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Glacier area variation and climate change in the Chinese Tianshan Mountains since 1960

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Abstract: Based on the statistics of glacier area variation measured in the Chinese Tianshan Mountains since 1960, the response of glacier area variation to climate change is discussed systematically. As a result, the total area of the glaciers has been reduced by 11.5% in the past 50 years, which is a weighted percentage according to the glacier area variations of 10 drainage basins separated by the Glacier Inventory of China (GIC). The annual percentage of area changes (APAC) of glaciers in the Chinese Tianshan Mountains is 0.31% after the standardization of the study period. The APAC varies widely for different drainage basins, but the glaciers are in a state of rapid retreat, generally. According to the 14 meteorological stations in the Chinese Tianshan Mountains, both the temperature and precipitation display a marked increasing tendency from 1960 to 2009 at a rate of 0.34℃·(10a)$^{-1}$ and 11 mm·(10a)$^{-1}$, respectively. The temperature in the dry seasons (from November to March) increases rapidly at a rate of 0.46℃·(10a)$^{-1}$, but the precipitation grows slowly at 2.3 mm·(10a)$^{-1}$. While the temperature in the wet seasons (from April to October) grows at a rate of 0.25℃·(10a)$^{-1}$, but the precipitation increases at 8.7 mm·(10a)$^{-1}$. The annual and seasonal climatic trends accelerate the retreat of glaciers.

Keywords: Chinese Tianshan Mountains; glacier area; climate change; temperature; precipitation

1 Introduction

The Tianshan Mountains, which runs through China, Kirgizstan and Kazakhstan in Central Asia, and with its 15953 glaciers having a total area of 15416 km^2 (Liu, 1995; Shi, 2008),

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has attracted a large amount of attention for climate change research during the past decades (Li *et al*., 2006; Aizen *et al*., 2006; Bolch, 2007; Kutuzov *et al*., 2009; Narama *et al*., 2010). With global warming, most mountain glaciers, including those in Tianshan Mountains, are in a state of rapid retreat (Haeberli *et al*., 2007; Hoelzle *et al*., 2007; Wu *et al*., 2008; Li *et al*., 2009; Bolch *et al*., 2010; Nie *et al*., 2010). There are 9035 glaciers in the Chinese Tianshan Mountains, with an area of 9225 km^2 and a volume of 1011 km^3 (Shi, 2008). Glacier variation has been noticed since the early comprehensive field survey on glaciers in 1958 (Ren, 1988), but long-term observation on glacier variation, as well as the relationship between climate change and glacier variation, has been limited, except for those on Glacier No.1 at the headwaters of Urumqi River (Li *et al*., 2003). On the basis of observation data during 1958–1988, Ren (1988) presented a preliminary discussion on glacier fluctuation and its relation to the climate changes in the Chinese Tianshan Mountains. With the development of Geographic Information System (GIS) and Remote Sensing (RS), abundant information about glacier fluctuation has been acquirable (Ding *et al*., 2006; Li *et al*., 2010a). Based on high-resolution remote sensing images taken at different times and hameochronous meteorological data, many scientists have focused on regional glacier variation and climate change (Wang *et al*., 2009; Yao *et al*., 2009).

According to the Glacier Inventory of China (GIC), the Chinese Tianshan Mountains can be subdivided into the following four 2nd-grade drainage basins: Balchas (Balkhash), Tarim, Junggar, and Turpan-Hami internal drainages. Most research on glacier change in the Chinese Tianshan Mountains has been carried out at the Tarim and the Junggar internal drainages, but the sensitivity of glacier systems to climate warming varies in different areas (Wang *et al*., 2008b). Many case studies on glacier change in the Chinese Tianshan Mountains exist; however, we still have no systematic knowledge of glacier variation in the Chinese Tianshan Mountains according to the warming and wetting climate. In this paper, we present a comprehensive analysis of glacier variation in the Chinese Tianshan Mountains since 1960, and a discussion on the response of glacier area variation to climate change.

2 Data processing

2.1 Glacier area data

Observations on several typical glaciers in the Chinese Tianshan Mountains indicated that glacier area variation can reflect climate change (Li *et al*., 2003; Yao *et al*., 2009; Wang *et al*., 2008b). In this study, we collected related references on glacier area variation in the Chinese Tianshan Mountains since 1960, from a total of about 3000 glaciers (Table 1 and Figure 1). Discussion on glacier area variation with the data sources at different spatial and temporal scales is helpful for estimating the large-scale glacier variation, in spite of its limitations (Ren, 1988; Hu, 2004; Ding *et al*., 2006; Li *et al*., 2010a).

The state of glacier area variation should be standardized into a comparable quantity before further statistical analysis. Annual percentages of area changes (APAC) are applied in this paper, which is commonly used in glacier area variation comparison for different spatial and temporal scales (Nie *et al*., 2010; Ding *et al*., 2006; Wang *et al*., 2008a). The APAC is defined as follows:

$$\mathrm{APAC} = \frac{\Delta S}{S_0 \Delta t} \quad (1)$$

Table 1 Data sources of glacier area variation in the Chinese Tianshan Mountains

2nd-grade drainage basin*	3rd-grade drainage basin	Study region in references
Balchas internal drainages (5X0)**	Ili River (5X04)	Kax River (Liu *et al*., 1999) and Kuksu River (Li *et al*., 2010a)
Tarim internal drainages (5Y6)	Aksu River (5Y67)	Aksu River (Liu *et al*., 2006; Li *et al*., 2010a)
	Ogan River (5Y68)	Tugebieliqi Glacier (Yao *et al*., 2009)
	Kaidu River (5Y69)	Kaidu River (Liu *et al*., 2006; Li *et al*., 2006)
Junggar internal drainages (5Y7)	Yiwu River (5Y71)	Northern slope of Karlik Range (Wang *et al*., 2009)
	Baiyang River (5Y72)	Northern slope of Bogda Range (Li *et al*., 2010a)
	Manas River (5Y73)	Urumqi River (Kang, 1996; Chen *et al*., 1996; Li *et al*., 2010a), Toutun River (Li *et al*., 2010a; Kang, 1996), Santun River (Kang, 1996), and Hutubi River (Kang, 1996)
	Ebinur Lake (5Y74)	Kuytun River (Li *et al*., 2010a) and Sikeshu River (Liu *et al*., 1999)
Turpan-Hami internal drainages (5Y8)	Aydingkol Lake (5Y81)	Southern slope of Bogda Range (Li *et al*., 2010a)
	Miaoer Gully (5Y82)	Southern slope of Karlik Range (Wang *et al*., 2009)

Note: * Drainage basin ID number in Glacier Inventory of China is attached in the parentheses.

** There is only one 3rd-grade drainage basin (Ili River, 5X04) in the Balchas internal drainages (5X0), so sometimes Balchas internal drainages is replaced by Ili River (Basin) in expressing, such as Hu, 2004.

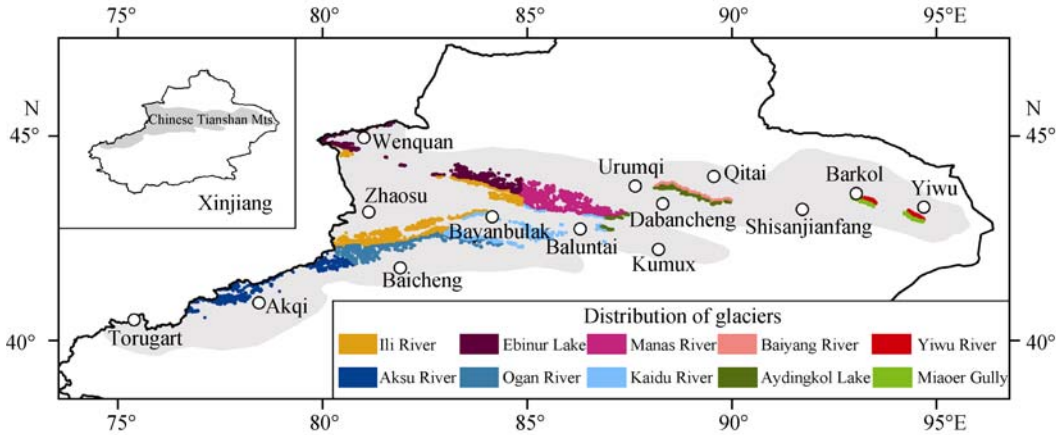

Figure 1 Distribution of glaciers and meteorological stations in the Chinese Tianshan Mountains

where ΔS is the variation of glacier area (km^2), S_0 is the glacier area at the initial status (km^2), and Δt is the number of years (a).

Glaciers are not evenly distributed in different drainage basins, so the arithmetic mean value may enlarge the weight of some drainage basins with fewer glaciers. An area-based weighted method is considered in this study. The number of 3rd-grade drainage basins in this study is i, and there are j sections of references for each 3rd-grade drainage basin (i, j=1, 2, 3…). The glacier area at the initial status is S_{0ij}, variation of glacier area is ΔS_{ij}, the number of years is Δt_{ij}, and the initial year is t_{0ij}. If we ignore the difference of study periods among these references, the percentage of glacier area variation in the Chinese Tianshan Mountains is

$$\frac{\Delta S}{S_0}=\sum_{i=0}^{n}\left(\frac{S'_i}{S'}\frac{\sum_{j=0}^{n}\Delta S_{ij}}{\sum_{j=0}^{n}S_{0ij}}\right) \tag{2}$$

where S'_i is the true area of glaciers in the drainage basin, and S' is the area of glaciers in the Chinese Tianshan Mountains. Both S'_i and S' are acquired from the World Glacier Inventory (WGI), provided by the website of National Snow and Ice Data Center (NSIDC) of USA (http://nsidc.org/data/glacier_inventory/browse.html). In its database, the glaciers in the Chinese Tianshan Mountains belong to two regions: the "Pamirs/Tianshan" and the "Tarim Basin" in Central Asia.

If the variation of glacier area per unit time for every single reference remains stable, we can unify the study period by interpolation. From the year of 1960 to the year of T ($1960 < T < 2010$, but $1990 \leqslant T \leqslant 2006$ is recommended), the percentage of glacier area variation is

$$\frac{\Delta S}{S_0}=\sum_{i=0}^{n}\left\{\frac{S'_i}{S'}\frac{\sum_{j=0}^{n}[\frac{\Delta S_{ij}}{\Delta t_{ij}}(T-1960)]}{\sum_{j=0}^{n}[S_{0ij}+\frac{\Delta S_{ij}}{\Delta t_{ij}}(t_{0ij}-1960)]}\right\} \tag{3}$$

Then the APAC is

$$\text{APAC}=\sum_{i=0}^{n}\left\{\frac{S'_i}{S'}\frac{\sum_{j=0}^{n}\frac{\Delta S_{ij}}{\Delta t_{ij}}}{\sum_{j=0}^{n}[S_{0ij}+\frac{\Delta S_{ij}}{\Delta t_{ij}}(t_{0ij}-1960)]}\right\} \tag{4}$$

It may be said here that the APAC in formula (4) is a constant value, because of its supposition above.

2.2 Meteorological data

The temperature and precipitation data during 1960–2009 in the Chinese Tianshan Mountains are provided by China Meteorological Date Sharing Service System, which is administered by National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). According to the ridge line of the Tianshan Mountains in China (Hu, 2004), 14 meteorological stations were chosen in this study: Wenquan, Qitai, Zhaosu, Urumqi, Baluntai, Dabancheng, Shisanjianfang, Kumux, Bayanbulak, Baicheng, Torugart, Akqi, Barkol and Yiwu (Figure 1).

Single-element regression was applied in analyzing the linear trend of temperature and precipitation. Space interpolation was used for computing the spatial distribution of the climate trend, which was managed in ArcGIS 9.2 with Inverse Distance Weighted (IDW). This multiple method of single-element regression and space interpolation is widely used in mountain climatic research, such as applied to the Qilian Mountain (Jia *et al.*, 2008), Hengduan Mountains (Li *et al.*, 2010b), etc.

3 Results

3.1 General situation of glacier area variation

The computation of the glacier area variation for all the glaciers in the Chinese Tianshan Mountains presents prohibitive logistical difficulties, because of the huge number and area of glaciers. In previous studies, scientists have estimated the glacier area variation according to the selected glaciers. 960 glaciers in the Chinese Tianshan Mountains were studied, and it was found that the total area was reduced by 4.7% (slightly higher than the mean percentage of West China, 4.5%), in the past 30–40 years starting from the 1960s (Ding *et al*., 2006). Li *et al*. (2010a) recently researched 1800 glaciers in Xinjiang (1543 glacier in the Chinese Tianshan Mountains), and the total area was reduced by 11.7% starting from the 1960s/1970s to the 2000s.

So, in this study, we weighted the data according to the glacier area of ten drainage basins. The result indicated that the total area of glaciers in the Chinese Tianshan Mountains was reduced by 11.5% in the past five decades. With the assumption that the variation of glacier area per unit time for every single reference remains stable, the APAC has been 0.31% a^{-1} since 1960.

3.2 Spatial distribution of glacier area variation

In order to investigate the spatial distribution of glacier area variation in the Chinese Tianshan Mountains, we calculated the APAC for every reference, and sorted them into ten drainage basins (Figure 2). Research of Liu *et al*. (1999) indicated that the west section of the Chinese Tianshan Mountains belongs to an active glacier zone (APAC=0.19%), and the Junggar and the Turpan-Hami internal drainages belong to a less active glacier zone (APAC=0.15%). According to the APAC, Ding *et al*. (2006) classified the glaciers in West China into three groups by the boundaries of 0.1% a^{-1} and 0.2% a^{-1}. However, the APAC in recent research has been much more than 0.2% a^{-1}, as shown in Figure 2. The glaciers in the Chinese Tianshan Mountains are in a state of rapid retreat, so the APAC is related with the monitoring period. Generally, the APAC has been higher in recent measurements than that in earlier measurements, which is evidenced by research in the Ili River Basin (Liu *et al*., 1999; Li *et al*., 2010a), the Ebinur Lake Basin (Liu *et al*., 1999; Li *et al*., 2010a), etc.

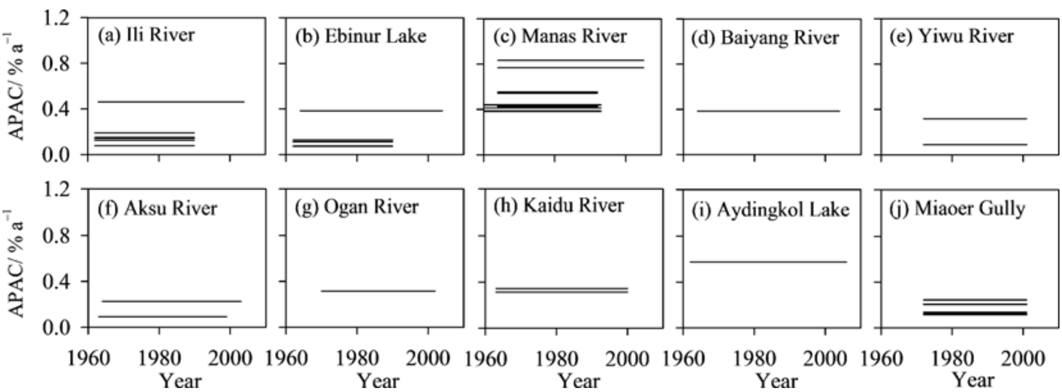

Figure 2 APAC variations of glaciers in the Chinese Tianshan Mountains for different drainage basins during 1960–2009

Take glaciers in Urumqi River Basin (a part of the Manas River Basin in the Junggar internal drainages, according to the GIC) as an example. Urumqi City (the capital city of the Xinjiang Uygur Autonomous Region) and the Tianshan Glaciological Station (TGS) of Chinese Academy of Sciences (CAS) are located nearby, so there is plenty of research on glacier area in this basin. From 1959 to 1993, the glacier area was reduced by 13%, with an APAC of 0.38% a^{-1} (Kang, 1996). Research during 1964–1992 also came to a similar conclusion

(13.8% of the glacier area was lost, APAC=0.49% a^{-1}) (Chen *et al*., 1996); however, the latest report indicated that 34.2% of glacier area was lost during 1964–2005, and the APAC was even up to 0.83% a^{-1} (Li *et al*., 2010a). These three studies were conducted in the same region, and the various results indicated the significant shrinking of glaciers in the Chinese Tianshan Mountains.

For the northern slope of the Chinese Tianshan Mountains, significant shrinking occurred in the middle section (especially for the Manas River Basin), where the APAC increased approximately from the previous 0.4% a^{-1} to the present 0.8% a^{-1}. For the southern slope, great shrinking was observed in the Turpan-Hami internal drainages, especially for the Aydingkol Lake Basin (the APAC is up to 0.6% a^{-1}, approximately). These regional differences in glacier area variation may arise from the differences in regional climate changes, the attribute of glacier, and so on. These contributing factors will be discussed in more detail at a later stage.

4 Discussion

4.1 Effect of climate change trend on glaciers

Among all the contributing factors to the glacier area variation, climate change may play an important role (Kang *et al*., 2002; Wu *et al*., 2008; Wang *et al*., 2009; Duan *et al*., 2009). The glacial fluctuation in a time scale longer than a century is controlled mainly by temperature, instead of precipitation. For glacial fluctuation in a time scale shorter than 10 years, or in a limited spatial scale, the glacial fluctuation is also determined by precipitation (Gao *et al*., 2000). During 1960–2009, a warming and wetting trend was observed in the Chinese Tianshan Mountains (Figure 3). According to the 14 meteorological stations, temperature increased at a rate of 0.34℃·$(10a)^{-1}$, which means the temperature increased by 1.7℃. The trend is similar with that found in the Xinjiang Uygur Autonomous Region [0.33℃·$(10a)^{-1}$], and significantly higher than that throughout China [0.22℃·$(10a)^{-1}$] (Liu *et al*., 2009). Precipitation in the Chinese Tianshan Mountains increased at a rate of 11 mm·$(10a)^{-1}$, which means it increased by 55 mm in the past 50 years. The linear trend is a little higher than that in Xinjiang (Liu *et al*., 2009).

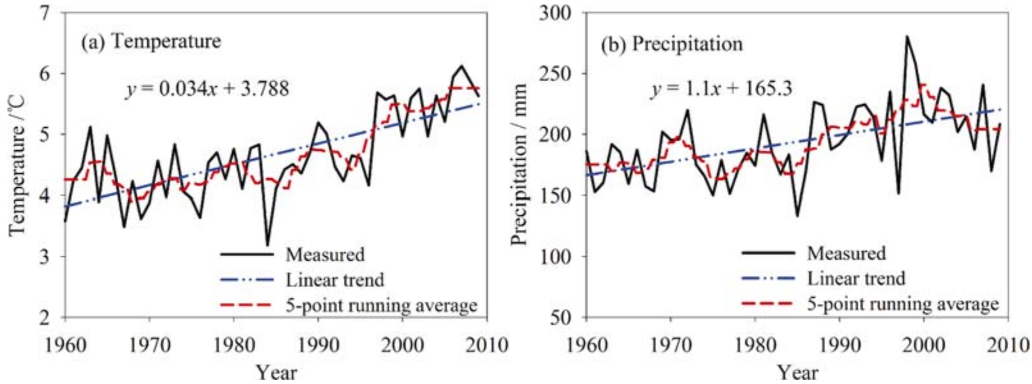

Figure 3 Variation of temperature (a) and precipitation (b) in the Chinese Tianshan Mountains during 1960–2009

There is a phase lag of about 12–13 years for mountain glacier variation to climatic change in the Northern Hemisphere (Wang *et al.*, 1992), but the lag period may be much shorter in the Chinese Tianshan Mountains. From the late 1950s to the early 1970s, retreating glaciers in the Chinese Tianshan Mountains grew in number and in magnitude, resulting from the low-temperature and high-precipitation in the 1950s and the high-temperature and low-precipitation in the 1960s (Ren *et al.*, 1988; Liu *et al.*, 1999). After the 1960s, as a result of growing temperature and precipitation, the retreat rate slowed down from the early 1970s to the late 1980s (Ren *et al.*, 1988; Liu *et al.*, 1999), and significant shifting occurred in late 1970s for small glaciers (Dyurgerov *et al.*, 2000). Since the early 1990s, the increase in precipitation has been more significant than that of temperature, causing the glaciers to rapidly shrink (Liu *et al.*, 1999).

4.2 Effect of climatic seasonality on glaciers

Seasonality in glacier accumulation is a result of differences in seasonal climate. According to a study on Glacier No.1 at the headwaters of Urumqi River, the dry season is classified as from November to March, and the wet season as from April to October (Li *et al.*, 2008). During 1960–2009, the temperature in the dry season increased at a rate of 0.46℃·$(10a)^{-1}$, which is higher than that in the wet season [0.25℃·$(10a)^{-1}$]; The precipitation in the wet season increased at a rate of 8.7 mm·$(10a)^{-1}$, which is much higher than that in the dry season [2.3 mm·$(10a)^{-1}$].

The combination of decreasing temperature and increasing precipitation in the summer (usu. wet season) is the best condition for glacier accumulation (Kang *et al.*, 2002). In general, the increase of precipitation is beneficial to glacier accumulation because the increase in solid precipitation can enhance the reflectance and avoid melting (Kang *et al.*, 2002). The increasing temperature in the dry season may shorten the accumulation period and lengthen the melt period; but the increasing temperature in the wet season may contribute to the melt directly (Wang *et al.*, 2009). The long-term meteorological data suggests that the temperature in the wet season has increased steadily, but the precipitation has been dropping since 2000. So the influence of wetting is counteracted by warming.

In Figure 4, warming is more significant in the eastern section of the Chinese Tianshan Mountains than that in the western section. For the spatial distribution of precipitation amplification, an increasing trend is seen from east to west and from south to north. The water vapor originates partly from the Atlantic Ocean via the Westerlies, and partly from the Arctic Ocean in the mountain pass in the western Junggar Basin, resulting in the spatial distribution of precipitation, that is, an increasing trend from east to west and from south to north (Hu, 2004). The climatic change trend above mentioned diversifies the distribution of temperature and precipitation in the Chinese Tianshan Mountains.

4.3 Effect of climatic spatiality on glaciers

Figure 5 shows the variation of temperature and precipitation for ten 3rd-grade drainage basins in the Chinese Tianshan Mountains, where the steps are the mean value for interdecadal period. Although the warming and wetting trends look similar in general, there are differences in the trends going from west to east and north to south. According to Figure 5, the

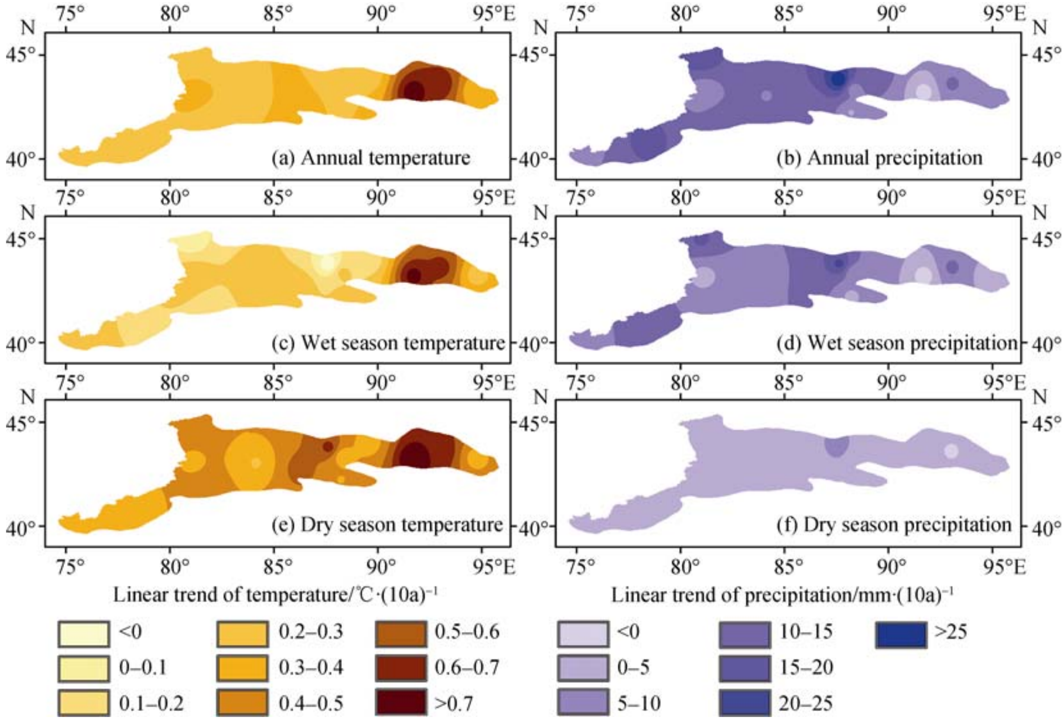

Figure 4 Distribution of temperature and precipitation variation in the Chinese Tianshan Mountains during 1960–2009

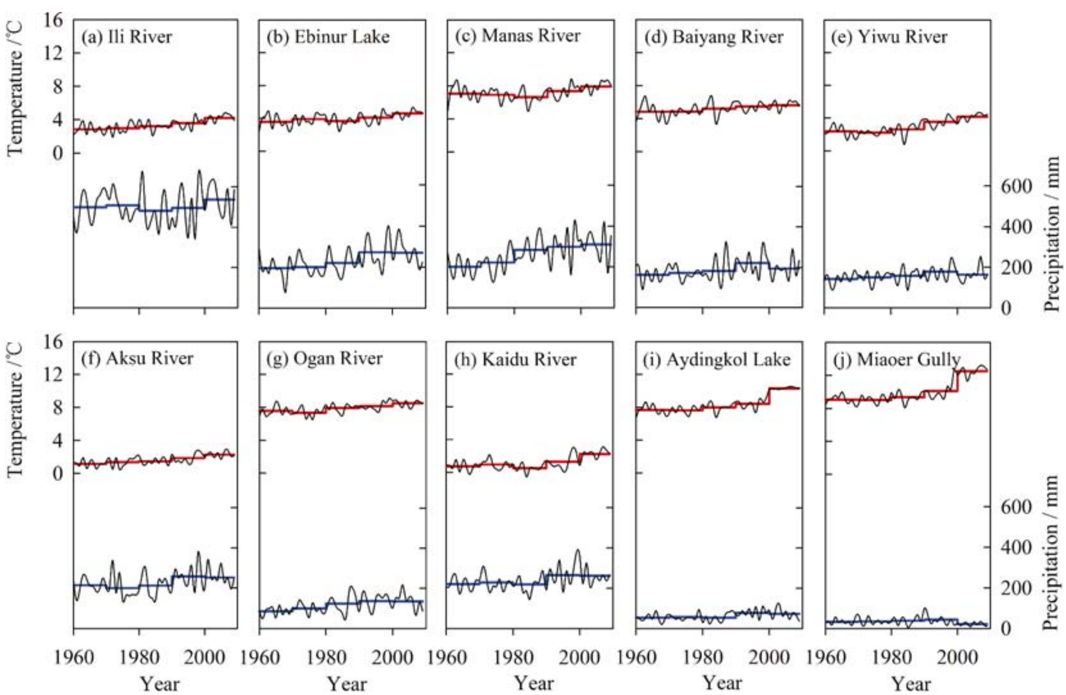

Figure 5 Temperature and precipitation variation for different drainage basins in the Chinese Tianshan Mountains during 1960–2009

temperature in the southern slope of the Chinese Tianshan Mountains is higher than that in the northern slope in general; however, the precipitation displays the opposite relationship in general. Since the 1980s, the temperature grew rapidly for almost every drainage basin, especially in recent years for the Turpan-Hami internal drainages. The 1990s was a period with high precipitation, but in the 2000s, precipitation has kept steadily or dropped a little with an exception of the Ili River Basin.

The above climatic spatiality affects glacier area variation. For example, the Aydingkol Lake Basin is located with the Baiyang River Basin to the north and the Kaidu River Basin to the west. These three basins are located close to each other, and the mean area for a single glacier is similar, which is 0.47 km^2, 0.43 km^2 and 0.56 km^2, respectively. The linear increasing trend of temperature in the Aydingkol Lake Basin, the Baiyang River Basin, and the Kaidu River Basin, is 0.56℃·$(10a)^{-1}$, 0.21℃·$(10a)^{-1}$, and 0.33℃·$(10a)^{-1}$, respectively. The linear increasing trend of precipitation is 6.2 mm·$(10a)^{-1}$, 11.3 mm·$(10a)^{-1}$, and 11.5 mm·$(10a)^{-1}$, respectively. According to Figure 2, the APAC in the Aydingkol Lake Basin is much higher than the others. However, this characteristic can not be demonstrated for the whole Chinese Tianshan Mountains because glacier variation is a result of various factors. In addition, the representativeness of meteorological stations is also important.

4.4 Glacier size and glacier area variation

The sensitivity of glacier area to climate change is related to glacier size, with the smaller glaciers being more sensitive to climate warming than the larger ones (Ye *et al.*, 2001). The change in glacier area lags behind climate change. For larger glaciers (length > 5 km), the lag time is about 8 years, and for smaller glaciers (length ≤ 5 km), the lag time is about 2 years (Ding *et al.*, 1996). In the Chinese Tianshan Mountains, the low APAC mainly occurs for glaciers in which the area is less than 1 km^2 (Figure 6). With the climatic warming, small glaciers are at risk of being strongly impacted. It is predicted that the smaller glaciers (area < 1 km^2) on the northern slope of the Chinese Tianshan Mountains will likely disappear within the next 20–40 years (Li *et al.*, 2010a). In fact, for most of the ten 3rd-grade drainage basins, the mean area of a single glacier is less than 1 km^2, with the exceptions of the Aksu River Basin and the Ogan River Basin in the western part of the Tarim internal drainages (mean area just larger than 2 km^2). Based on the size distribution of glaciers in the Chinese Tianshan Mountains, the present rapid rate of shrinking cannot be avoided.

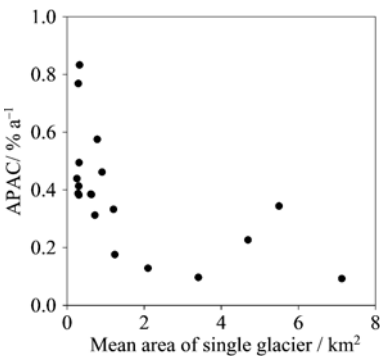

Figure 6 Relationship between mean area of a single glacier and APAC

5 Conclusions

According to the area variations of about 3000 glaciers in the Chinese Tianshan Mountains, it is concluded that the glacier area has been reduced by 11.5% in the past 50 years. The glacier area fluctuation is related to climate change, the attributes of the glacier, and so on, but the warming in the past 50 years is the principal cause for the glaciers area variation in the Chinese Tianshan Mountains.

Fluctuation of mountain glaciers area is an indicator of climate change. As the major headwater of many rivers in Xinjiang, the Chinese Tianshan Mountains play an important role in regional development. The glaciers are distributed all over the Chinese Tianshan Mountains, and it is very meaningful to study glacier area variation. The following are some recommendations for future studies. (1) With most mountains glaciers shrinking in China, the long-term observation of some typical glaciers is still necessary. Both field observation and appropriate modelling is helpful for enriching the scientific knowledge of mountain glacier variation. (2) In lab practice, a difference in remote sensing image interpretation may occur because of different operators, so that sometimes the same data may be interpreted differently. Unification and consummation of the technical process of image interpretation is also a fundamental task. (3) It is a systemic and essential project for regular glacier inventory. In order to investigate glacier variations since the completion of the first GIC, a second GIC was initiated in 2007, which will be invaluable for research on glacier change (Shi *et al*., 2010).

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