Response of the snowmelt and glacier runoff to the climate warming-up in the last 40 years in Xinjiang Autonomous Region, China*

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Abstract Some analytical results of the measured runoff during 1950s to 1980s at outlet hydrological stations of 33 main rivers and climatic data collected from 84 meteorological stations in Xinjiang Autonomous Region are presented. Comparison of hydrological and climatic parameters before and after 1980 shows that the spring runoff for most rivers after 1980s increased obviously at a rate of about 10%, though the spring air temperature did not rise very much. Especially, an increment by 20% for alpine runoff is observed during May when intensive snow melting occurred in the alpine region. To the contrary, the runoff in June decreased about 5%. When the summer or annual runoff is taken into account, direct relationship can be found between the change in runoff and the ratio of glacier-coverage, except the runoff in August when the glacier melting is strong, indicating that climatic warming has an obvious effect on the contribution of glacier melting to the runoff increase.

Keywords: **climate change, snowmelt and glacier runoff, response.**

The influence of climate change on runoff process plays an important role in the research of global change, and the snowmelt and glacier runoff are an important topic in this realm because of their high sensitivity to climate change[1].

The snowmelt and glacier runoff are relatively abundant in the northwest of China. Some studies have been conducted to reveal the response of glacier runoff to climatic change, especially the relationship between changes in annual runoff, air temperature, precipitation and the glaciers variations in the last 30 years[2]. However, the seasonal runoff change was poorly investigated. Because the snowmelt and glacier runoff emerge within a special period in the year, the influence of climate change on runoff cannot be demonstrated clearly by using its annual change. Through comparison of changes in runoff, air temperature and precipitation during various periods (yearly, monthly and seasonally), some features of snowmelt and glacier runoff responding to climatic warming in Xinjiang Autonomous Region in the last 40 years are analyzed in this paper.

1 Data and method

A majority of the data used in this paper are the monthly air temperature and precipitation collected from 84 meteorological stations, 9 hydrological stations and rainfall gauges in Xinjiang

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Autonomous Region. The monthly runoff at outlet runoff stations for 33 main rivers with a long observational sequence were adopted. The distribution of all stations is shown in fig. 1. The datum duration was from 1956—1989, except for a few stations that were set up after 1956.

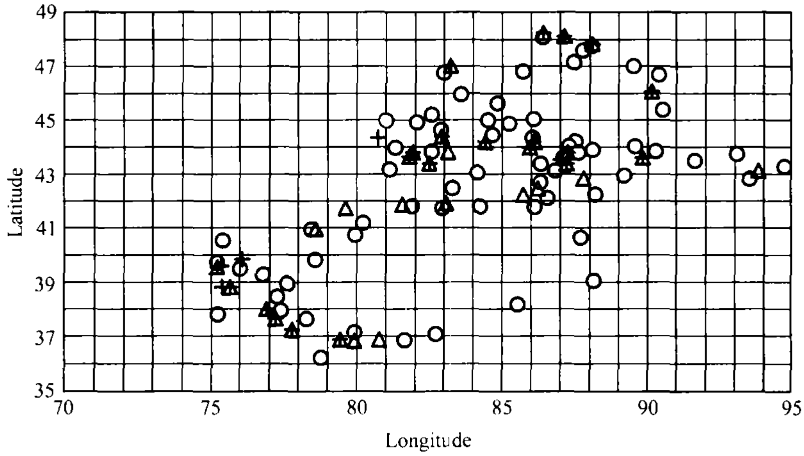

Fig. 1. The distribution of the hydrological and meteorological stations. ○, Meteoreological station; +, Rainfall station; △, Hydrological station.

Generally, the response of runoff to climatic warming at the regional scale could be analyzed either by the trend method[3] or by the comparison of the changes of each characteristic parameter in various periods[4]. The latter method was utilized in this paper.

There was a climate jump in 1973 according to the meteorological data in the last 40 years in Xinjiang region. The 1980s saw the more obvious climatic warming[5]. In order to demonstrate the impact of climatic warming on runoff, the last 40 years were divided into two periods, namely 1980—1989 and 1956—1979. Similarly, stations in the mountainous and plain areas (< 1 500 m a.s.l.) are treated separately. Stations with an elevation higher than 3 000 m a.s.l. are not considered because of their sparse distribution. The changes in air temperature, precipitation and runoff during the two periods were compared.

2 Changes in air temperature, precipitation and runoff

2.1 Changes of mean annual air temperature, precipitation and runoff

A comparison of the data of 1980s with those of 1960s—1970s in the region shows that (table 1): (i) the mean annual air temperature (T_a) rose by 0.38℃; (ii) the mean annual precipitation (P_a) increased by 8.4%; (iii) the mean annual runoff (R_a) decreased by 0.5%. Considering the latitude effect, there is a larger difference in the change of annual precipitation and mean air temperature at the stations below 1 500 m a.s.l. For stations above 1 500 m a.s.l. the average changes in annual precipitation and mean air temperature were smaller than that in plain. In fact, the magnitude of increases in air temperature and precipitation declined obviously with the increase in elevation. However, the runoff increased in alpine regions, but decreased at plain stations while precipitation increased. The reason comes from the regulation effect of glaciers in response to a slighter rising of air temperature in alpine regions. Therefore, the climate in alpine regions was relatively stable. Consequently, the runoff at river outlet experienced small changes. Because changes of annual runoff depended primarily on changes in annual precipitation, there was not an obvious relation between runoff change and the ratio of glacier coverage (table 2). The changes in runoff, precipitation and air temperature correlated well with latitude. Sound warming was found at higher latitude which was consistent with the global changing pattern[1]. The change in precipitation was complicated ,vithout a unified pattern. In Xinjiang there was a larger difference in precipitation within 36°—43°N (South Xinjiang), but slight within 43°—49°N (North Xinjiang). The runoff changes were similar to that of precipitation, which had a little declination with the increase of latitude, i.e. increasing in South Xinjiang, but decreasing in North Xinjiang.

Table 1 The change of T_a, P_a and R_a in 1980s compared with that of 1960s—1970s

	Region	> 3 000 m a.s.l.	> 1 500 m a.s.l.	< 1 500 m a.s.l.	All
R_a	number of stations		10	23	33
	average of elevation/m		1 835	1 029	1 281
	change(%)		2.09	-1.6	-0.45
P_a	nnumber of stations	4	24	69	93
	average of elevation/m	3 532	2 168	864	1 108
	change(%)	2.7	6.6	9.0	8.4
T_a	number of stations	4	14	70	84
	average of elevation/m	3 533	2 392	852	1 109
	change(%)	0.1	0.11	0.43	0.38

Table 2 The correlation between R_a, T_a, P_a and station location

	Number of stations	Latitude	Longitude	Elevation	Glacier covering ratio
R_a	36	-0.37	-0.15	-0.03	0.08
P_a	93	-0.34	-0.09	-0.12	
T_a	85	0.46	0.11	-0.46	

2.2 Seasonal changes in air temperature, precipitation and runoff

Climate change has effect not only on the annual runoff, but also on its temporal distribution, especially for rivers with a large snowmelt and glacier supplement, which could be elucidated by the seasonal change of runoff in the last 40 years[6] (tables 3 and 4).

Table 3 The average change of seasonal hydrological and meteorological characters

	Season	> 3 000 m a.s.l	> 1 500 m a.s.l	< 1 500 m a.s.l	All
Runoff(%)	winter		6.7	-2.8	0.4
	spring		16.0	8.5	10.9
	summer		0.1	-4.4	-3.0
	autumn		-8.0	-3.1	-2.4
Precipitation(%)	winter	13.4	-6.7	-25.1	-20.9
	spring	-14.3	0.3	5.7	4.3
	summer	10.6	10.5	9.0	9.4
	autumn	11.4	21.4	33.0	30.0
Temperature/℃	winter	0.2	0.16	1.07	0.92
	spring	-0.03	-0.14	0.06	0.03
	summer	0.0	0.14	0.07	0.30
	autumn	0.18	0.14	0.30	0.28

Table 4 The correlation between station location and hydrological and meteorological seasonal characters

	Season	Latitude	Longitude	Elevation	Glacier covering ratio
Runoff(%)	winter	-0.32	-0.13	-0.20	0.09
	rpring	-0.43	-0.29	-0.13	0.19
	summer	-0.35	-0.19	0.13	0.23
	autumn	-0.22	-0.03	-0.22	-0.04
Precipitation(%)	winter	0.45	0.14	0.07	
	spring	-0.16	0.20	-0.07	
	summer	-0.53	-0.38	0.11	
	autumn	-0.10	0.19	-0.22	
Temperature/℃	winter	0.24	-0.10	-0.42	
	spring	0.24	0.06	-0.29	
	summer	0.21	-0.01	-0.06	
	autumn	0.54	0.30	-0.37	

2.2.1 Air temperature. The change of air temperature was very obvious, and the air temperaturerising in winter (up to 0.9℃) contributed greatly to the rising annual air temperature. In various seasons, the air temperature rising had a positive correlation with the latitude, especially in Autumn. This kind of climate change coincided with that of the global pattern[1]. Comparison of the air temperature between alpine and plain areas showed that the temperature rising in autumn and winter was smaller in alpine than that in plain. However, in summer it was inverse and in spring the air temperature in alpine even decreased.

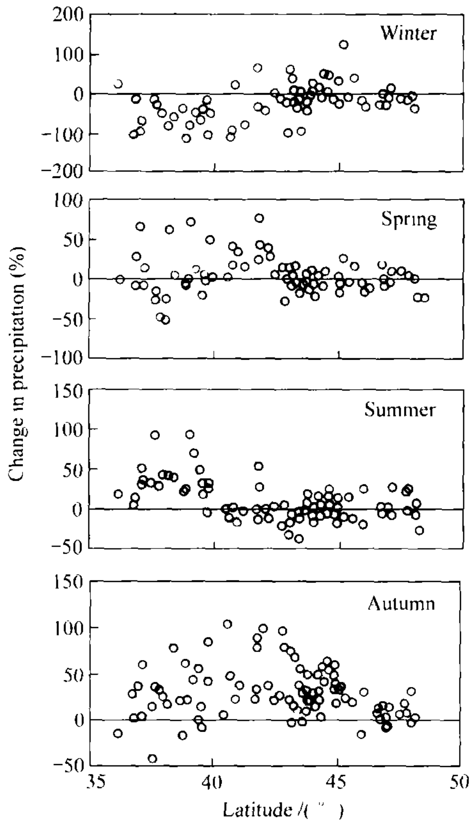

Fig. 2. The change of seasonal precipitation.

2.2.2 Precipitation. The mean seasonal precipitation increased in three seasons, obviously in autumn, except winter regardless of the latitude. In winter and summer, the change in precipitation had a strong relationship with the latitude, but the tendency was inverse. In the South Xinjiang, both the increase in summer and the decrease in winter were great (fig. 2). However, we could not judge whether it was the changing tendency of the precipitation under the condition of climate warming in this region.

2.2.3 Runoff. The runoff increased significantly in spring by an average value of about 10% in the 1980s compared with that of 20 years before. The runoff in spring still increased notably although the increase of air temperature in spring was not obvious. This is due to the following facts: (i) the increase of snow precipitation in the previous autumn provided more melting snow in spring, and (ii) at the same time, climatic warming advanced the snow-melting process in drainage basins, which was completely consistent with the numerical results of the relevant models for changing trend[7,8]. In all seasons, the change in the runoff was inversely related to the latitude; runoff change in spring was the most pronounced. Viewed from seasonal change in the runoff, there was no obvious correlation between the runoff change and glacier covering in alpine, but the correlation coefficient was the highest in summer when the glacier runoff supply was most abundant.

2.3 Monthly change in air temperature, precipitation and runoff

Because the snowmelt and glacier runoff supplies rivers with water in a very short period and the current magnitude of climate warming was relatively slight, it was not suitable to describe the change of the runoff by annually or seasonally averaged value. So, it was necessary to do analysis by means of the mean monthly change in runoff. Table 5 shows the changes in runoff, precipitation and temperature in 1980—1989 versus 1956—1979.

2.3.1 Change in mean monthly air temperature. The monthly change was not regular. Except in winter, the temperature increased and decreased alternatively in other seasons with a random pattern.

Table 5 The change of monthly mean runoff, precipitation and air temperature in 1980s compared with that of 1960s—1970s

	Region	elevation	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
R(%)	>1 500	1 835	8.40	7.85	1.60	-1.31	26.15	-6.33	0.88	2.37	-1.79	0.62	2.01	5.7
	<1 500	1 029	-0.52	-1.81	-5.61	-6.77	19.09	-5.12	-2.90	-6.62	-3.29	-2.09	-3.85	-2.78
	all	1 281	2.27	1.21	-3.36	-5.07	21.29	-5.50	-1.72	-3.81	-2.82	-1.24	-2.02	-0.13
P(%)	>3 000	3 532	-0.60	0.35	0.75	-0.70	-3.80	-1.60	-0.50	-0.90	-0.30	3.58	0.53	0.68
	>1 500	2 174	-0.60	-0.39	0.08	1.11	-0.53	3.62	-0.95	-1.94	3.62	4.83	0.53	0.25
	<1 500	837	-0.74	-0.88	-2.49	-0.95	2.91	4.24	-1.82	-0.87	2.93	3.77	1.20	-0.32
	all	1 216	-0.71	-0.75	-1.82	-0.42	2.02	4.08	-1.60	-1.15	3.11	4.04	1.03	-0.18
T/℃	>3 000	3 533	0.13	0.35	-0.08	-0.53	0.50	-0.43	0.13	0.35	-0.15	-0.08	0.85	0.25
	>1 500	2 392	0.43	0.04	-0.53	-0.26	0.38	-0.41	0.34	0.50	0.17	-0.18	0.48	0.39
	<1 500	852	1.83	0.90	-0.24	0.07	0.36	-0.51	0.24	0.49	0.20	0.04	0.67	1.08
	all	1 109	1.60	0.76	-0.29	0.01	0.36	-0.49	0.26	0.49	0.19	0.00	0.64	0.96

R, runoff; *P*, precipitation; *T*, temperature.

2.3.2 Change in mean monthly precipitation. Except in spring, precipitation variations in other seasons were similar. In June, August and October, the precipitation increase was great.

2.3.3 Change in mean monthly runoff. The river runoff in Xinjiang depends mainly on the snowmelt and glacier runoff, and in addition only a few stations were set up in alpine area. As a result, there was not a responding correction between mean monthly runoff and the precipitation, but the variation of the snowmelt and the glacier runoff changes following the air temperature fluctuation is obviously reflected in mean monthly runoff.

Through considering the monthly change of runoff for seven typical rivers (fig. 3), it is shown that the runoff increased greatly in May and decreased in June. Similar situations prevail in the whole Xinjiang area (fig. 4), and could be explained by means of the large snowmelt supply when the air temperature rises in May, and the decay of glacier covering ratio after June.

The average elevation of the selected hydrological stations is about 1 300 m a.s.l., while the drainage basins mean elevation is about 2 500—3 000 m a.s.l. Fig. 5 presents the changing processes of mean snow depth in 1981—1996 at four meteorological stations (Xinyuan, Zhaosu, Xiaoquzi and Daxigou). The snow melting started from mid-February (for 929 m a.s.l.) to mid-April (for 3 540 m a.s.l.), and ended correspondingly from mid-March to mid-July. So the supply dura-

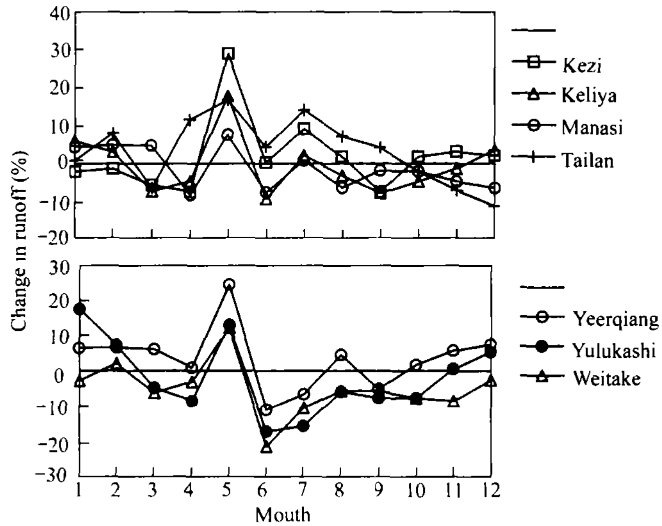

Fig. 3. The change of monthly runoff in seven typical rivers.

tion of snowmelt was within May—June. In May, the air temperature rose notably leading to an increase in snow-melting runoff; however, in June, as the time for snow ablation and disappearance moved up, snow-melting supply decreased and therefore runoff decreased, even though precipitation increased, which was more obvious for high elevation and large glacier-covered areas (table 5 and fig. 4). The river runoff in Xinjiang increased obviously only in May. But the runoff in some alpine areas in the northwest U.S.A. increase not only in spring (February—May), but also in October[4]. The reason for this difference lies mainly in the different supplying types of rivers, as well as difference in climate. Rivers in Xinjiang have a relatively small amount of snow-melting supply, while the alpine rivers in the northwest U.S.A. are basically dependenct on precipitation in winter. In conclusion, the amount of snow-melting supply determines a river's response to climatic warming.

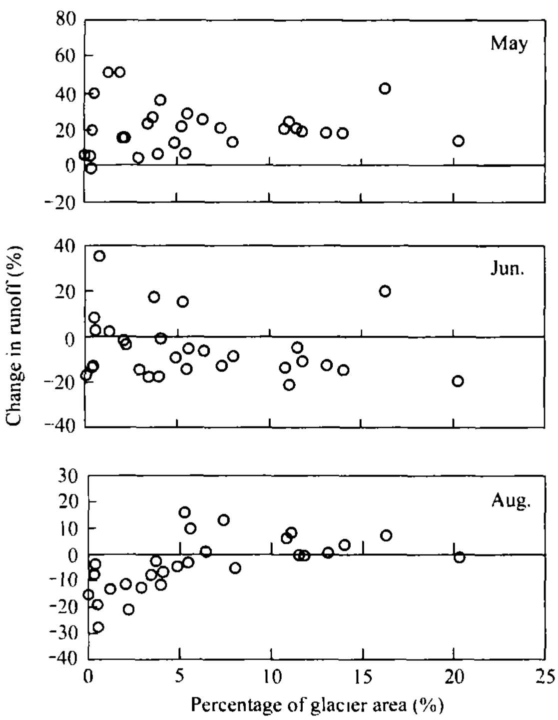

Fig. 4. The relationship between runoff in May, June and August and glacier covering.

From June to August glaciers supply water to river runoff. July and August especially the latter were the time when glaciers ablated most heavily and the air temperature increased by 0.3—0.5℃ which leaded to an increase in runoff, although precipitation decreased at the same time. In August, the change in river runoff had a strong positive correlation with the ratio of glacier coverage, which further showed the increase tendency of glacier runoff and its modulation effect on runoff under the

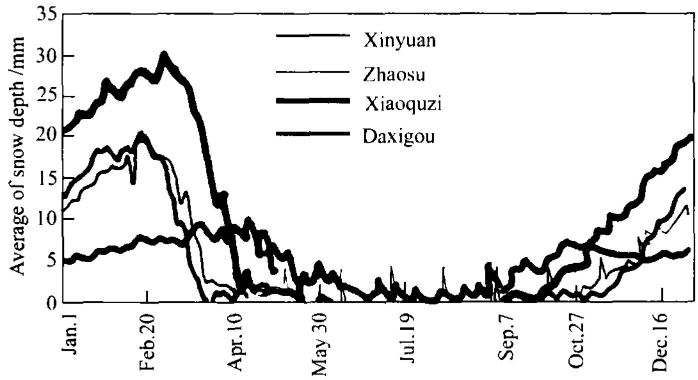

Fig. 5. Annual change of mean snow depth at four meteorological stations at various elevations in Tianshan region during 1981—1996.

condition of climate warming, i.e. glaciers can weaken and alleviate the disadvantageous effect of climate warming on river runoff.

3 Summary and discussion

Through comparison of the changes in air temperature, precipitation and runoff between 1980—1989 and 1956—1979, some preliminary results could be obtained as follows:

(1) The changes in air temperature and precipitation were greater at low elevation alpine area than at medium and high elevation alpine areas, which reflects the relative stability of climate in alpine regions.

(2) In the 1980s the air temperature had an obvious rise, especially in winter, temperature rise has a positive correlation with latitude. As for changes in precipitation, it increased commonly. In winter and summer, precipitation changes with latitude, with a positive correlation in winter and negative in summer.

(3) In spring, especially in May, air temperature increased, which enhanced and shortened snow melting processes. As a result, runoff increased by 20% in May and decreased in June, although precipitation increased in this month.

(4) Glacial ablation was most strenuous in August and there was a good correlation between the change in runoff and the ratio of glacier coverage. In this period the glacial ablation enhanced, as the air temperature rose obviously (up to 0.5℃). As a result, the alpine runoff still increased with decreasing precipitation in August, which reflects the significant modulation effect of glacier on river runoff.

Due to different geographical locations and surfaces conditions of drainage basins, lack of data for alpine regions, the complexity in the runoff formation processes of snowmelt, glacier and rain runoffs as well as the interaction among them, it is hard to make a quantitative estimation of snowmelt and glacial runoff change caused by climatic warming. Further work will be necessary.

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