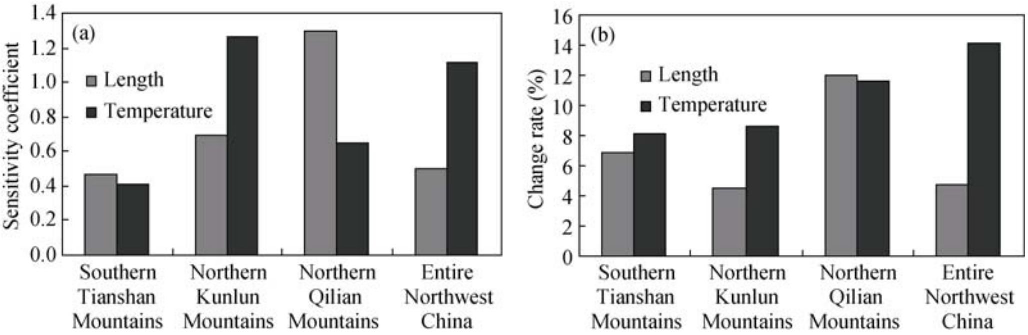

Figure 10 Sensitivity coefficients of annual runoff to the length and temperature of snowmelt period (a); the change rates of annual runoff caused by length and temperature of snowmelt period (b)

The change rates of runoff caused by length and temperature of snowmelt period in Figure 10 are calculated by using Formula (2). During 1960–2010, the mean change rate of runoff caused by the length of snowmelt period is 4.69% while the runoff change rate caused by temperature is 14.15% in the mountainous areas of Northwest China. Thus, the impact of temperature on runoff is greater than the impact of length on it.

The runoff change rates caused by snowmelt period temperature and length varies from region to region. In southern Tianshan Mountains, northern Kunlun Mountains and northern Qilian mountains, the runoff change rates caused by length are 6.89%, 4.56% and 11.96%, respectively, while those caused by temperature are 8.16%, 8.68% and 11.66%, respectively, which may be related to runoff recharge proportions from glacier and snow melt water and precipitation.

3.7.2 Sensitivity coefficients of annual runoff to precipitation

The sensitivity of average annual runoff to snowmelt rainfall in the study area is (0.518, Figure 11) obviously lower than the sensitivity of annual runoff to snowmelt temperature (1.114). Among them, the sensitivity of runoff to precipitation in northern Qilian Mountains is the strongest and the sensitivity coefficient is 0.595, followed by that in southern Tianshan Mountains with the sensitivity coefficient of 0.332, which may be related to the recharge proportion of runoff from precipitation. In addition, it is worth mentioning that the sensitivity of runoff to snowmelt rainfall in northern Kunlun Mountainous is the lowest and the sensitivity coefficient is only −0.123, which indicates the precipitation increase may lead to runoff recharge decrease. There are two possible reasons: 1) Although precipitation can recharge runoff to a certain extent, precipitation is often accompanied by cooling temperature. Owing to larger runoff recharge proportion from glaciers in northern Kunlun Mountains, the runoff recharge from precipitation may be lower than glacial melt water reduction caused by temperature decrease. 2) Because weather stations are at lower elevation and not sufficient, the selected meteorological data can not be fully representative of the climate characteristics in the mountainous area, so the results need to be further verified, and then the observation for mountain climate change should be strengthened in the future.

Average annual runoff in the mountainous area caused by change of snowmelt period precipitation changes by 7.69%. Among them, the annual runoff change in southern Tianshan Mountains caused by precipitation is the largest with a rate of 9.67%, followed by that in northern Qilian Mountains at a rate of 4.56%, and the change rate in northern Kunlun Mountains is −2.93% (Figure 11).

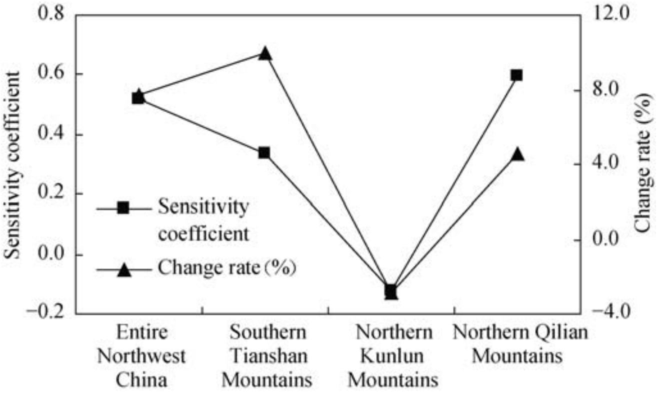

Figure 11 Sensitivity coefficients of annual runoff to precipitation of the snowmelt period and the change rates of annual runoff caused by precipitation

4 Conclusions

(1) During the period 1961−2010, the mean onset of snowmelt period in the mountainous areas of the arid land of Northwest China moves 15.33 days earlier while the average of cessation of snowmelt period shifts 9.19 days later, therefore, appropriate water management measures should be developed in water resources management.

(2) In recent 50 years, the length of snowmelt period increases by 24.5 days, and the temperature rises by 0.857℃. The largest increasing length of snowmelt period occurs in northern Tianshan Mountains with 26.83 days, while the shortest increasing length of snowmelt period is in northern Qilian Mountains with 20.65 days and the temperature rises the highest by 1.05℃, but the smallest increase is in northern Kunlun Mountains with 0.617℃.

(3) Because the runoff recharges proportions from glacier and snow melt water and precipitations in different rivers are different, the sensitivities of annual runoff in different regions to snowmelt period length, temperature and precipitation differ obviously. The strong-

est sensitivity of runoff to temperature of snowmelt period occurs in northern Kunlun Mountains with sensitivity coefficient of 1.266, where is the weakest sensitivity of runoff to precipitation, while the strongest sensitivities of runoff to snowmelt period length and to precipitation occur in northern Qilian Mountains.

(4) Snowmelt period length changed by 1% can make annual runoff change by 0.497% while temperature of snowmelt period changed by 1% can induce annual runoff to change by 1.114%. However, precipitation changed by 1% can induce annual runoff to change by 0.518%. For the period 1960–2010, snowmelt period length, temperature and precipitation changes cause annual runoff changed by 4.69%, 14.15% and 7.69%, respectively.

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