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I have attached the revised copy of your paper 43A038 for volume 43 of the Annals. I am pleased to report that I am accepting your paper on the condition that you revise it to incorporate the editorial changes recommended using track changes in the attached version. Dr. Peter Mayes has edited the paper in detail, I have reviewed it and added a sentence in the Acknowledgements thanking him. Also note that there are some issues with your figures (I have attached them and there is a note in the files). You must also now revise the references to conform to IGS standard (see the web page and attached instructions). Numbered references are not acceptable. After accepting the changes please run the grammar and spell checker once more as the number of changes is large and often errors creep in when there are so many changes.

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This paper has been approved for Annals volume 43 by the Chief Editor, Ellen Mosley-Thompson, pending the minor revisions incorporated below. December 6, 2005

Glacier retreat as a result of climate change due to warming and increased precipitation in the Tarim River Basin, Northwest China

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ABSTRACT. The Tarim River basin, a river system formed by the convergence of nine tributaries, is the most heavily glacierized watershed in arid northwest China. In the basin there are 11,665 glaciers with a total area of 19,878 km^2 and a volume of 2,313 km^3. Glaciers in the basin play a significant role in the water resource system. It is estimated that glaciers provide about 133×10^8m^3 of meltwater annually, contributing 39% of the total river runoff. With the influence of global warming, northwest China has experienced a generally warmer and dryer climate since the mid-19th century. However, a so-called "warm and wet transition" has occurred since the late 1980s, shown by an increase both in precipitation and stream discharge in the Xinjiang Autonomous Region and neighboring regions. This paper describes how glaciers in the Tarim River basin have responded to such warming and increased precipitation, and what impact such glacier changes exert. We analyzed the variations of more than 3000 glaciers since the 1960s using topographical maps, high resolution satellite images and aerial photos of the river basin. Our results indicate that glaciers in the basin were mostly in retreat in the past 40 years, and ice wastage has significantly influenced the water resources in the Tarim River basin. An estimation by a degree-day meltwater model shows the positive anomaly in stream runoff of the Tailan River can be partly attributed to the increase in glacier runoff (it amounted to one third of the stream discharge), and a rough estimation using observed average ablation on the termini of 15 glaciers in China verifies that the mass loss calculated by a glacier area-volume relation is reasonable.

1. STUDY AREA

The Tarim basin, with a total area about $1.02 \times 10^6 km^2$, in the southern part of the Xinjiang Autonomous Region, is the longest inland river basin in China. It is composed of the Tarim River and nine tributary water systems, including the Akesu, Kaxgar, Yarkant, Hotan, Kaidu-Konqi, Dina, Ogan, Keriya and Qarqan rivers (Mao, 2001). The Tarim River has a total length of 2350km, measured from the source of the Yarkant River that originates on the north slope of Karakorum Mountains. Its main stream extends 1321km flowing around the western and northwestern edge of the Taklamagan Desert (Fig.1). It lies in a continental warm temperate and arid zone. There is no runoff generated within the main stream area, because of the high evaporation (1125 to 1600mm/year) and the extremely low precipitation (between 17.4 and 42.8mm per year) (Mao, 2001). The surface runoff is mostly generated from highly glacierized areas and grassland/forest regions in the encompassing high mountain slopes of the Tian Shan, eastern Pamirs, Karakorum and Kunlun mountains. Yang's (1991) estimation shows that glacial runoff in the basin amounted to $133.4 \times 10^8 m^3$, 38.5% of the total discharge at the outlets of the Tarim River.

Figure 1

Presently, only three tributaries, the Akesu, Hotanr and Kaidu-Konqi ~~R~~rivers, provide water to the main stream due to intensive development and utilization of water resources in the other tributaries of the Tarim River basin that flowed into the main stream in the early 20th century. With the continuous increase in water consumption from the main stream, the adjoining lakes and 320km of the lower reach of the river has not received any water input since the 1970s, and Taitema Lake, a lake near the end of the river, disappeared in 1974. Consequently, desertification, ecological degradation and associated conditions became more and more serious in the lower reaches of the river (Tan and others, 2004).

According to the China Glacier Inventory (CGI), there are 11,665 glaciers within the Tarim River basin. These glaciers have a total area and volume of $19{,}877.7 km^2$ and $2{,}313.3 km^3$, respectively, and account for 25.2%, 33.5% and 41.3% of the total number, area and volume of all glaciers in China (Shi and others, 2005). Glaciers are primarily distributed in ~~6~~six major catchments, namely the Keriya, Hotan, Kaxgar, Yarkant, Akesu and Ogan, where they comprise 97% of the total glacial area of the Tarim River basin. Of all these major catchments, the Hotan and Yarkant rivers account for 54% of the total glacial area in the whole basin. Accordingly, these highly glacierized catchments provide most of the glacial runoff to the Tarim River system.

2. THE RECENT CHANGE OF CLIMATE TOWARD WARMING AND INCREASED PRECIPITATION

Shi and others (2003) have suggested that the apparent transition from warm and dry to warm and humid conditions that has occurred during the last two decades is a strong indicator of climate change. Observations indicate that air temperature has been increasing at a rate of 0.2°C/decade in the past 50 years in western China, especially during the 1980s-1990s. The 1990s may not only be the warmest period in the past century but the past 1000 years. The average air temperatures of 128 stations during the period 1987 to 2000 have risen by 0.7 °C as compared with the average temperature from 1961 to 1986 (Wang and Dong, 2002).

Figure 2

At the same time as air temperature began to increase, the trend in precipitation switched from a decrease to an increase. The average yearly precipitation from 1986 to 2000 in western China increased by 23% compared with that from 1956 to 1986. Precipitation during the period 1987 to 2000 increased by 11% in northern Xinjiang and 32% in southern Xinjiang relative to that from 1960 and 1986 within the Tarim basin (Hu Ruji, 2002; Han Ping, 2003). It demonstrated that the precipitation increase mainly occurred during the winter, spring and summer seasons during the 1990s and decadal means increased by 45%, 33% and 28%, respectively, compared with the average in the whole observational period (Song and Zhang, 2003). However, precipitation in autumn decreased by 3%. Observations also showed that precipitation in the mountainous region of Tianshan increased, by 24% in winter and 16% in summer. Because there are no meteorological stations in the glacierized area, it can only be deduced that glaciers received more snowfall in the winter and spring seasons prior to the late 1980s. Among 26 large rivers in Xinjiang, 18 that originate in the mountainous regions of Altai Shan, Tian Shan, eastern Pamirs and Karakorum have experienced runoff increases of between 5-40% over the period 1987 to 2000 compared to 1956 to 1986. This increase is very evident in rivers from the south slope of southwestern Tian Shan (Zhang and others, 2003) as shown by the representative Tailan River (Fig.2).

In addition to the influence of increasing precipitation, significant runoff increases within most rivers could be the result of an increase in glacial runoff due to enhanced warming, leading to glacier melting. Such an increase in the runoff is directly related to the proportion of glacial runoff supply in a watershed (Yang, 1991). But we have no knowledge about glacier changes and their influence on river runoff in most parts of the northwest China because glaciers with long term monitoring are scarce, and observations of glacier changes at a regional scale are very poor. Therefore, we selected the Tarim River basin as an experimental basin to study glacier changes during the last 50 years through the use of remote sensing and Geographical Information System (GIS) techniques, in order to understand how glaciers respond to the recent warming and increased precipitation. After analyzing data of glacier variations based on short-term field observations and long-term hydro-meteorological data in the study region, we will further discuss the possible impact of glacier variation on water resources in the basin.

3. GLACIER CHANGES IN THE TARIM RIVER BASIN

3.1 Data and methods

In our study, we used topographical maps (1: 100,000) based on aerial photographs acquired during the 1960s and 1970s and Landsat TM and ETM^+ images obtained from 1999 to 2001 – although this study is limited by the lack of Landsat TM and ETM^+ images in the southeast area of the basin (Fig. 3). The method of image processing and glacier boundary extraction are the same as used by many different authors in China (e.g. Liu and others, 2002, 2003, 2004; Lu and others, 2002; Shangguan and others, 2004a & b). All satellite images have been geometrically corrected to topographical maps, and projected into the Krosovsky spheroid and Albers equal area conical projection (Fig.3). Then all the corrected images were orthorectified to a digital elevation model (DEM) with 90m resolution in order to clear up the influence of the shadow effect of high mountainous ridges. In general, errors of geometrical correction are about 1 pixel, for instance, and the error is about 31.5m for the Landsat TM image determined by randomly selected independent points other than ground control points used for the geometrical correction. Glacier boundaries on the corrected images were identified through visual interpretation. The boundary of the termini of debris-covered glaciers was recognized usually based on the geomorphological pattern in the image draped over a DEM. Commercial GIS software was applied to such identification and vectorization of glacier boundaries. Glacier boundaries during the 1950s to 1970s were vectorized from topographical maps modified with a careful reference to the information from the CGI. The attribute data consisting of more than 27 elements for a glacier vectorized from such maps were obtained from the glacier inventory, with relevant corrections for area, length and so on based on this vectorization. Glacier changes during the time span were then obtained by applying the overlay function of GIS software. The error for extracting glacier changes in this way is commonly about 90m, considering errors in image correction and visual interpretation which vary from 1 to 2 pixels. Using this procedure, we got data for more than 3,000 glaciers, excluding those glaciers with length changes less than 90m.

Figure 3

3.2 Glacier change in the past 40 years

As mentioned above, we acquired data of glacier changes of 3,081 glaciers with a total area of around $1*10^4 km^2$, accounting for 50.3% of the total glacial area and 26.4% of total number of glaciers in the Tarim River basin (Table 1). Considering the total area of glaciers, our sample reflects the general status of glacier variations in the basin.

Our results (Table 1) demonstrate that over recent years, although some glaciers were advancing, most glaciers in the basin were retreating (73.9%). When the amount of glacier advance was compared to the amount of glacier retreat, the net difference was a decrease of 4.6% in the total area over the period 1960s to 1970s. This means glacier retreat is the dominant phenomenon, and it can be attributed to the influence of recent climate warming. As for glacier changes in each tributary, glacier retreat was significant in the Kaidu River flowing from the south slope of the middle section of

Tian Shan and the Gez River originating in the eastern Pamirs. Glaciers in these two basins have lost 11.6% and 10% of their total glacier areas, respectively. Glacier changes were less distinct in the Akesu River in the southwestern Tian Shan and the Hotan River on the north slope of western Kunlun Mountains, where the reduction in area was 1.4% and 3.3%, respectively. Here 32.9% of measured glaciers in the two rivers were advancing. These differences are also reflected by the percentage area of retreating and advancing glaciers versus the total measured glacier area in each river tributary. The area of retreating glaciers in the Akesu River is only 7.9% of the total measured glacier area in the river basin, but that in the Yarkant River is as high as 81.2% of the whole glacier area in the basin. Generally speaking, the area of retreating glaciers of every tributary is over 50% of the total area of studied glaciers except that of the Akesu River. The results show that the shrinkage of small glaciers is dominant in the Akesu River basin, while almost all glaciers in the Yarkant and other Rivers were retreating.

Table 1

4. INFLUENCE OF GLACIER CHANGE ON WATER RESOURCES

Glacier changes significantly affect variations of water resources, including variations of net ice volume and of glacial runoff amounts due to changes of surface area for runoff generation because of terminus shrinkage. In the following sections, we will present a brief discussion about each aspect.

The volume of ice of a glacier is estimated based on a modified equation suggested by Liu and others (2003). The equation is $V = 0.04*S^{1.35}$, where V is the ice volume (km^3) and S is the area (km^2) of a glacier. This empirical equation was derived from ice penetrating radar thickness measurements of six valley glaciers, five cirque glaciers, one hanging glacier, one ice cap and three cirque-hanging glaciers (an area ranging from 0.46 to 165 km^2) in the Tianshan Mountains and seven glaciers (an area from 0.1 to 7 km^2) in the Qilian Mountains, as well as some measurements in the Qinghai-Xizang (Tibet) Plateau. On the basis of the area of shrinkage of the glaciers in the basin (Table 1), the estimated total ice volume of the monitored 3,081 glaciers generally decreased by 35.5km^3, or $319.3\times10^8 m^3$ water equivalent (assuming an ice density of 900kg/m^3). The ice loss is 1.2 times the total discharge from outlets of the Kaidu, Ogan, Akesu, Kaxgar, Yarkant and Hotan rivers (Zhou, 1999). The annual mean decrease was $8.9\times10^8 m^3$ from 1963 to 1999, corresponding to the average annual discharge observed at the Keleke hydrological station on the upper Gez River in the eastern Pamirs.

Table 2

Good statistical relationships can be found within the dataset of 3,081 glaciers regarding the change in glacier area and the decline in glacier volumes between the early 1960s and 1999/2001. To reflect the relationships in enough detail, we divided the sample glaciers into three size groups, i.e. $\leqslant$1km^2, 1-5km^2 and $\geqslant$5km^2 (Table 2). With these groups, we can estimate changes of those non-monitored glaciers in the

Tarim River basin during the same period. The estimated total reduction both in area and volume of glaciers in the whole basin from the early 1960s to 1999/2001 is 1307.2km^2 and 87.1km^3, respectively, equivalent to 6.6% and 3.8% of the early 1960s area and volume. The ice loss corresponds to an average thinning by 3.8m of all glaciers in the basin. The ice volume decrease approximates 783.5×10^8m^3 water equivalent, which is twice the average annual discharge of the main river tributaries of the Tarim River basin (Xia, 1998). On average, glaciers in the Tarim basin provided an extra 21.8×10^8m^3 of meltwater annually, about 5.7% of average annual discharge of the Tarim River.

The Tailan River lies on the south slope of the southwestern Tian Shan and is a tributary of the Akesu River. Close to the outlet of the river is the Tailan hydrological station (1550m a.s.l., 41°33′N 80°30′E, see Fig.1) that monitors a drainage area of 1324km^2. Within the catchment, the glacierized area is 432.9km^2, and the glacier meltwater provides a large proportion (about 60%) of the total runoff of the river. *In situ* glaciological and hydrological observations at the terminus of Qiong Tailan glacier, a 108 km^2 glacier at the head of the Tailan River, were conducted during 1977 and 1978 (Kang and others, 1985). According to data from a hydrological station located 1 km below the glacier terminus (here referred to as the Tailan glacier station, 2981m a.s.l) and ablation measurements at different elevations on the glacier, calculations reveal that the runoff modulus of the glacier during the period May to September is 0.1m^3/(s·km^2) above the Tailan glacier station, and 0.061 m^3/(s·km^2) above the Tailan hydrological station. The estimation shows that glacier meltwater supplies 74% of river runoff above the Tailan glacier station and 57.7% of river runoff above the Tailan hydrological station.

Figure 4

To discuss the impact of glacier change on river runoff or water resource variations in the Tailan River, we applied a degree-day ablation model to estimate glacial runoff in the river. Firstly, we extracted the altitudinal area of each 100m elevation band from a DEM of 90m resolution and produced the area hypsometry of all the glaciers in the Tailan River basin (Fig.4a). Then we calculated the degree-day factors derived from stake measurements at different elevations (34 stakes were placed at elevations between 3150 m and 4400 m) along the Qiong Tailan glacier and meteorological data at the Tailan glacier station (2981 m) during 1977 and 1978. Combining air temperature data of the Tailan hydrological station (1550 m) and the Aksu weather station from 1957 to 1998 and short term temperature data (to determine the lapse rate during the summer season) in the glacier area, we can calculate glacial runoff during the time span from 1957 to 1998 by assuming the degree-day factors apply to corresponding elevations of other glaciers without measurements, assuming that they don't change with time. Results indicate that the yearly variation of glacial runoff at the outlet of the Tailan River coincides well with that of the river runoff (Fig.4b). Both glacial and river runoffs experienced the same trend ranging from dimished runoff in the early 1950s to increased runoff in the early 1980s, showing a synchronous response to the recent climate change. As indicated by the decadal mean runoff depth, the outlet runoff was more plentiful during the periods 1957 to 1960 and 1991 to 1998, whereas glacial runoff had positive anomalies during 1981 and 1998. Starting from 1981, the decadal anomalies of glacial runoff were 14.9mm and 22.6mm higher than the average glacial runoff, accounting for 4.5% and 6.6%, respectively, of the average from 1957 to 1998. The mean runoff depth in the 1990s, a high-flow decade, is 68 mm (12%) higher than average runoff during the observational period, and the increased glacial runoff is a third of the total quantity of increased river runoff in the 1990s. Although the 1980s was a low-flow decade, glacial runoff showed an increase. This changing pattern indicates to a certain extent that the influence of glacier retreat on streamflow has become stronger than ever before.

Figure 5

We may delineate the influence of glacier retreat on glacial runoff for a river basin as large as the Tarim River basin and validate, in another way, whether glaciers in the basin have lost the sum of ice masses that we derived from the remote sensing method. In theory, glacial runoff variation is definitely closely related to intensified glacial ablation resulting from climatic warming. For a retreating glacier responding to climate warming, we can presume that glacier area decreases at a rate of the annual average of the total area reduction during the period considered. But for all glaciers in the Tarim Basin, we established a hypothetic glacier with an area elevation distribution calculated from the total area of glaciers in the basin and empirical equations suggested by Kuzminchenok (1993). Glacier shrinkage occurred on the lower part of the hypothetic glacier and the annual area decrease of the hypothetic glacier was equal to the averaged area reduction of all glaciers in the basin. Glacial runoff in each year on the retreating terminus of this hypothetical glacier can be calculated if we know the ablation intensity on its terminus. Publications document that there are more than 15 glaciers in western China currently being investigated, or monitored in different time periods in the past. Of all the investigated glaciers, ablation has been measured on the terminus area of 15 glaciers during field reconnaissance since the 1950s. The terminus elevations of these glaciers range from 2640 to 5450 m a.s.l and the annual ablation intensities on these glacier termini vary from 1.3 to 6.9 m w.e. with an average ablation depth of 3.5 m w.e./year (Kayastha and others, 2003; Liu and others, 1996; Li and others, 1996; Su and others, 1998; Zhang and Bai, 1980; Zhang and Zhou, 1991; Yao and Ageta, 1993; Liu and others, 1992; Mountaineering and Expedition Term of Chinese Academy of Science, 1985; Lanzhou Institute of Glaciology and Geocryology, 1981-2002). Supposing the average annual ablation on the termini of these glaciers can represent the terminus ablation of glaciers in the Tarim River basin, the total meltwater generated is estimated to be 1.27 $\times 10^8 m^3$ w.e. in the above mentioned sub-area of glaciers where the annual ice loss was 36.1km^2. In the Tarim River basin, the cumulative glacial runoff calculated by this method amounted to $893.4 \times 10^8 m^3$ from the entire glacier melt from 1963 to 2001 (Fig.5). This amount of glacial meltwater will never be generated again after 2001 due to the complete disappearance of the ice masses. This sum of glacial runoff is almost the same as the total annual runoff of all rivers in Xinjiang territory. Such a loss of glacial runoff is of vital significance to water resources in the Tarim River basin where the water supply is extremely limited, directly impinging upon human activities and environmental preservation efforts. The calculated loss of total glacial runoff is $110\times10^8 m^3$ (or 14%) higher than the estimated volume decrease by the glaciological method used in ice volume estimation. The difference between the two totals possibly results from the degree to which the ablation intensity was not reflected in the calculated loss of total glacial runoff since this is lower than the actual area of the glacier termini being lost in the basin. However, the similarity of the two estimations indicates that the volume-area relation is reliable enough to estimate the ice volume decrease of glaciers under retreat in the basin during the past several decades. In fact, this implies that the assigned ablation intensity is very close to the real average on glacier termini of the entire basin.

5. CONCLUSIONS

The analyses presented in this paper allow us to draw three conclusions. First, most of the glaciers in the Tarim River basin have been retreating in the last few decades with a smaller portion advancing. Glacier changes exhibit obvious regional differences within this large river basin because of the differences of glacier properties (dynamic response), local climatic settings and the amplitude of climate changes during recent decades. Glaciers in the east Pamirs and the south slope of the central Chinese Tian Shan have experienced intensive wastage during the period of study. Glacier retreat in the basin can be attributed to climatic warming in the past decades. Although, increased precipitation has occurred since the late 1980s, it has not brought about a reversal of glacier retreat. In other words, most glaciers are still retreating even though the climate has become wetter in the last two decades.

Secondly, the glaciers in the Tarim River basin have lost a total area of $1,307.2 km^2$ from 1963 to 1999/2001, corresponding to a loss of ice mass of $87.1 km^3$, equivalent to about 6.6% and 3.8% of the area and volume of the early 1960s. The total decrease of glacier ice is equivalent to $783.5\times10^8 m^3$ water equivalent and an annual decrease of $21.8\times10^8 m^3$.

Finally, a calculation using a degree-day model has been made for glacial runoff in the small glacierized Tailan River basin. This estimation has captured the changing runoff pattern influenced by climate change, especially the recent increase in glacial runoff due to the rise in air temperature after the late 1980s. This means that an increase in glacial runoff can be predicted to continue is the current warming trend persists. An experiment demonstrated that the estimated wastage of ice masses in the whole Tarim River basin is a reliable one. For a large highly glacierized basin, glacial runoff change due to glacier retreat is of great significance to water resource variations, but we need to make more efforts to understand how individual glaciers in different river basin respond to climate change and how glacier changes influence variations of glacial runoff and water resources.

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Table 1 Glacier changes in the main tributaries of the Tarim River basin in the past 40 years; note that we only include glaciers with absolute length changes larger than 90 m. All glaciers in the table were either retreated or advanced

River basin	Period	Number of Glaciers	CGI area (km^2)	Area change(km^2)	Change proportion (%)	Number of advancing glaciers	Reference
Akesu	1963-1999	247	1760.7	-58.6	-3.3	126	this study
Kaidu	1963-2000	462	333.1	-38.5	-11.6	98	this study
Gez	1960-1999	753	1889.7	-188.1	-10.0	198	this study
Keriya	1970-1999	297	687.2	-22.8	-3.3	94	this study
Hotan	1968-1999	757	2620.6	-37.1	-1.4	204	Shangguan and others, 2004a
Yarkant	1968-1999	565	2707.3	-111.1	-4.1	85	Shangguan and others, 2004b
Sum		3081	9998.5	-456.2	-4.6	805	

Table 2 Statistical relationships between glacier areas and volumes in the early 1960s and 1999/2001 in the Tarim River basin. S_{TM} and V_{TM} are glacier area and volume in 1999/2001; S_{MAP} and V_{MAP} are glacier area and volume in early 1960s; the units are km^2 for area and km^3 for volume.

Size group	Sample number	Statistical relationship of area vs. area and volume vs. volume	R^2 and p
$S \leqslant 1km^2$	1843	$S_{TM} = 0.8782 \times S_{MAP} - 0.0092$	0.70, $p<0.0001$
		$V_{TM} = 0.848 \times V_{MAP} - 0.0001$	0.66, $p<0.0001$
$1 < S < 5km^2$	930	$S_{TM} = 0.929 \times S_{MAP} - 0.0838$	0.76, $p<0.0001$
		$V_{TM} = 0.905 \times V_{MAP} - 0.0037$	0.79, $p<0.0001$
$S \geqslant 5km^2$	308	$S_{TM} = 0.998 \times S_{MAP} - 0.3423$	0.99, $p<0.0001$
		$V_{TM} = 0.996 \times V_{MAP} - 0.0408$	0.99, $p<0.0001$

Fig.1 Sketch map showing the river system and glacier distribution in the Tarim basin (5Y** represents codes of watersheds used in the China Glacier Inventory (the sketch is used courtesy of Prof. Mi Desheng who produced the map))

Fig.2 Temporal variation of annual discharge at the outlet of the Tailan River on the south slope of the southwestern Tian Shan

Fig.3 Comparison of glacier distribution in the periods 1960s-1970s (the blue polygon) and 1999 to 2001 (Landsat TM/ETM$^+$ composite image with band 4 (red), 3 (green) and 2 (blue)) in the Tarim River basin.

Fig.4 The hypsometry of glacier area in the Tailan River deduced from a 90m resolution DEM (a) and the decadal anomaly of glacial runoff based on the calculation of a degree-day ablation model compared with the runoff anomaly at the Tailan hydrological station (b)

Fig.5 Diagram showing the contribution of glacier shrinkage to glacial runoff in the whole Tarim River basin (annual runoff: the runoff generated by a sub-area of glacier terminus that disappeared in the year; and cumulative runoff: the cumulative value of the above-mentioned annual runoff)

Figure 1

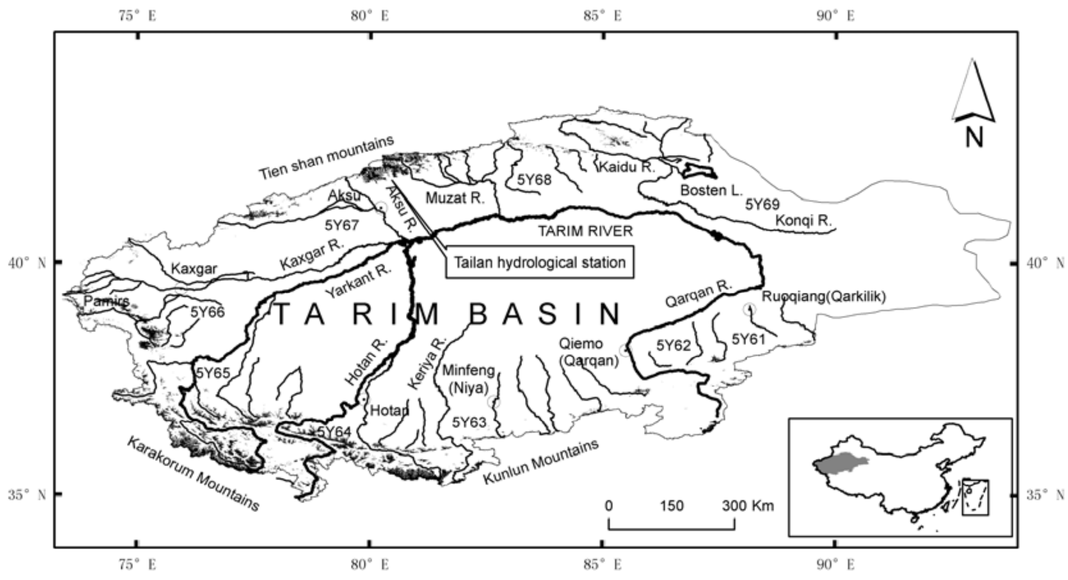


Figure 2

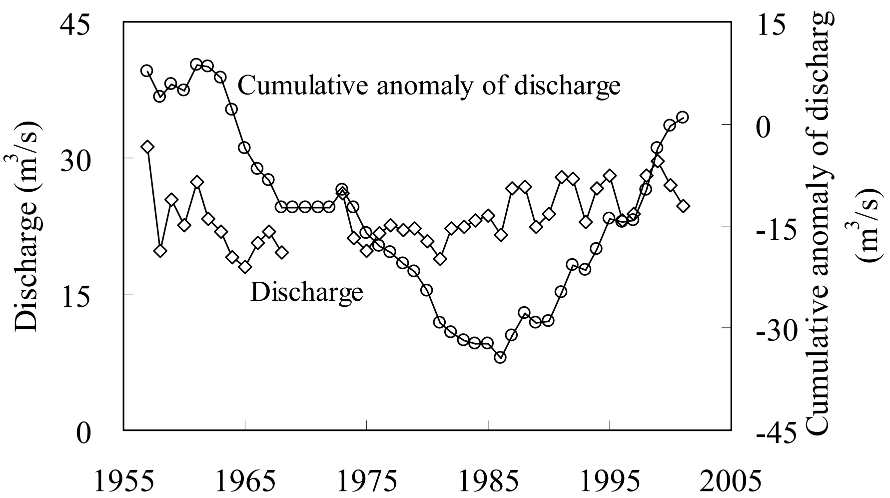


Figure 3

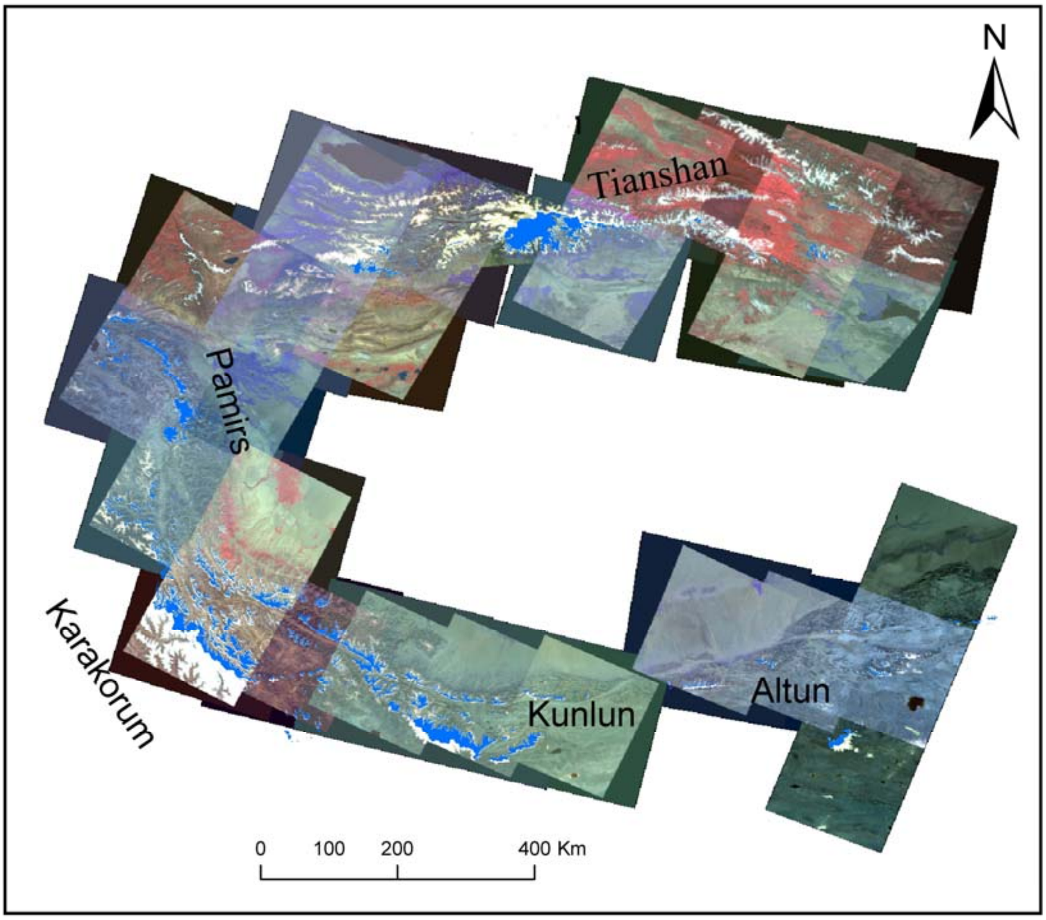
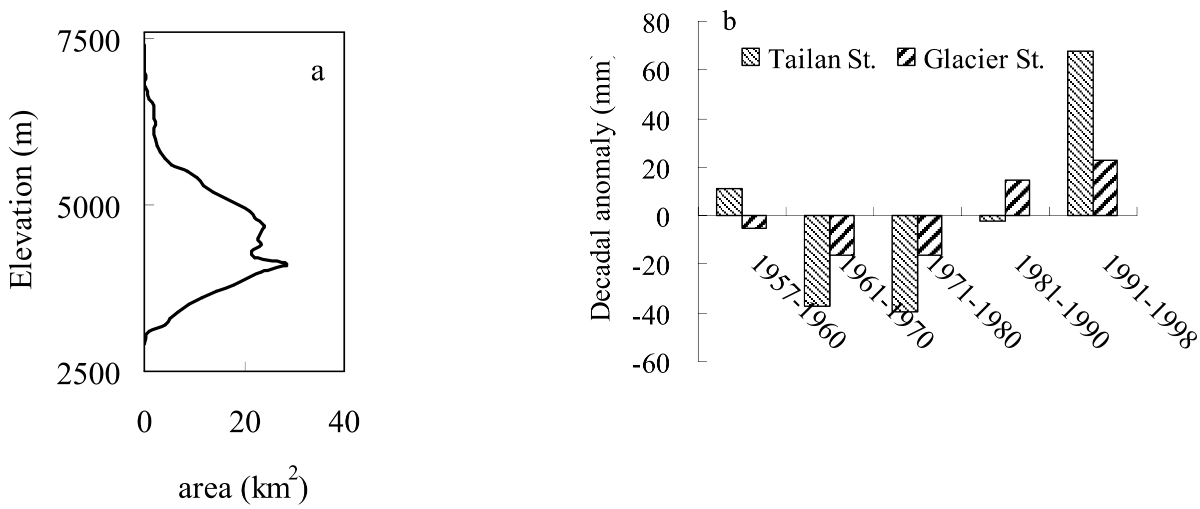


Figure 4



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Hello Shiyin,

I am pleased to accept paper 43A069 (Ding and others) for publication in the Annals volume 43.
I made some additional edits to the Acknowledgements to tidy up the English.
Thank you also for acknowledging my editorial assistance. It was my pleasure.
I note that you have numbered your references in the final draft but you will now need to prepare your paper in IGS format for the camera ready version. To assist you, I have attached several files. You may also review the guidelines on the IGS web page.

From this point forward you do not need to send me copies of the paper. All future correspondence on the paper will be with Magnus, Christine and their staff at the IGS office (annals@igsoc.org). I have copied them so they will have a signed copy of your accepted draft paper for their records.

It was a pleasure working with you on the paper. I appreciate that you were always so responsive to my inquiries.

Best regards,
Ellen

IGS Code: 43A069

The retreat of glaciers in response to recent climate warming in western China*

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ABSTRACT. Glaciers in China are primarily located in the Qinghai-Xizang (Tibet) Plateau and surrounding high mountains. The China Glacier Inventory (CGI) indicates that there are over 46,200 glaciers in western China. Meteorological records indicate that air temperature in western China has risen by 0.2°C per decade, and 1998 was the warmest year since 1951; precipitation in the region has increased by 5% to 10% per decade from 1953 to 1997. Using remote sensing and GIS methods, we have monitored the changes in >5,000 glaciers over the past 50 years. We concluded that >80% of glaciers in western China are retreating and have lost 4.5% of their combined areal coverage although some of the glaciers have advanced. In addition, glacier changes over the past few decades reveal some regional differences. For example, glaciers in the central and northwestern parts of the Qinghai-Xizang (Tibet) Plateau were relatively stable, while glaciers in the mountains surrounding the plateau experienced extensive wastage. Mass-balance variations for some glaciers in western China reveal accelerated ice shrinkage in the last two decades.

1. GLACIERS IN CHINA

Western China is characterized by numerous mountainous ranges and high, broad plateaus; 14 mountain ranges parallel one after the other from north to south, including the Altay, Tian Shan, Pamirs, Karakorum, Kunlun, and the Himalaya, with the later four ranges surrounding the Qinghai-Xizang (Tibet) Plateau. These four mountain ranges and plateau are the highest ones in the world; for example, the average elevation of the Qinghai-Xizang (Tibet) Plateau is as high as 4,500m above sea level. The cold environment resulting from these high elevations provides excellent conditions for alpine glaciers to develop. It is estimated the total glacierized area in China and other Central Asia mountains is 114,800km^2 (Dyurgerov, 2002). In

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the mountain ranges of Central Asia, 46,377 glaciers are situated within China; they have a total area of 59,425km^2 (fig. 1) (Shi and others, 2005), according to China Glacier Inventory (CGI), based on aerial photographs taken from the late 1950s to the early 1980s and large scale topographic maps.

Figure 1

Our analysis based on the observed physical properties, like the ice temperature, surface velocity, general climatic characteristics over glaciers in various areas in western China, indicates that glaciers in western China can be categorized into three types: extremely continental, sub-continental, and monsoonal maritime glaciers (Shi and Liu, 2000); each are characterized by different physical properties such as ice temperature, precipitation, and air temperature over the glacierized regions. Continental glaciers are mainly located in the middle and western Kunlun Shan, Qiangtang Plateau, east Pamirs, west Tanggula Mountains and west Qilian Shan. Sub-continental glaciers are distributed over Tian Shan, the northern slopes of the middle and western part of the Himalaya and the north slope of the Karakorum Mountains. Of all glaciers in western China, small glaciers with area $<$1.0 km^2 have the highest percentage of 77%, although their total area is only 20% of the total of Chinese glaciers. Large glaciers (>10 km^2 in area) are relatively scarce, but their area accounts for 37.6% of the total; among these large glaciers, 33 glaciers are $>$100 km^2 in area, but they occupy 10.4% and 26.3% of the total area and total ice volume, respectively of glaciers in China (Shi and others, 2005).

Glaciers are an economically important freshwater resource in China and other parts of Central Asia (Yang and Zeng, 2001), because many large river systems in the region have their sources in glacierized regions, for example, Huanghe, Changjiang, Yarlung Zangbo (Bramaputra), Tarim, Mekong, Nujiang (Salween), and the Ganges, all of which are the key freshwater sources for millions of people in the region. Therefore, changes in glaciers are likely to have a significant impact on human activities and preservation of the environment, especially, in those river systems which depend on significant meltwater from glaciers to provide an adequate supply of water. Until recently, there has been not a general agreement about glacier changes in the region; in particular, the impact on water resources caused by recent glacier retreat taking place under present-day warming. In this paper, however, we will present an integrated assessment about glacier changes in China during the past several decades.

2. CLIMATE CHANGE DURING LAST DECADES

Global climate change was well described in IPCC 2001 (Folland and others, 2001). The IPCC report showed that global climate warming since the end of the 19th century has increased the Earth's temperature by 0.6±0.2°C, and the warming is more pronounced on land-surface areas at mid- and high latitudes in the Northern Hemisphere. Such rapid warming was largely attributed to the enhanced anthropogenic emission due to fossil energy consumption. It was shown that the increase in air temperature during the 20th century is likely to have been the largest of any century during the past 1000 years. In addition, the 1990s are likely to have been the warmest decade of the millennium (Folland and others, 2001). An intensification of the global hydrological cycle was also observed; measurements of land-surface precipitation showed an increase of 0.5 to 1%/decade throughout the mid- and high latitudes of the Northern Hemisphere. Over much of the sub-tropical land areas, rainfall has decreased during the 20th century (by ̃ 0.3%/decade) (Folland and others, 2001).

The general warming during the last century in western China is also the case, but with some peculiarities. An analysis of climate in the region determined that the increase in air temperature during last 120 years is about 1.2°C, twice as much as the global warming rate, and the most evident warming occurred during the recent two decades (Wang and Dong, 2002). However, a cooling trend was recorded during the 1980s and 1990s in the north-central Qinghai-Xizang (Tibet) Plateau as shown from an analysis of $\delta^{18}O$ in an ice core from the Malan Ice Cap (Wang and others, 2003) and from variations in the altitude of the 0°C isotherm in the atmosphere based on radiosonde measurements (Zhang and others, 2005). Similarly, most of western China also saw an increase in precipitation during the past 50 years; for example, precipitation increased by 18% during the last half of last century in the northwest provinces (Xinjiang, west Gansu, and north Qinghai provinces) of China (Wang and others, 2004), However, seasonal snow cover observed at meteorological stations tended to increase on the Plateau, but no obvious trend was observed in Xinjiang since 1950s (Qin and others, in press).

3. A BRIEF REVIEW OF MEASUREMENTS OF GLACIER CHANGES

Several glaciers have been monitored during several decades in China. They are Glacier No.1 at the source region of the Urumqi River in Tian Shan, Qiyi Glacier in the middle part of Qilian Shan, Hailuogou Glacier on the east slope of Gongga Shan, Xiaodongkemadi Glacier in Tanggula mountains, and Meikuang Glacier in the eastern Kunlun mountains. Besides, changes of several tens to several hundreds of glaciers have been measured during different time spans in the last century. In the following, we give a brief introduction about these results.

Glacier No.1: The glacier has two branches; it is located at the source of the Urumqi River on the north slope of Tian Shan. It is a cirque-valley glacier; it had a length of 2.20 km and an area of 1.73 km^2 in 2000 (Jiao and others, 2004). The glacier has been monitored since 1959; it was determined that this glacier has had a continuous retreat of its terminus and was completely separated into two glaciers in 1993. The glacier has shrunken by 0.22 km^2 from 1962 to 2001, and the terminus of the lowest part of the east branch retreated 171 m by 2000 (fig. 2). The retreat of the glacier is closely related to a general mass loss of 10,597 mm from 1959 to 2002. Mass wastage has been accelerating; there has been a total mass loss of 4,437 mm since 1995/1996.

Figure 2

Figure 3

Qiyi Glacier: The Qiyi Glacier is a cirque-valley glacier with area of 2.98 km^2 and a length of 3.8 km. The mass-balance series was reconstructed based on observations during two periods: 1974-1977 and 1983-1988 and the meteorological data at a station about 50 km north of the glacier. Statistical equations have been established to relate mass balance components (equilibrium line altitude, ablation and accumulation rates, as so on) to meteorological parameters at this station. The estimated mass balance of the glacier was positive between 1956 and 1988, with a cumulative sum of 1,637 mm (fig.3a) (Liu and others, 1992). In general, the mass-exchange level on the glacier was low. However, there exists a transition during the year 1976 from positive to negative anomalies in mass balance and location of the equilibrium line altitude. Furthermore, the decreasing trend in mass balance turned to be more obvious after 1976 than before. Photogrammetry in 1956 and *in-situ* observations during 1975 and 1997 indicate that the terminus of this glacier was retreating at a rate of 2 m a^{-1} during 1956 and 1975, and at a rate of 1 m a^{-1} from 1975 to 1997 (Liu and others, 2000). The most recent observation shows that glacier terminus retreat was up to 2m again in 2001/02.

Hailuogou Glacier: The Hailuogou Glacier, on the eastern slope of Gangga Shan, slocated at the eastern margin of the Qinghai-Xizang (Tibet) Plateau, is a large valley glacier with a length of 13 km and area of 25.7 km^2. The mass balance was reconstructed based on the mass-balance measurements during 1990 and 1997 and hydrological observations 1 km down to the glacier terminus and meteorological data of a station about 60 km to the glacier (Xie and others, 1998). Mass balance of the glacier demonstrates that this glacier has been in a mass-loss state, with periodic fluctuations, since 1960 (fig.3b), further confirmed by the observed 545 m retreat of the terminus since 1966 (Xie and others, 1998; Su and others, 1999). Although the terminus of the glacier has been in general retreat, it was relatively stable from 1970 to the late 1980s, in retreat at a rate of 17 m a^{-1} during 1990 and 1995 and in an accelerated retreat of 18.3 m a^{-1} in 1996-1998.

Meikuang Glacier and Xiaodongkemadi Glacier: Observations on Xiaodongkemadi Glacier and Meikuang Glacier, which were started in 1989, showed a change to an accelerated mass loss after 1993 and 1994. The cumulative mass balance of the two glaciers amounted to -2,200mm and -1,600mm, respectively, after 1993/1994 (Pu and others, 1998). As a response to the negative mass balance, the two glaciers began to retreat in 1994, for example, Xiaodongkemadi Glacier has retreated by 13m during the period 1994 to 2001 (Pu and others, 2004).

Different researchers have compiled statistics about the percentage of glaciers that are retreating or advancing in China during different periods of time; statistical data was based on various measurements of glacier changes with topographic maps or, occasionally, *in-situ* observations (Zhang and Wang, 1995; Su and others, 1998; Li and others, 1986). Their analyses show that 55.4% of the glaciers were in retreat from the 1950s to the 1970s with 48% retreating glaciers and 30% stable glaciers during the 1960s and 1970s. Two-thirds of 178 glaciers sampled were in a state of retreat during 1973 and 1981.

4. REGIONAL PATTERN OF GLACIER CHANGES

With the improvement of satellite remote sensing, remotely-sensed digital images have been widely used to extract information about changes of glaciers in China (Liu and others, 2002, 2003, 2004, 2005; Lu and others, 2002; Shangguan and others, 2004a, b; Jin and others, 2004). Table 1 shows regions where glacier changes during the last 50 years were documented with remote-sensing techniques and geographic-information system methodologies. Remote-sensing imagery is geometrically corrected on the basis of rectification to topographic maps. To remove the influence of shadowed areas on images and to reduce interpretation errors, we applied an orthogonal correction to imagery by referencing to a digital elevation model (DEM) with 90-m cell resolution (level 1, the cell resolution used for 1:250,000 scale DEM's of topography), so that the positional error is reduced to about 1 pixel. Errors of visual identification of glacier margins on images are estimated at 1-2 pixels. Therefore, data showing changes in lengths of glaciers are reliable only when they exceed 90 m. With this technique, we have analyzed changes of >5,000 glaciers with length changes >90m (complemented, in part, by results from other researchers) during the past several decades in different areas of western China. We have made a comparison of glacier area identified by the visual interpretation with that made by the computer-based classification for assessing the accuracy of the digitized glaciers. In general, the visual interpretation has a larger error for glaciers less than 0.02km^2, with errors between 8%-12%; while for large glaciers the errors are reduced to 1% (Shuanguan and others, 2006). In the following, we present a brief discussion about glacier changes in different regions of western China.

Table 1

Qilian Shan: A comparison of glacier termini from Landsat Thematic Mapper (TM) images acquired in 2000 and 2001 and aerial photographs taken in 1956, 1966, and 1972 indicated that the monitored 33 glaciers monitored on the northeastern slope of the eastern end of the mountains were all in a state of recession, with a mean length reduction of 11.5 m a^{-1}. Six glaciers completely disappeared during 1972 and 2001. In the western section of the mountains, 95% of the monitored glaciers retreated at a mean rate of 4.9 m a^{-1} in length, but we determined that 10 glaciers were advancing during 1956 and 2000-01. Our analysis indicated that about 170 glaciers monitored in the northwestern slope of the western section lost 4.8% of their total area during 1956-1990, with a much more intensive area reduction (23%) for small glaciers

($\leq$1km^2) (Liu and others, 2003).

Tian Shan: There are >9,000 glaciers, with a total area of 9,225 km^2, in the Chinese Tian Shan. Repeat aerial photogrammetric mapping from two acquisitions of aerial photographs have been carried out for measurement of glacier variations in the Urumqi River basin (1962 and 1992) and source tributaries of Yili River basin (1962 and 1989) on the north slope of the Tian Shan. All of the 251 glaciers studied were retreating during the periods indicated above, but the total reduction in area was different in both basins. Glaciers in the Urumqi River basin lost 13.8% of their area; there was only a 3.1% reduction for glaciers in the Yili River basin. However, the estimated change in ice volume indicates that the average thickness of glaciers after thinning is very similar, 5.8 m for the Urumqi River basin and 6.1 m for the Yili River basin (Liu and others, 2002). As for glacier changes on the south slope of the Chinese Tian Shan, our analysis based on a comparison with aerial photographs taken in the early 1960s with Landsat TM images in 1999 and 2000 shows that 69.4% of the monitored glaciers were in a state of recession and that 30.4% have been advancing during the past 40 years. Subtracting the increase in area from the advance of some monitored glaciers with a total glacier area of 2,093.8 km^2 in the early 1960s, glaciers in the southern Tian Shan still lost 4.6% of their area.

Eastern Pamirs: The earliest glaciological investigations by Chinese scientists began in 1956, when a joint team of mountaineering specialists and glaciologists established benchmarks at the termini of 16 glaciers in the region. The glaciers were revisited sequentially in 1960, in late 1970s and in 1987; their observations of glaciers proved that glacier retreat was a common characteristic, except for one glacier which began to advance after the late 1970s (Su and others, 1998). Analysis of Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat TM images acquired in 2001 show that glaciers in the region were losing their ice mass, although about 26% glaciers were in advance when compared with aerial photographs taken in 1965 (additional aerial photographs of some glaciers were taken in 1975).

Table 2

The Karakorum: The north slope of the Karakorum is one of the most highly glacierized areas in China and is where the second highest mountain peak in the world is located. Early research from *in situ* observations in 1937, topographic maps in 1968, and a Landsat Multispectral Scanner (MSS) image in 1973 shows K2 (Qoger) Glacier retreated by 1.7 km between 1937 and 1968; however, the retreat slowed between 1968 and 1973. Similar changes occurred in two nearby glaciers, but two advancing glaciers in the region were found during the same period (Zhang, 1980). A careful analysis based on maps and Landsat Enhanced Thermal Mapper (ETM$^+$) imagery indicates that glacier changes in this region are quite complicated; some of the large glaciers were in a steady state (equilibrium) or have advanced or even surged during recent decades (Table 2) (Shangguan and others, 2004a).

Qinghai-Xizang (Tibet) Plateau: The broad area and regional high elevation of the Qinghai-Xizang (Tibet) Plateau provide optimum conditions for the development of glaciers under present-day climatic conditions. Glaciers on the plateau account for 84% and 81.6%, respectively, of the total area and volume of glaciers (including those in Karakorum and Qilian Shan) in China. Due to the complex meteorological factors of the Westerlies and South Asian monsoons, glaciers on the plateau belong to monsoonal-maritime - (temperate, southeast part and Hengduan Mountains), sub-continental - (Himalaya, central northeast part), and extremely continental - (central and northwest part) type glaciers. Changes in glaciers on the Qinghai-Xizang (Tibet) Plateau manifest different responses from the influence of diverse patterns of climate in the large region. Glaciers in the Kunlun Mountains, a mountain range along the northern margin of the Plateau, which extends from west to east, generally retreated during the past four decades, but the reduction in glacier area is larger (17%) from that in 1966 (Liu and others, 2002) at the eastern end and smaller (0.3%) from that in 1970 (Shangguan and others, 2004b) to the western end of the mountains, with intermediate changes in the central section of the mountains (Liu and others, 2004). In the central part of the plateau, glaciers were in relative equilibrium, but with a trend toward a general retreat state during the past three decades; for example, a decrease of 1.7% in glacier area in the basin that serves as the source of the Yangtze River (Lu and others, 2002). However, glaciers on the north slope of the Himalaya have experienced extensive wastage as indicated by Jin and others (2004); many small glaciers might have actually disappeared during the last 20 years.

5. DISCUSSION AND CONCLUDING REMARKS

By integrating the results of glacier changes in western China during the past 50 years (Table 3), we conclude that 82.2% of all the monitored glaciers were in state of retreat, while the remaining glaciers were advancing. This does not mean that advancing glaciers necessarily advanced over the entire observational period. Many may now be in retreat following some earlier expansion in the past two decades as regional climate warming has been much more evident since the 1980s than in earlier decades. Even compensating for the increase in area of some glaciers, the glaciers that have been monitored still show a total area loss of 4.5% from the late 1950s to late 1970s. As reflected by mass-balance variations on Glacier No.1 and other representative glaciers, mass wastage has tended to accelerate since the late 1970s or early 1980s, and especially during 1990s. We conclude that widespread and intensive mass loss of glaciers can be forecast under continuing global warming.

Table 3

As noted from Table 3, the period of observation of glacier changes differs for the regions considered here. This is due to differences in the acquisition times of the aerial photographs and satellite images. To examine the regional characteristics of glacier changes, we calculated annual percentages of glacier area changes (henceforth APAC) in every river basin or mountain region as shown in Figure 4. Of the 15 glacierized basins or mountains regions monitored, the APAC shows large regional differences that can be classified into three groups: Class A [APAC ≤ 0.1%/yr (regions 3, 5, 6, 8, 14)]; Class B [0.1% < APAC ≤0.2% (regions 2, 4, 10)] and Class C [APAC > 0.2% (regions 1, 7, 9, 12, 15)]. These regional differences in glacier area reduction may arise from some combination of the differences in (1) monitoring period, (2) regional climate changes and (3) individual glacier responses to those changes.

Figure 4

To examine this further, we use recent climate change on the Qinghai-Xizang (Tibet) Plateau (henceforth TP) to explore regional differences in the high elevation regions in western China. A comprehensive analysis of climate change over the TP from 1967 and 1997 was conducted by Zhao and others (2004). They divided the TP into four sub-regions and used a dataset consisting of records from 50 meteorological stations across the TP (Table 4). Over this three decade period a warming trend was found in all four regions, although the nature of the warming trend differed regionally. Air temperatures increased more during the cold season (October – March) than the warm season (April – September), particularly on the northern part of the TP where the cold season mean increased ~1°C over the three decades. In contrast, the increase was ~0.4–0.5°C in the central and southeastern parts of the TP. Over the same time period, warm season temperatures increased ~0.35–0.65C in the central and southeastern parts of the TP. Over the same period annual precipitation totals decreased in the northeast while they increased in the northwest, central and southeast. The largest increase in annual precipitation was ~13 mm, representing 35% of the 31-year mean (1967-1997), was in the northwestern part of the TP, mainly on the north slope of the western Kunlun Mountains. In the southeastern region of the TP, the average annual precipitation increase was ~30 mm, 5.3% of the 31-year mean (1967-1997). In the interior (central region) the average annual increase was ~20 mm or 4.1% of the 31-year mean while in the northeast the annual mean precipitation decreased ~4 mm, 2% of the 31-year mean. Based on ice core $\delta^{18}O$ records and radiosonde observations Shi and others (2006) suggest that the northern part of the TP may have experienced a cooling trend in the last few decades (1961-2002). The results presented by Zhao and others (2004) suggest that the greatest warming over the TP was not in the central region.

As the central and northwestern parts of the Plateau contain predominately polar type glaciers, it is possible that their slower dynamic response might explain why they have exhibited small changes during the last 40 years. Glacier changes in the southeast part of the TP may have resulted from the smaller warming trend and increased precipitation, coupled with the fact that temperate glaciers that dominate the region are more dynamically sensitive. Many of the glaciers in this region have advanced, indicating an overall positive mass balance. Data from two meteorological stations in the area, Gangri Gabu range, record a 20% increase in annual precipitation (1961-2002), that likely contributed to a positive mass balance for many of the glaciers over the last two decades. Glaciers in the northeastern TP fall into the sub-continental or the sub-polar type glacier categories. During the last four decades (prior to 2000), pronounced warming and reduction of precipitation, especially since the late 1980s, likely resulted in a dramatic mass loss for glaciers as evidenced in the Anyêmaqên Mountains where the largest annual mean area reduction in the percentage of glaciers was observed (Table 4).

In summary, over the last five decades the overall trend for glaciers in western China has been one of retreat; however, regional differences exist. These we attribute to different dynamical responses of the glaciers as a function of their different sizes and physical properties along with regional differences in climate changes. We conclude that strong warming and reduced precipitation are likely key drivers for the extensive reduction in ice cover in the eastern and southern parts of the TP. In contrast, recent cooling in the northwestern and central part of the Plateau may partially explain the relatively stable condition of those glaciers. The modest warming trend and increase in precipitation in the southeastern part of the Plateau could account for the modest changes in glaciers there. Although precipitation has increased in northwest China (Tianshan, Qilian Shan, eastern Pamirs, and so on), the strong warming may be the principal factor driving glacier retreat although large glaciers with heavy debris cover in their ablation areas may also contribute to the variations of ice extent in the region.

Glacier recession is a key factor in the variability of water resources in the arid river systems of the northwest China. The recent increase in discharge by these rivers may be partially related to the increase in glacial runoff caused by loss of ice during glacier retreat. Although the glaciers that we (and others) have monitored account for only 10% of the number and 24% of the total area of glaciers in China, our results may be extrapolated to infer glacier changes in various mountain regions of China. However, a more comprehensive glacier monitoring effort is needed as there are regions where glacier changes have yet to be assessed. In addition, to determine ice volume changes and validate these results requires higher resolution images with stereoscopic capability, such as the ASTER instrument, synthetic aperture radar (SAR)/interferometric SAR (InSAR), and laser altimetry techniques. Furthermore, field investigations must be intensified and modeling techniques applied to several typical glacierized watersheds to better understand glacial-runoff processes.

ACKNOWLEDGEMENTS

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Table 1 Data types used for analyzing glacier changes during past decades in selected mountain regions in China (CBERS: China-Brazil Earth Resource Satellite; Landsat TM: Landsat Thematic Mapper; Landsat ETM$^+$: Landsat Enhanced Thematic Mapper; Landsat MSS: Landsat Multispectral Scanner; ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiomete; K:1,000)

Mountain Range	Data types and the dates of first time of data acquisition		Data types and the dates of the second time of data acquisition	
Qilian Shan	1:50K/100K topographic maps, aerial photographs	1956, 1966,1972	Landsat TM	2000, 2001
Tian Shan	1:100K topographic maps, aerial photographs	1962, 1964	Aerial photographs Landsat TM	1992, 1989 1999, 2000
Kunlun Shan	1:100K topographic maps, aerial photographs	1970, 1966	Landsat MSS Landsat TM / ETM+	1976, 1989 2000
Karakorum	1:50K/100K topographic maps, aerial photographs	1937, 1968	Landsat MSS Landsat ETM$^+$	1973 2000
East Pamirs	1:100K topographic maps, aerial photographs	1962-65, 1975, 1985	Landsat TM ASTER	2001 2001
Inner Qinghai-Xizang (Tibet) Plateau	1:100K topographic maps, aerial photographs	1974	Landsat TM	2001
Southeast Qinghai-Xizang (Tibet) Plateau	1:100K topographic maps, aerial photographs	1980	CBERS, Landsat TM	2001
North slope of Mount Qomolongma	1:50K/100K topographic maps, aerial photographs	1970	ASTER, CBERS	2001, 2002

Table 2 Changes of some large glaciers during the last 30 years on the north slope of the Karakorum (Shangguan and others, 2004a)

Glacier code as used in CGI	Topographic map			Landsat ETM+ (2000)	
	year	length(km)	Terminus elevation (m)	Length change (±21.3m)	Terminus elevation (m)
5Y654D0042	1976	29.4	4100	-478	4130
5Y654D0048	1976	6.1	4780	2050	4280
5Y654 D0053	1968	42	4000	Stable, debris covered	
5Y654 D0077	1968	5.3	5030	910	4920
5Y654 D0078	1968	2.8	5080	140	5040
5Y654 D0096	1968	17.7	4120	-2662	4460
5Y654 D0097	1968	10.7	4620	1998	4580
5Y654C0081	1976	10	5280	stable	
5Y654 C0092	1976	14.5	5014	stable	
5Y654C0116	1976	20.8	4760	stable	
5Y654 C0128	1976	28	4520	stable	
5Y654 C0145	1976	27.8	4412	stable	
5Y654 C0163	1976	26	4250	stable	
5Y653K0072	1976	20.7	5220	stable	
5Y653Q0185	1976	4.4	5040	-278	5120

Table 3 Changes in glaciers in representative regions in western China during the past few decades monitored by remote-sensing method

Mountain regions	Time span for observations	Number of glaciers	Glacier area at the first measurements (km^2)	Changes in glacier area ($\pm km^2$)	Changes in glacier area (%)	Number of advancing glaciers	References
West Qilian Mountains	1956-1990	170	162.8±3.3	-7.8±0.2	-4.8	0	Liu *and others*, 2002
Tian Shan	1962/63/64-1989/ 1999/2000	960	2382.6±119.1	-111.3±0.6	-4.7	224	This study and Liu Chaohai *and others*, 2002
Qinghai-Xizang (Tibet) Plateau	1966,1968/69/70/80- 1999/2000/2001	2572	7282±218.5	-236±7.1	-3.2	387	This study, Liu *and others*, 2002, 2004, 2005; Lu *and others*, 2002; Jin *and others*, 2004; Shangguan *and others*, 2004a, b
East Pamirs	1960, 1975-1999	753	1889.7±94.5	-188.1±9.4	-10.0	198	This study
Karakorum	1968-1999	565	2707.3±243. 7	-111.1±10	-4.1	85	Shangguan *and others*, 2004a
Total		5 020	14424.4±679	-654.3±27.2	-4.5	894	

Table 4 Climate change during 1967 and 1998 over the Qinghai-Xizang (Tibet) Plateau (Zhao and others, 2004)

Sub-region of the Qinghai-Xizang (Tibet) Plateau	October - March mean air temperature (℃)	April – September mean air temperature (℃)	Annual air temperature(℃)	Annual precipitation (mm)
Northwest	1.0	0.0	0.6	13.2
Northeast	1.1	0.6	0.9	-3.9
Southeast	0.4	0.4	0.4	29.1
Inland	0.5	0.5	0.5	19.8

Figure captions

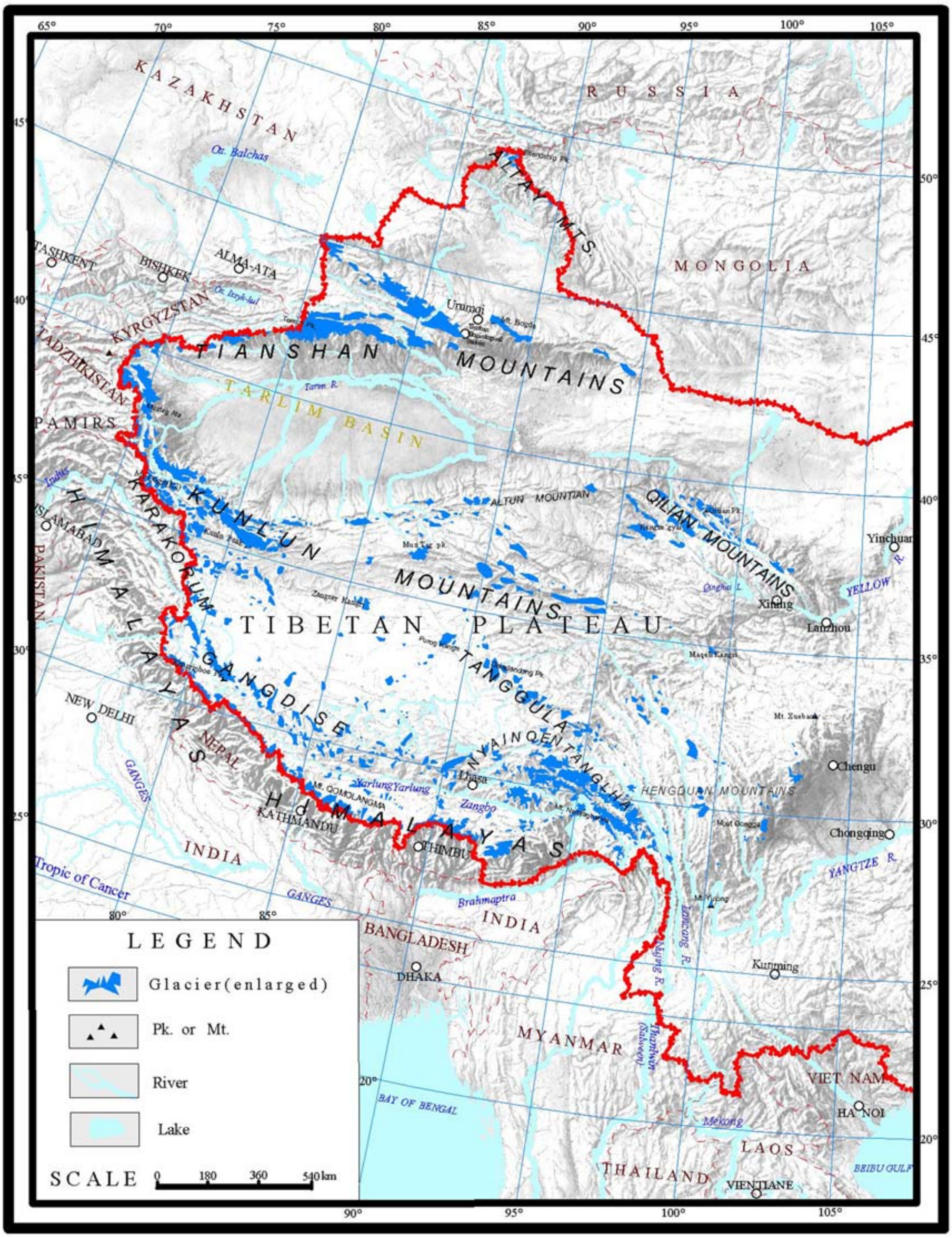
Figure 1. Geographical setting and glacier distribution in western China (grateful acknowledgement to Prof. Mi Desheng for producing this map)

Figure 2. Repeated photogrammetric mapping of Glacier No.1 at the source of the Urumqi River, Tianshan, at different times during the past 40 years (upper panel) (Wang and others, in press) (broken line with number indicating the terminus position in the numbered year and solid line with number is the altitude isoline), and mass-balance processes (lower panel) (adapted from Li and others, 2003)

Figure 3. Reconstructed annual specific mass balance for Qiyi Glacier (a) and Hailuogou Glacier (b).

Figure 4. Annual percentages of glacier area changes in each river basin or mountain ranges (Upper panel); the lower panel shows the monitored regions (1: Gaiz River; 2: Yerkant River; 3: Hetian River; 4: Keriya River; 5: Xinqingfeng (XQF) Ice Cap; 6: Geladandong Mountain; 7: Pengqu River; 8: Gangri Gabu range; 9: A'nyêmaqên mountains; 10: Western Qilian Shan; 11: Aksu River; 12: Kaidu River; 13: Kashi River; 14: Sikeshu River; 15: the Urumqi River).

Figure 1


KAZAKHSTAN
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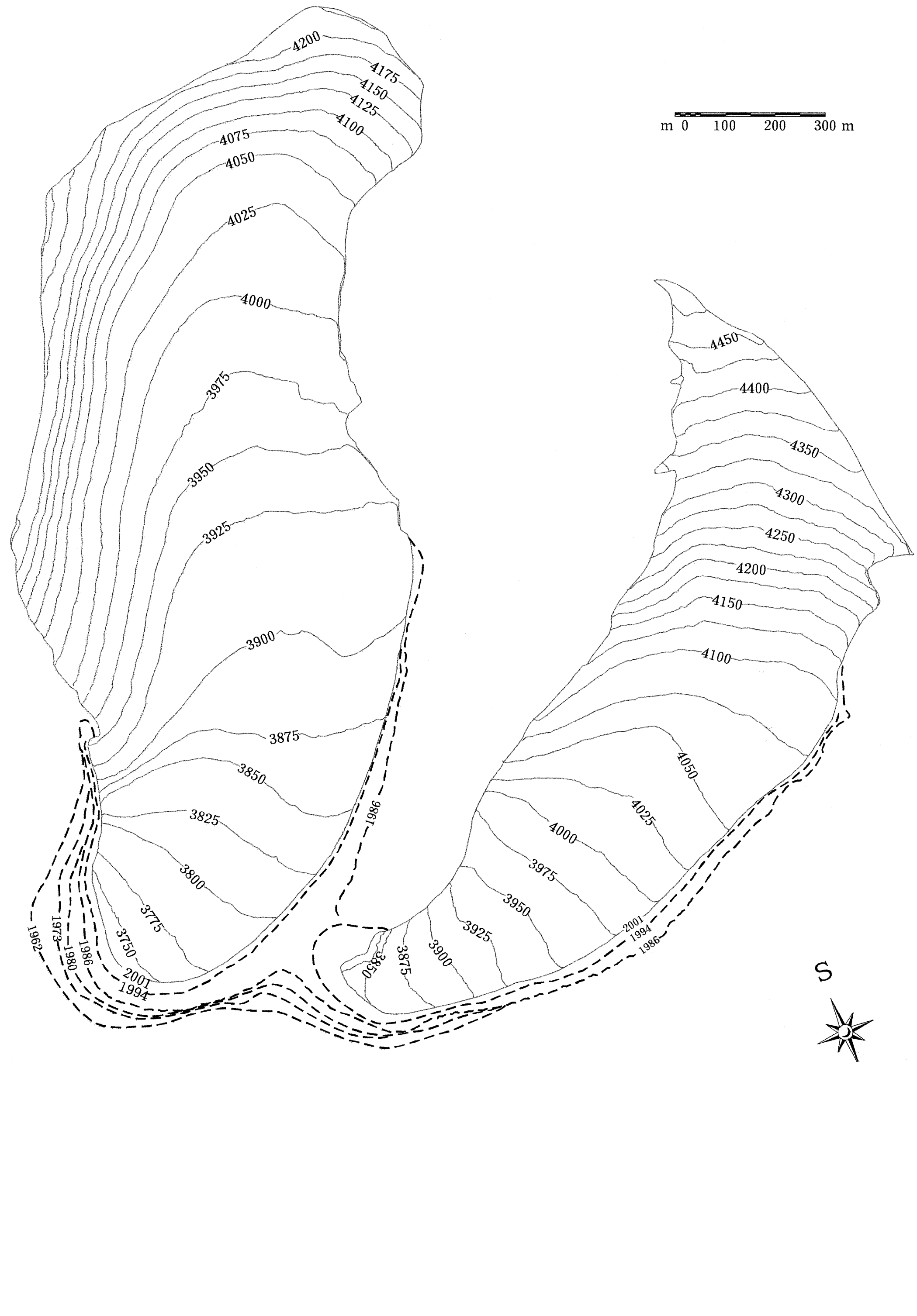
TASHKENT
BISHKEK
ALMA-ATA
Urumqi
KYRGYZSTAN
TADZHIKISTAN
TIANSHAN MOUNTAINS
TARIM BASIN
PAMIRS
KUNLUN MOUNTAINS
ALTUN MOUNTIAN
QILIAN MOUNTAINS
KARAKORUM
HIMALAYAS
ISLAMABAD
PAKISTAN
TIBETAN PLATEAU
Xining
Lanzhou
Yinchuan
YELLOW R.
GANGDISE
TANGGULA
NYAINQENTANGLHA
HENGDUAN MOUNTAINS
NEW DELHI
NEPAL
KATHMANDU
MT. QOMOLANGMA
Lhasa
Yarlung Zangbo
THIMBU
Chengu
Chongqing
YANGTZE R.
INDIA
GANGES
Tropic of Cancer
Brahmaptra
BANGLADESH
DHAKA
Kunming
MYANMAR
BAY OF BENGAL
VIET NAM
HA NOI
LAOS
THAILAND
VIENTIANE
Mekong
BEIBU GULF
LEGEND
Glacier(enlarged)
Pk. or Mt.
River
Lake
SCALE 0 180 360 540km

Figure 2



m 0 100 200 300 m
S
4200
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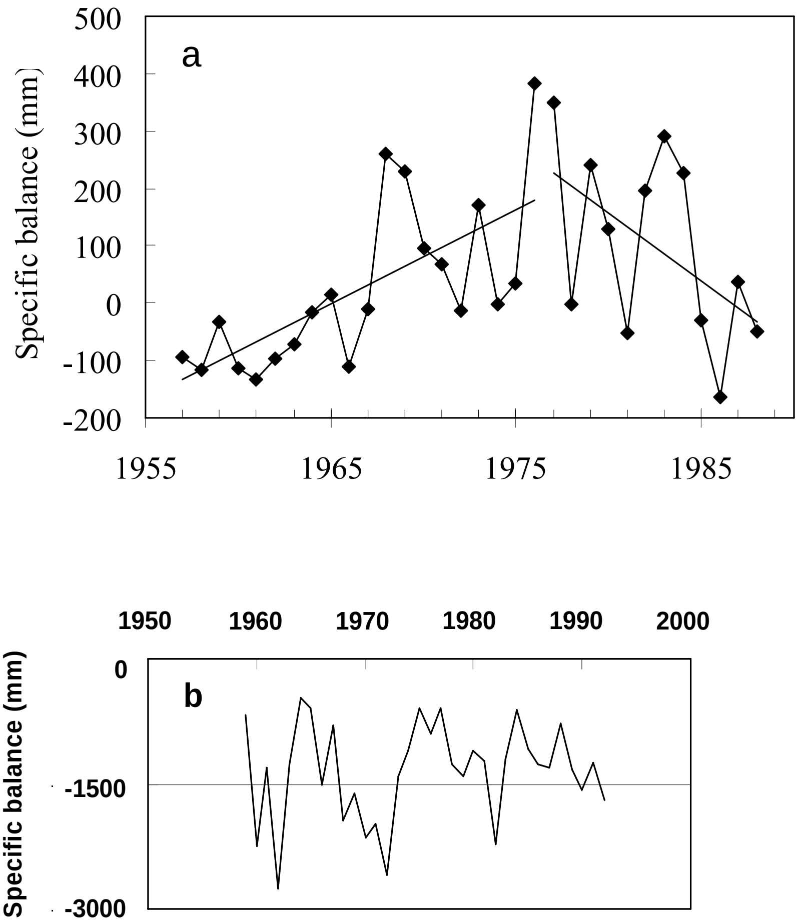
Figure 3


a
Specific balance (mm)
500
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100
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1985
b
Specific balance (mm)
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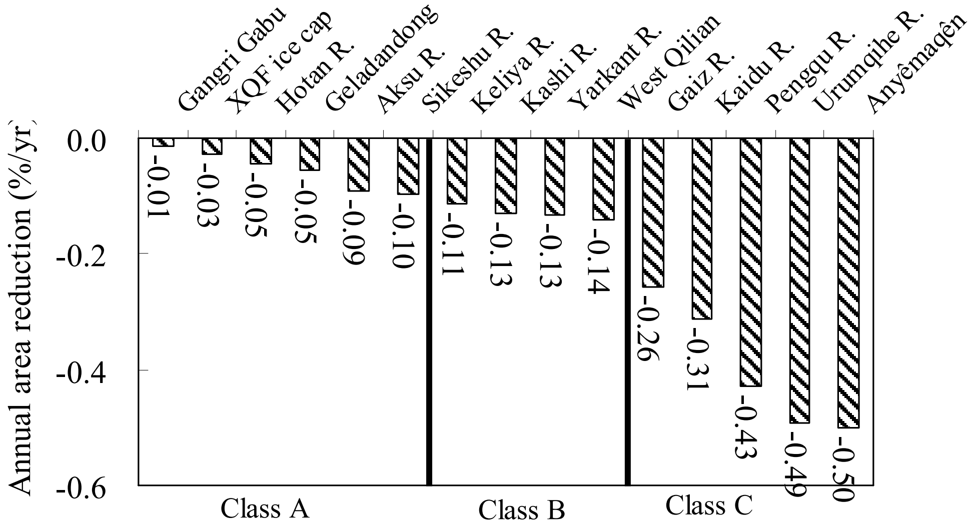
1990
2000
0
-1500
-3000

Figure 4



Gangri Gabu
XQF ice cap
Hotan R.
Geladandong
Aksu R.
Sikeshu R.
Keliya R.
Kashi R.
Yarkant R.
West Qilian
Gaiz R.
Kaidu R.
Pengqu R.
Urumqihe R.
Anyêmaqên
Annual area reduction (%/yr)
0.0
-0.2
-0.4
-0.6
-0.01
-0.03
-0.05
-0.05
-0.09
-0.10
-0.11
-0.13
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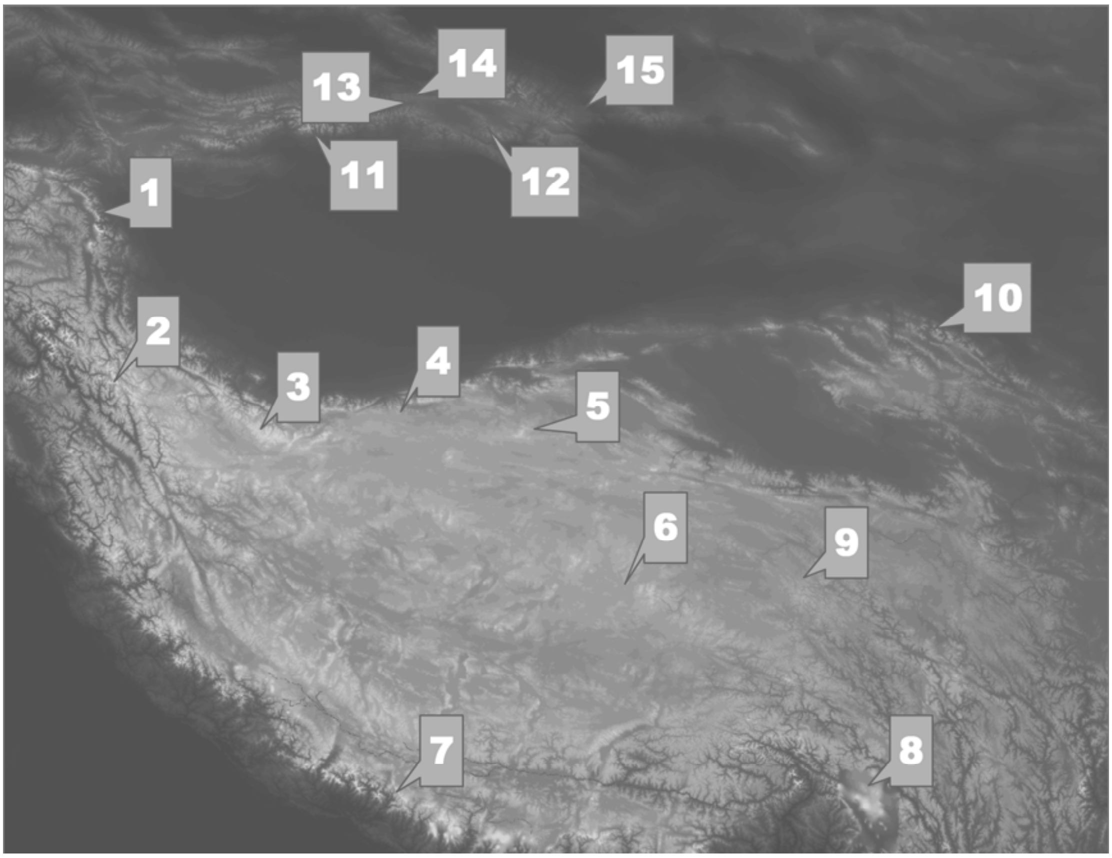
-0.14
-0.26
-0.31
-0.43
-0.49
-0.50
Class A
Class B
Class C



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Hello Shangguan Donghui,

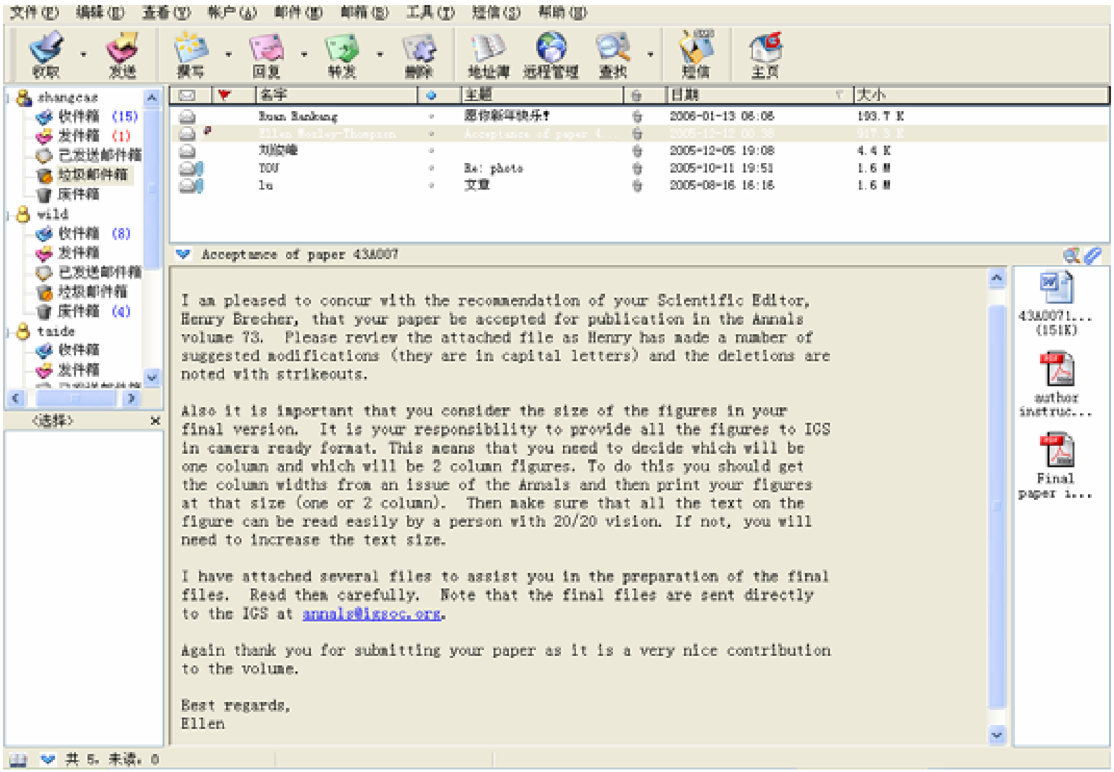
I am pleased to concur with the recommendation of your Scientific Editor, Henry Brecher, that your paper be accepted for publication in the Annals volume 73. Please review the attached file as Henry has made a number of suggested modifications (they are in capital letters) and the deletions are noted with strikeouts.

Also it is important that you consider the size of the figures in your final version. It is your responsibility to provide all the figures to IGS in camera ready format. This means that you need to decide which will be one column and which will be 2 column figures. To do this you should get the column widths from an issue of the Annals and then print your figures at that size (one or 2 column). Then make sure that all the text on the figure can be read easily by a person with 20/20 vision. If not, you will need to increase the text size.

I have attached several files to assist you in the preparation of the final files. Read them carefully. Note that the final files are sent directly to the IGS at annals@igsoc.org.

Again thank you for submitting your paper as it is a very nice contribution to the volume.

Best regards,
Ellen



Monitoring the glacier changes in the Muztag Ata and Konggur mountains, East Pamirs, based on Chinese Glacier Inventory and recent satellite imagery

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ABSTRACT. Glaciers in the Muztag Ata and Konggur mountains of the East Pamir Plateau in northwestern China have been monitored by applying aerial photo stereomodels (1962/1966) and Landsat TM (1990) and ETM$^+$ (1999) images, all of which have been compared in order to detect areal and frontal changes through the past four decades. The mean frontal retreat of glaciers in the Muztag Ata and Konggur mountains increased from 6.0m yr^{-1} between 1962/1966 and 1990 to 11.2m yr^{-1} between 1990 and 1999, with an overall glacier length reduction of 9.9% for the whole study period. The glacier area has decreased by 7.9%, which is mainly triggered by changes observed in the most recent period (1990-1999), when the annual rate almost tripled to 1.01km^2 yr^{-1}. This reveals that the most drastic changes, particularly the reduction of glacier area, have occurred in the last decade in this region. Based on meteorological data from Taxkogan station since 1957, we conclude that climate change, particularly the rise in summer temperature after 1994, is the main forcing factor in glacier shrinkage.

INTRODUCTION

Changes in mountain glaciers are one of the natural indicators of climate change (Oerlemans, 1994). With global warming, the glaciers in middle and low latitudes have retreated continually and the mass balance of the glaciers has been continuously negative since the 1990s (E.G. Yao and others, 2004). Several investigators have pointed out that glacier shrinkage can contribute substantially to rising sea-level, e.g. Zuo and others (1997) and Van De Wal and others (2001). Glaciers have an important role in climate change, sea level rise and flood hazards. This is why investigation of glacier mass balance and glacier area fluctuations is an important component of the Global Climate Observing System (GCOS) (Haeberli and others, 2000). The Global Land Ice

Measurements from Space (GLIMS) project was carried out to monitor land glacier changes using Landsat Enhanced Thematic Mapper Plus (ETM^+)/Thematic Mapper (TM), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and other remote sensing images (Kieffer and others, 2000; Paul and others, 2002b; Kääb and others, 2002).

The Chinese Glacier Inventory (CGI), finished in 2002 (Mi and others, 2002), was one of the significant steps in providing integrated knowledge about glaciers in China and forms the key data base for further studies on regional glacier fluctuations, their responses to climate change, as well as their influence on water resource variations. A pronounced atmospheric warming of 0.7^{o}C occurred over western China during the past 50 years (Li Dongliang and others, 2003), with a likely climate shift from warm-dry to warm-wet conditions in northwestern China (Shi and others, 2002). Glacier retreat prevailed in recent decades throughout China, as shown by field observations and satellite remote sensing monitoring (Zhen Li and others, 1998; Ren and others, 1998; Li and others, 2003; Liu and others, 2003; Yang and others, 2003; He and others, 2003; Jin and others, 2004). However, there are still several regional gaps where glacier behavior is presently unknown. Because we are interested in characterizing response of glaciers to climate change in different regions with various climatic settings, it is necessary to extend our monitoring of glaciers to a region like the Muztag Ata and Konggur mountains in the eastern Pamirs. Another reason for our interest is that water resources are a key factor for society and economic development in this drought-prone inland region. Glacier runoff here plays an important role as a source of water for one of the key tributaries of the Tarim River, the Kaxgar River, which supports daily life, agriculture, livestock and industry in the city of Kaxgar. The glacier changes in the Tarim basin are estimated over the past several decades (Fig. 1) by comparing the photogrammetrically-derived (CGI) with Landsat TM/ETM^+ satellite images acquired on more recent dates. The results of this study are important and useful for investigations of hydrological change and for regional water resource management.

STUDY AREA

The Muztag Ata and Konggur mountains are located on the eastern Pamir Plateau (38^o-39^{o}N, 74^{o}40'-75^{o}40' E). They range in elevation from a minimum of about 3,000 m a.s.l. to a maximum of 7,546m a.s.l. and 7,719m a.s.l. at the two summits, respectively. Several valley glaciers descend from the ice caps with snow line elevations of 5,200-5,700m a.s.l. and terminus positions between

3,900 and 4,900 m a.s.l. for most of them, according to the CGI (Yang and others, 1989; Liu and others, 2001). Glaciers in the study region feed three rivers; the Taxkogan River, a tributary of the Yarkant River, and two tributaries of the Kaxgar River, the Kusan River and Gezhe River (Fig. 1).

These glaciers belong to an extremely continental type, with one of the coldest environments in low and mid-latitude regions (Zhang, 1980; Su and others, 1989; Wu and others, 2003; Li and others, 2004) and one of the driest glacierised areas in China. The data at Taxkogan meteorological station (37°46′N, 75°14′E, 3090.9m) show that annual precipitation remains below 70mm and mean summer temperature (June to August) is as high as 15.1℃. It is estimated that monthly mean air temperatures can be higher than 0℃ over glacier terminus areas during the warm season (May to September), so intensive ablation may occur in June-August.

According to the CGI, there are more than 302 glaciers in the Muztag Ata and Konggur mountains, covering a total area of 1067.24km^2 (Liu and others, 2001; Yang and others, 1989). The majority are small glaciers as shown in Figure 2 (53.5% of less that 1 km^2), but because there are some larger glaciers, the mean glacier area is 2.82km^2.

METHODS AND DATA SOURCES

The data sources used in this study are listed in Table 1. Glacier outlines from the CGI were interpreted and measured by stereo-photogrammetry from aerial photographs at a scale of 1:46,000/50,000 taken during 1962/1966. They were transferred to 1:100,000 topographic maps in the Universal Transverse Mercator (UTM) coordinate system referenced to the World Geodetic System of 1984 (WGS84). Finally, the glacier outlines were digitized as GIS (geographic information system)-based vector files (total 302 glaciers) for further processing. The 1981 DEM was produced by digitizing the 40 m-interval contours and spot heights from the same topographic maps, using ARCVIEW software. Two Landsat TM images and two Landsat ETM$^+$ images with almost no cloud and snow cover were chosen and used. Composite images from bands 5, 4 and 3 (30m resolution) were produced first and merged with the band 8 (15m resolution) Landsat ETM$^+$ image. These images were orthorectified with the Orthobase Generic Pushbroom package using the 1:100,000 topographic maps and the 1981 DEM. Twenty independent verification points (Dwyer, 1995; Zhen Li and others, 1998) were selected from each image in order to check the accuracy of co-registration. The result showed that the residual root-mean-square error (RMSE) of all images was less than 44.9m (Table 1).

Different methods have been suggested for image classification to extract glacier borders (Paul, 2000; Zhang and others, 2001; Paul and others, 2002b), with image ratio and supervised classification the most commonly used. Compared with other methods the ratio of TM3/TM5 (Rott, 1994) with a threshold larger than 2.1 gives the best result in this work because of the influence of slope shadows. Due to the limitations of the method employed (Paul and others, 2002a), misidentification is frequent, for instance, on seasonal snow patches adjacent to glaciers or on debris-covered surfaces which are difficult to distinguish from bedrock owing to their similar spectral properties. In these cases, visual interpretation was applied combined with multispectral satellite images and the 1981 DEM (Paul and others, 2004a). Glacier extents in 1990 and 1999 were obtained by these methods. The error in area for most glaciers was generally less than 1% for both Landsat ETM$^+$ and TM. Unfortunately, 27 glaciers of less than 0.2km^2, derived from Landsat TM in 1990, had to be excluded because of the limitation of the spatial resolution of Landsat TM and the geometric correction error of 6-9% of glacier area (Paul and others, 2002a). In addition, two glaciers covered by cloud and three glaciers covered by debris (the total area was 229.03km^2) were also excluded since it was difficult to decide where the glacier boundary was. Thus, the first results of glacier changes derived from the 1962/1966 CGI and observed from 1990 and 1999 satellite images were computed for a sample of about 297 glaciers of the Muztag Ata and Konggur mountains.

Results

Glacier area changes

Glacier area has decreased significantly between 1962/1966 and 1999 in the Muztag Ata and Konggur Mountains (Table 2), with a total area loss of 66.02km^2, which is equivalent to 7.9% of the original area in the early sixties. Area reduction of glaciers of 1-5km^2 contributes 44.6% of the total area loss. As a whole, the mean size of glaciers in the Muztag Ata and Konggur mountains decreased from 2.82km^2 to 2.63 km^2 between 1962/1966 and 1999. Area reduction was 1.01km^2 yr^{-1} between 1962 and 1990; however, this had increased almost four times in the most recent period of 1990 to 1999 (4.26 km^2 yr^{-1}). This clearly shows the acceleration of glacier retreat in the region in the most recent decade.

Larger glaciers have lost more total area than small glaciers (Fig. 3a). As for the relative changes of glaciers of different sizes, percentages of area reduction of small glaciers are usually higher than those of large glaciers (Fig. 3b). This means that small glaciers are more sensitive to climate change than large glaciers. The few exceptions to this area loss result are some glaciers within some of the size classes that showed an area increase throughout the period (Fig. 3b), whereas three glaciers which WGMS (WORLD GLACIER MONITORING SERVICE) ID is CN5Y663B17, CN5Y662D25 and CN5Y662F1 disappeared. This may be one of the reasons that for glaciers less than $0.2km^2$ and between 5 and $10km^2$ in size the change is relatively small because of the offset effect of advancing glaciers.

The comparison of glacier changes with other regions in China was given in Table 3. Glacier changes in the Muztag Ata and Konggur mountains appear larger than in other extreme continental-type regions (Liu and others, 2004; Yang and others, 2003) and parts of sub-continental-type regions in China. However, they are smaller than those of maritime-type and other parts of sub-continental-type glaciers (Yang and others, 2003; Li and others, 2003; He and other, 2003). These result suggested that glaciers in the Muztag Ata and Konggur mountains are disintegrating rapidly since the 1962s.

Glacier frontal changes

In general, an average 9.9% glacier front retreat was detected during the period from 1962/1966 to 1999. Figures 4 (a) and (b), respectively, show the absolute and relative length changes of individual glaciers against their lengths in the early 1960s. Comparisons of glacier terminus positions in the last few decades indicate that 167 glaciers were retreating, about 40 were advancing and that changes of about 90 glaciers cannot be determined. Similar to the change in glacier area, glaciers experienced a slow retreat in length at a mean rate of $6.0m\ yr^{-1}$ between 1962 and 1990 and a rate of $11.2\ m\ yr^{-1}$ in the 1990s. Thus, in the 1990s the glaciers have been getting shorter at a much more rapid rate, 1.9 times as high as in the approximately 30 years before 1990.

As most values are above the diagonal line, relative change in area is larger than the corresponding change in length for most of the glaciers during the time span under consideration (Fig. 5). It is also deserved to note that the change of glaciers' area is not always synchronous to the change of glaciers' length. Some retreating glaciers expanded in area due to the increase of accumulation area but decreased at the terminus, and vice versa for advancing glaciers. This implies that change can occur on any part of a glacier. The ratio of mean retreat rate of glacier fronts during the 1990-1999 periods to that during 1962-1990 (1.9) is less than the ratio (4.0) for glacier area. However, length changes (9.9%) are greater than area changes (7.9%) if all the sampled glaciers are considered.

TEMPERATURE, PRECIPITATION AND GLACIER CHANGES

There are only a few meteorological stations, with relatively short-term instrumental records, in western China, especially in the mountain regions. The Taxkogan meteorological station is the only meteorological station on the Pamir Plateau in China located above 3,000m a.s.l. (Fig. 1). The station was set up in 1957 and has operated to the present. The summer temperature and annual precipitation at the Taxkogan station from 1957 to 2000 are shown in Figure 6. The summer temperature rose by 0.7^{o}C between 1957 and 2000 and the winter temperature, not shown, did not rise appreciably. In this time span, three cold periods occurred: 1961-1968, 1973-1977 and 1985-1993. Annual precipitation has increased slightly in the last four decades, which represents favorable climatic conditions for glaciers. Therefore, we believe that glacier retreat during the past 40 years can be attributed mainly to air temperature rise in the Muztag Ata and Konggur mountains. We also expect that a sharp retreat of glaciers in the region may happen in the future due to the warming in the most recent decade. However, some glacier advances might be a response to the three periods of cooling and the increase of annual precipitation, along with the glacial dynamics responses of individual glaciers.

The study of Pu and others (2003) verifies that surface ablation on an occasionally observed glacier was intensified due to atmospheric warming from the 1960s/1980s to 2001 in the Mt. Muztag Ata region. Hydrological analysis gives the result that glaciers in the Kangxiwa River valley headwaters of the Kaxgar River, have been losing mass at a rate of 123.5mm a^{-1} (Shen and others, 1997).

CONCLUSION

The present study supports the findings (e.g. Khromova and others, 2003; Paul and others, 2004b) that cold, high-mountain glaciers have been disintegrating rapidly since the 1970s. Our measurements show that glacier areas and frontal positions have decreased by 7.9% and 9.9%, respectively, between 1962 and 1999 in the Muztag Ata and Konggur mountains. Furthermore, a drastic acceleration of retreat since the 1990s is also found. The mean frontal retreat of glaciers increased from 6.0m yr^{-1} in the 1962/1966-1990 period to 11.2m yr^{-1} in 1990-1999 and the area shrinkage of glaciers in 1990-1999 increased about three times, to 1.01km^{2} yr^{-1}, from the annual rate in 1962/1966-1990. These accelerations are consistent with climate warming during recent decades.

Changes in glacier frontal positions and glacier area are easily observed phenomena to study the impact of climate change (Oerlemans, 1994) and its influence on water resources in arid regions (Yao and other, 2004). Glacier frontal changes are strongly enhanced but indirect, filtered and delayed signals of climate change (Oerlemans, 2001). They can be used to show that the few direct studies of mass balance variability are representative (Hoelzle and others, 2003) and to reconstruct historical climate variability (Oerlemans, 1994). The instrumental record at the Taxkogan meteorological station, which is more than 50 km away from the glacierized region, is not adequate to analyze climate changes in the Muztag Ata and Konggur mountains in detail. Nevertheless, glacier retreat is happening and the retreat has accelerated in the 1990s. Furthermore, glacier ice mass loss after 1980s has also led to increase magnitude and frequency of flash flood in Gezhe River because ablation of glacier surface accelerated as a consequence of atmospheric warming (Li Yan and others, 2003). Recently initiated mass balance measurements and ice core records from the Muztag Ata and Konggur mountains will help to better detect the climate-glacier-meltwater interaction.

Although glacier retreat in recent decades such as observed in the Muztag Aga and Kongur mountains is a response to climate fluctuations, there are also other factors affecting the changes in the glaciers, viz. glacier terrain, kinematics, dimensions, the sensitivity of different types of glaciers to climate change, and so on. Owing to the dynamic response, glacier fluctuations usually lag climate change by 5-20 years for medium-size glaciers (Ding, 1995; Liu and others, 1999). This characteristic means that some glaciers advance under conditions of regional atmospheric warming. As for the glacier dimensions, the narrow lowest parts and wide higher, ablation, area on most glaciers also influence the ratio of glacier area and glacier length variations.

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Table captions:

Table 1: Data sources used in this study

Image	Path/Row	Resolution (m) or Scale	Date	Quality	RMSE (m)	Source
Landsat 5 TM	149/33	30	7/6/1990	Cloud （2%） and very little snow	39.2	NASA (National Aeronautics and Space Administration)
Landsat 5 TM	149/34	30	7/6/1990	Cloud（2%） and very little snow	44.9	
Landsat 7 ETM+	149/33	15	9/25/1999	Cloud free	31.5	
Landsat 7 ETM+	149/34	15	9/25/1999	Cloud (6%)	34.5	
Topographic map	-	1:100,000	1981	-		Chinese military geodetic service
CGI	-	1:100,000	1962－1966	-		Aerial photographs
DEM	-	1:100,000	1981	-		Topographic maps

Table 2: Summary of glacier area data in the Muztag Ata and Konggur mountains according to area class

Area class[km^2]	Number	Mean Size [km^2]			Total Area[km^2]			Area Change [km^2 yr^{-1}]	
		1962/1966	1990	1999	1962/1966	1990	1999	62-90	90-99
<0.2	27	0.13	-	0.11	3.41	3.41*	2.9	—	-0.06
0.21-0.5	64/62	0.37	0.34	0.29	23.56	21.87	18.05	-0.06	-0.42
0.51-1.0	68/67	0.73	0.68	0.63	49.46	46.15	42.15	-0.12	-0.44
1.01-5.0	99	2.30	2.14	2.00	227.27	212.08	197.82	-0.54	-1.58
5.01-10.0	20	6.48	6.35	6.24	129.54	127.01	124.7	-0.09	-0.33
10.01-20.0	14	12.80	12.53	12.10	179.23	175.42	169.43	-0.14	-0.67
>20.01	5	45.15	44.78	43.45	225.74	223.94	217.24	-0.06	-0.74
all classes	297/294	2.82	2.73	2.63	838.21	809.88	772.19	-1.01	-4.26

Table 3: The comparison of glacier changes in China

Region Name	Glacier Type	Time Span	Glacier Count	Area change /km^2	%	Data source
Yulong Glacier No.1	Moraine-type	19th-2002	1		-40	He et al., 2003
A'nyêmagên	Sub-continental	1966-2000	58	-21.7	-17.0	Yang Jianping et al., 2003
Urumqi River glacier No.1	Sub-continental	1959-2000	1	0.22	-11.1	Li Zhongqin et al.,2004
Pengqu basin	Sub-continental	1970-2000/2001	99	-2.67	-9.0	Jin Rui et al., 2004
Nyainqen Tanglha MTS.	Sub-continental	1970-2000	870	-52.2	-5.7	This study
Karakorum	Sub-continental	1969-1999	565	-111.1	-4.1	This study
East Pamirs	Extreme-continental	1962/1966-1999	297	-66.02	-7.9	This study
Geladandong	Extreme-continental	1969-2000	753	-14.91	-1.7	Yang Jianping et al., 2003
Xingqingfeng glacier	Extreme-continental	1973-2000	88	-6.79	-1.6	Liu Shiyin et al., 2004

Figure captions:

Fig. 1. Location map of the study region in the Muztag Ata and Konggur mountains. Glacier masks (black) were derived from the digitized CGI of 1962/1966.

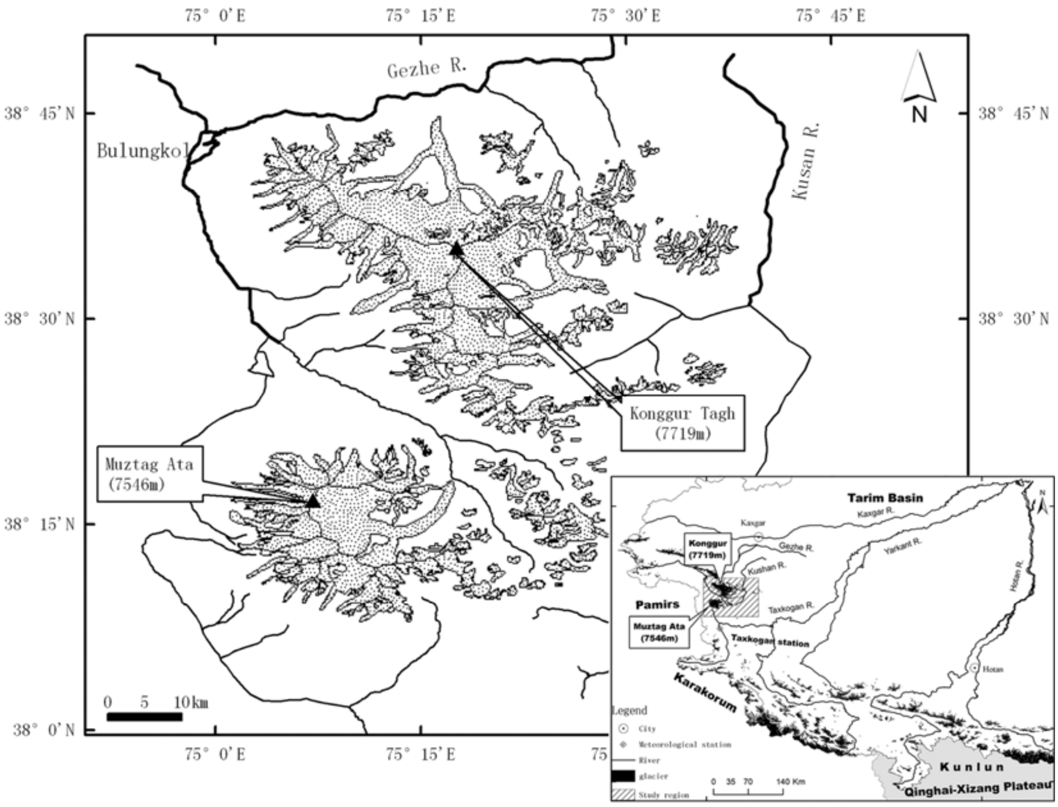


Fig. 2. Frequency of glacier area and number according to different area classes. The numerous glaciers in the 1-5km^2 range cover about 21.3% of the total glacierized area in the Muztag Ata and Konggur mountains.

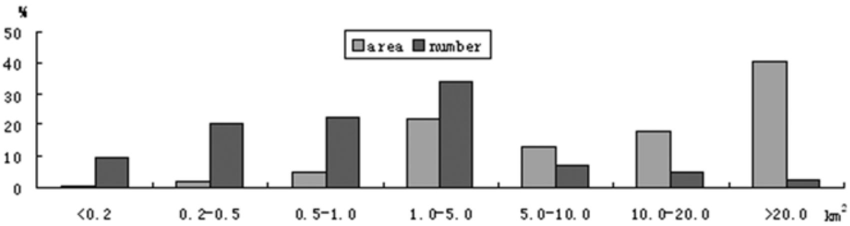
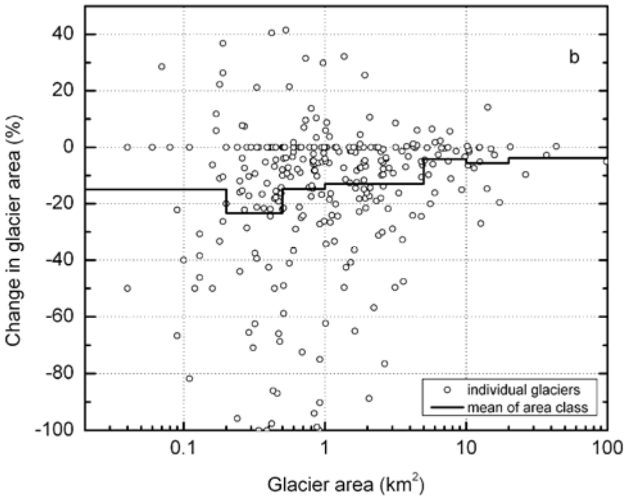


Fig. 3. Net (a) and relative (b) glacier area changes between 1962 and 1999. The changes are averaged for the area classes shown in Figure 2 (bold line). The smaller the glaciers, the higher their average percentage area loss. Two exceptions to the area loss are found in glaciers less than 0.2 km^2 and in the 5-10 km^2 range.



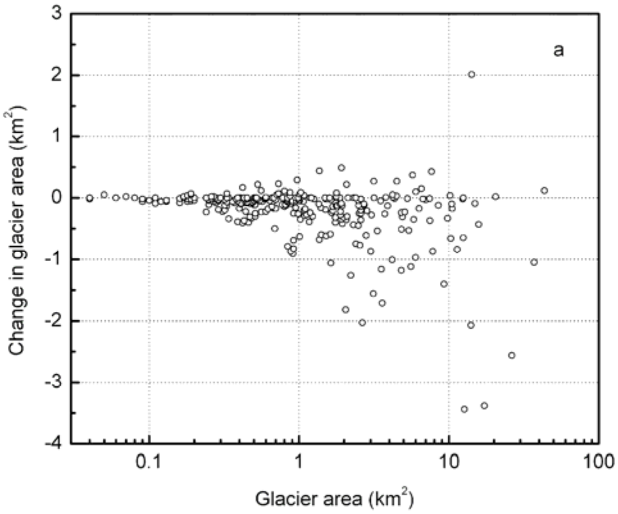
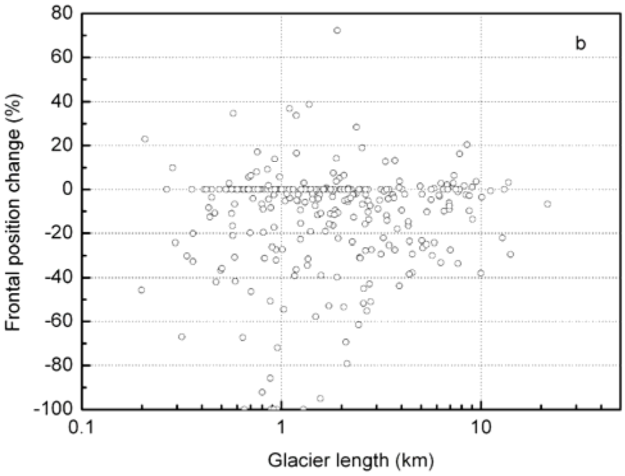


Fig. 4. Net (a) and relative (b) glacier front position changes between 1962 and 1999.



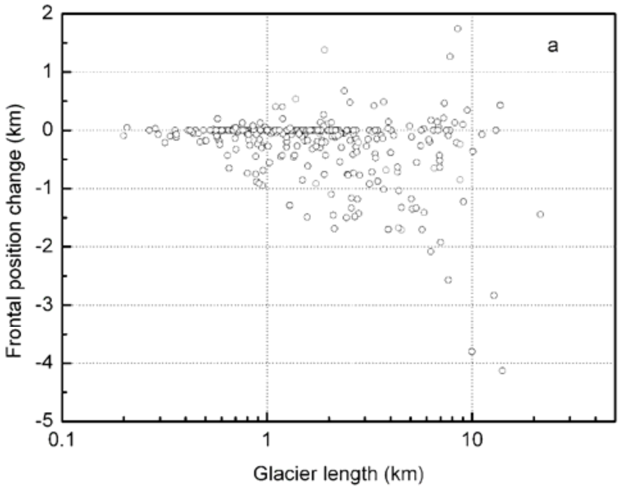


Fig. 5. Glacier area changes versus frontal changes (in %) between 1962 and 1999.

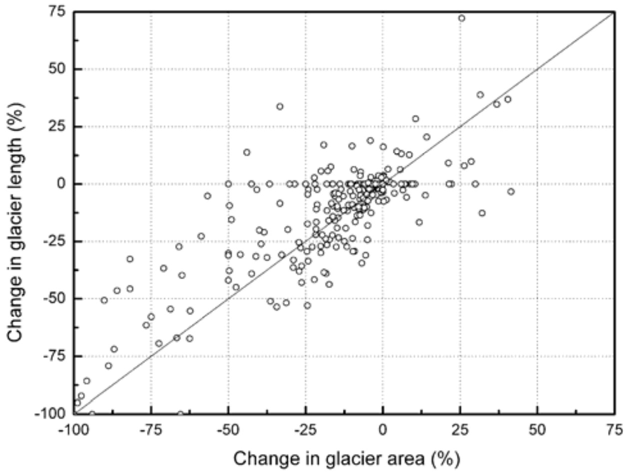
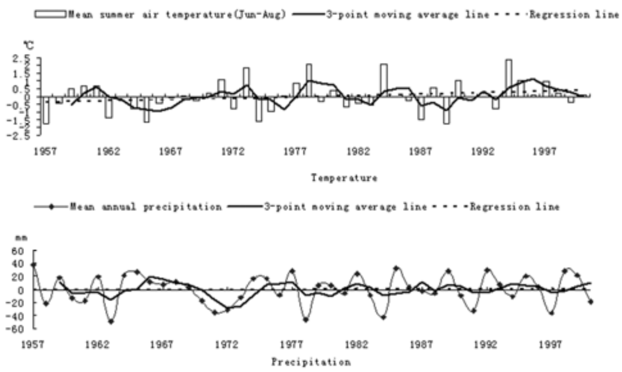


Fig. 6. Changes in mean summer air temperature (June-August) and mean annual precipitation at Taxkogan meteorological station.



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Hello Zhang Yong,

DeWayne Cecil, the Scientific Edtior for your paper (43A041), has recommended acceptance of your paper for the Annals volume 43. I am pleased to concur with him pending some final editorial revisions to your paper. Henry Brecher and I have both read the revised paper and made edits using track changes. There are several places in the paper where we were both confused as to exactly what you were saying. Those are highlighted with comments. Note that Henry made his changes in CAPITAL letters. A number of suggestions for improvement of your figures are also included.

As a reminder - it is important that you consider the size of the figures in your final version. It is your responsibility to provide all the figures to IGS in camera ready format. This means that you need to decide which will be one column and which will be 2 column figures. To do this you should get the column widths from an issue of the Annals and then print your figures at that size (one or 2 column). Then make sure that all the text on the figure can be read easily by a person with 20/20 vision. If not, you will need to increase the text size.

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Again thank you for submitting your paper as it is an excellent contribution to the volume.

Best regards,
Ellen

Application of a degree-day model for the determination of contributions to glacier meltwater and runoff near Keqicar Baqi Glacier, southwestern Tianshan Mountains

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ABSTRACT. A so-called "warm and wet transition" of climate in the arid portion of northwestern China has occurred since the late 1980s. A result of this climatic transition is an increase in runoff in Xinjiang and neighboring regions. In a warming and wetting change-of-climate scenario, we attempt to evaluate the impact of glacier meltwater and precipitation on increasing the outlet discharge (runoff) from Keqicar Baqi Glacier, southwestern Tianshan of China. In our research we have applied a degree-day model which is one of the most widely used methods of ice- and snow-melt computations for a multitude of purposes such as hydrological modelling, ice-dynamic modelling, and climate sensitivity studies. It is concluded that under the warming and wetting scenario, the primary supply for the runoff in this catchment is glacier meltwater with precipitation being the dominant secondary source; 84 percent and 8 percent of total runoff, respectively.

INTRODUCTION

There is a strong signal of climatic transition from warm and dry conditions to warm and humid conditions in northwestern China since the late 1980s (Shi and others, 2003). The average air temperature and average annual precipitation of western China from 1987 to 2000 have increased by 0.7 °C and 23 percent, respectively, compared to the average values from 1961 to 1986 (Wang and Dong, 2002; Song and Zhang, 2003). In a warming and wetting change-of-climate scenario in western China, there is a widespread increase in glacial meltwater which results in an increase in runoff in Xinjiang and neighboring regions (Hu and others, 2002; Han and others, 2003). Among 26 large rivers in Xinjiang, 18 rivers that originate in the Altai Mountains, Tianshan Mountains, Karakorum Mountains, and eastern Pamir Mountains have experienced increased runoff between 5 percent and 40 percent in the period from 1987 to 2000 compared to the period from 1956 to 1986. This increase is especially evident for the rivers from the south slope of the southwestern Tianshan Mountains of western China (Zhang and others, 2003).

However, due to the lack of observation data in the mountainous regions of western China, there is little research focused on the impact of increased glacier meltwater and precipitation on runoff. Hence, this paper attempts to simulate the meltwater of Keqicar Baqi Glacier in the southwestern Tianshan for the melt season of 2003 by applying a degree-day model, and analyzes the influence of glacier meltwater and precipitation on runoff. The results reported here are part of a study to document the response of glacial discharge and precipitation to changes in regional climate in the mountainous regions of northwestern China. The overall objective of this study is to provide a method for analyzing the potential changes in basin runoff due to changes in glacier meltwater and precipitation in mountainous regions.

STUDY AREA

Keqicar Baqi Glacier is a typical Turkistan glacier of the Akesu River Basin in southwestern Tianshan, China, with a total surface area of 83.56 km^2 (41°48.77′N, 80°10.20′E) (Fig.1). It is a large glacier formed by the convergence of several glacier tributaries and ranges from 3020 to 6342 m a.s.l. in elevation (Lanzhou Institute of Glaciology and Geocryology, 1987). One of the characteristics of the glacier is a debris layer covering most of the ablation area (Fig.1). The thickness of the debris layer ranges from 5 to 250 cm. In some places large rocks are piled up to several meters.

From a hydrological perspective, Keqicar Baqi Glacier exerts a considerable influence on water resources of the Ateoyinak River which flows into the Akesu River. Additionally, this glacier temporarily stores water as snow and ice over many timescales, especially at the source of the Ateoyinak River. It is evident from fig.2 that the discharge of the Akesu River has increased significantly. This appears to support the warming and wetting change-of-climate scenario. As compared with the period from 1957 to 1986, the annual discharge of the Akesu River during the 1987–2000 period increased by about 15 percent (Zhang and others, 2003).

DATA COLLECTION

From June to September 2003 a field programme was conducted on Keqicar Baqi Glacier, including ablation, meteorological and discharge measurements (Zhang and others, 2004). Meteorological data was obtained from two automatic weather stations (AWS) (A and B, Fig. 1) which were located on the glacier. The instrumentation at these stations collected data on air temperature, precipitation and wind speed. In this paper, the air temperature and precipitation are of the greatest interest.

Discharge was continuously observed approximately 300 m below the glacier terminus (Fig. 1) along the principal stream at 15 minute intervals, using mechanical stage recorders, pressure-type hydrological flow meters, and a hydrometric propeller. Ablation stakes distributed evenly on the glacier were used to monitor glacier melt throughout the melt season of 2003. The stakes were measured from July to

September at intervals of 20–25 days. Measured changes in the surface height were converted to water-equivalent melt ablation by using densities of 600 kg m^{-3} for snow and 900 kg m^{-3} for ice.

METHODS

Glacier meltwater

The amount of glacier meltwater was computed using a degree-day model. This model is dependent on a reported relationship between snow or ice melt and air temperature expressed in the form of a "positive temperature" (Braithwaite, 1995; Liu and others, 1998; Hock, 2003). Despite its simplicity, the degree-day model has proven to be a powerful tool for melt modelling, often outperforming energy balance models on a catchment scale, especially in remote high-mountain regions (US Army Corps of Engineers, 1971; WMO, 1986). The degree-day modelling approach was first used for an Alpine glacier by Finsterwalder and Schunk (1887) and since then it has been used all over the world for the estimation of snow or ice melt (Clyde, 1931; Collins, 1934; U.S. Army Corps of Engineers, 1956; Hoinkes and Steinacker, 1975; Braithwaite, 1995; Liu and others, 1998; Hock, 1999; Zhang and others, 2005).

For determining runoff contributions, the daily depth of meltwater, m for elevation band, h at time, t are obtained by using the following equations for snow and ice taken from Zhang (2005).

For snow,

$$m_{snow}(h,t) = \begin{cases} DDF_{snow}T(h,t)S(h,t) & : \quad T(h,t) > 0 \\ 0 & : \quad T(h,t) \le 0 \end{cases} \tag{1}$$

For ice,

$$m_{ice}(h,t) = \begin{cases} DDF_c T_c(h,t)S_c(h,t) + \ DDF_f T_f(h,t)S_f(h,t) & : \quad T(h,t) > 0 \\ 0 & : \quad T(h,t) \le 0 \end{cases} \tag{2}$$

where DDF is the degree-day factor; T and S are daily mean air temperature and surface area of different elevation bands, respectively; the subscripts c and f are debris-covered ice surface and debris-free ice surface, respectively.

The degree-day factor is different for debris-free ice, debris-covered ice and snow which is assumed constant in space and time in corresponding elevation band. These factors were taken from Zhang and others (2005). The air temperature recorded at station A (Fig.1) was used as input. Air temperature of different elevation bands was extrapolated by using a vertical lapse rate (VLR) of 0.006 °C m^{-1} as derived from the average temperature data from stations A and B. In addition, we extracted the area of each 100-m elevation band from a 90-m resolution Digital Elevation Model (DEM) using GIS technology and obtained the debris-covered, debris-free and snow-covered surface area on the glacier.

Precipitation

On Keqicar Baqi Glacier, the precipitation at the glacier terminus was 196.2 mm from July to September 2003. The maximum precipitation for a day was 29.3 mm, and often precipitation was < 0.1 mm in a day during our observations (Zhang and others, 2004).

For our computations, a linear increase in precipitation of 8.8 percent every 100 m was assumed for Keqicar Baqi Glacier (Zhang and others, 2004). Additionally, 26.0 percent was added to measured precipitation to account for the gauge undercatch error (Yang and others, 1989). A threshold temperature of 1.5 °C was used to discriminate liquid from solid precipitation (Ye and others, 1996).

Model testing

Melt simulations were evaluated using the following equations.

$$Y_1 = \frac{\sum_{i=1}^{n} |M_s - M_m|}{n\overline{M}_m} \tag{3}$$

$$Y_2 = \frac{\sqrt{\sum_{i=1}^{n} (M_s - M_m)^2}}{\sqrt{n}\overline{M}_m} \tag{4}$$

The criteria Y_1 and Y_2 are relative error and relative standard deviation, respectively (Hock, 1999), based on the differences between simulated melt, M_s and measured melt, M_t at each ablation stake on the glacier. The subscripts m and s denote measured and simulated, respectively. The superscript bar indicates the mean and n is the number of ablation stakes.

RESULTS

Simulated and observed meltwater equivalents at the ablation stakes are compared in Fig.3. The simulations represent the spatial means of 100 m altitudinal bands, whereas the stake measurements refer to an individual point inside each of these areas. Considering the simplicity of the melt model, there is a fair agreement between measured and simulated meltwater equivalents, although some points are not directly on the 1:1 line (Fig.3).

Table 1 lists the results of model evaluations using Equations (3) and (4). The results demonstrate that simulations of meltwater agree well with measured meltwater in the melt season of 2003 (Fig.3 (a)), although the degree-day factors obtained from the July data tend to underestimate the larger meltwater amounts on August and September (Fig.3 (c) and (d)). This error may be attributed to the different weather characteristics of different months. Zhang and others (2004) suggest that July 2003 was predominantly rainy with overcast conditions, whereas dry and sunny weather predominated in August and September 2003. The degree-day factor will vary according to the relative contributions of the energy-balance components (Ambach, 1988), and their relative importance varies with weather conditions. Therefore, our results should be interpreted with caution.

Based on the estimates of meltwater and precipitation, a calculation reveals that glacier meltwater and precipitation are approximately 84 percent and 8 percent, respectively, of the source of the total discharge in the Ateoyinak River source region. Variation of air temperature, precipitation and the components of discharge in the Ateoyinak River source region is shown in Fig.4. These results suggest that the main source of discharge of the Ateoyinak River is glacier meltwater, and that precipitation is a secondary source under a warmer and wetter climate scenario.

CONCLUSIONS

Our results suggest that with an increase in air temperature and precipitation in northwestern China, glacier meltwater becomes the predominant source for runoff to rivers in this area. We analyzed the impact of precipitation and glacier meltwater on the discharge (runoff) in the source region of the Ateoyinak River, southwestern Tianshan, using a degree-day model. This type of model is widely used when there is a lack of data for the alternative energy-balance approach. Results show that modelling glacier meltwater of Keqicar Baqi Glacier at the source of the Ateoyinak River during July–September 2003, based on the degree-day model, yielded a fair agreement between simulated and measured meltwater. Based on the calculated meltwater and precipitation, it was concluded that glacier meltwater and precipitation were approximately 84 percent and 8 percent, respectively, of the total discharge in the source region of the Ateoyinak River.

ACKNOWLEDGEMENTS

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TABLE CAPTIONS

Table 1 Results of the meltwater simulations of Keqicar Baqi Glacier for 2003 using a degree-day model. Y_1 and Y_2 are relative error and relative standard deviation, respectively, and are defined in equations (3) and (4). M_{sim} is average simulated meltwater equivalent (m).

FIGURE CAPTIONS

Figure 1 Location of Keqicar Baqi Glacier. The automatic weather stations (AWS) are located at A and B.

Figure 2 Temporal variation of annual discharge of Akesu River on the south slope of the southwestern Tianshan Mountains.

Figure 3 Measured vs simulated meltwater at the ablation stakes on Keqicar Baqi Glacier, July-September 2003.

Figure 4 Variation of air temperature (T, ^{o}C), precipitation (P, mm) and the component of runoff (Runoff depth, mm) in the source region of the Ateoyinak River.

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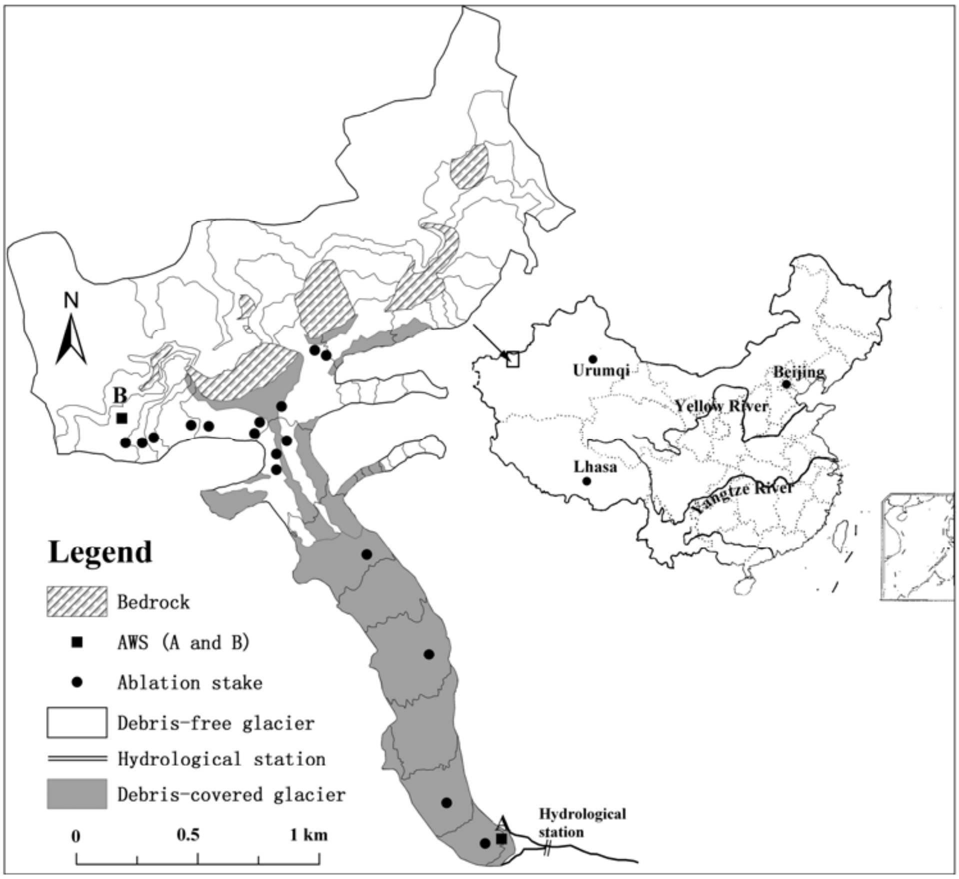
	Y_1	Y_2	M_{sim}	M_{obs}
July	0.01	0.02	0.73	0.73
August	0.11	0.15	0.81	0.80
September	0.12	0.19	0.78	0.72



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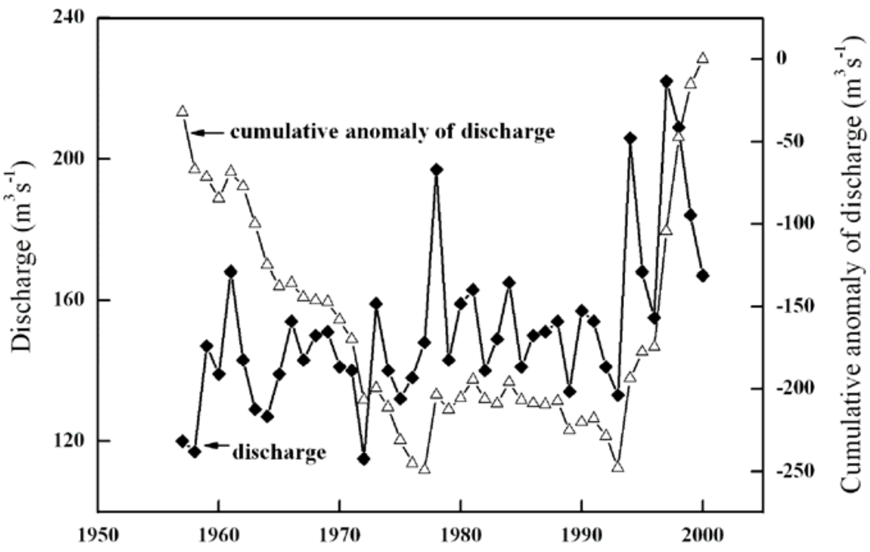

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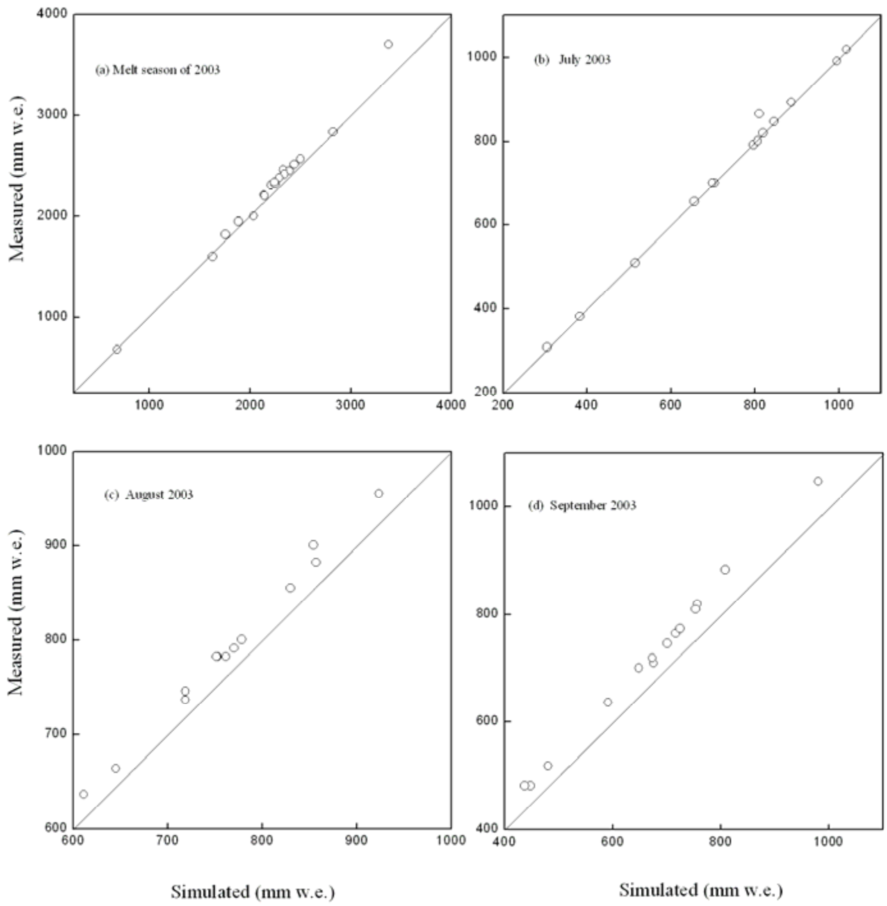

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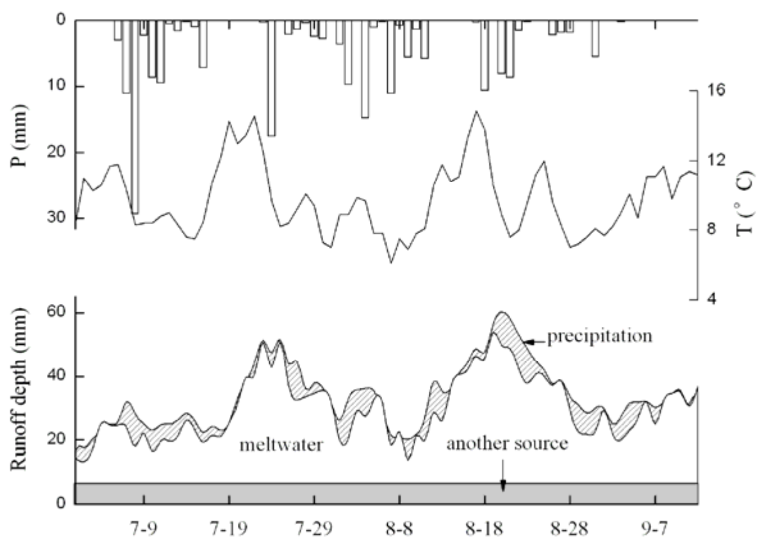

Figure 4 Variation of air temperature (T, ^{o}C), precipitation (P, mm) and the component of runoff (Runoff depth, mm) in the source region of the Ateoyinak River.

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Best regards,
Ellen

Observed degree-day factors and their spatial variation on glaciers in western China

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ABSTRACT. The degree-day factor is an important parameter for the degree-day model, which is a widely used method for ice and snow melt computation. Spatial variations of the degree-day factor largely impact the accuracy of modelling snow or ice melt. This study analyzes the spatial variability of degree-day factors obtained from observed glaciers in different regions of western China. Results clearly show that the degree-day factor for a single glacier is subject to significant small-scale variations, and the factor for maritime glaciers is higher than that for sub-continental and extremely continental glaciers. In western China the factors increase gradually from the northwest to the southeast. In general, the regional patterns of degree-day factors are detectable on the glaciers due to the unique climatic environment and heat budget of the Tibetan Plateau and surrounding regions. Low degree-day factors can be expected for cold-dry areas, whereas, high degree-day factors can be expected for warm-wet areas in western China. Depending on spatial variation of the characteristics of degree-day factors and the meteorological data, we can provide gridded degree-day models for non-monitored glaciers to reconstruct gridded historical glacier mass balance series in western China.

INTRODUCTION

The meltwater derived from snow and ice plays a crucial role in the annual streamflow of arid regions in western China (Yao and others, 2004), significantly affecting catchment hydrology by temporarily storing and releasing water on various time scales (Jansson and others, 2003). Although the melt process depends on different processes of the heat budget, modelling snow and ice melt using the energy balance model is relatively complex and much climatic data are needed as input. Hence, certain simplifying assumptions are widely used in practical computations of snow and ice melt. The degree-day model is generally considered to be one of the simplest but sufficiently accurate schemes to estimate snow and ice melt. Despite its simplicity, the degree-day model has proven to be a powerful tool for melt modelling, often on a catchment scale outperforming the energy balance model, especially in the remote high-mountain regions (US Army Corps of Engineers, 1971; Anderson, 1973;

WMO, 1986; Hock, 2003, 2005).

The degree-day model depends on a relationship between ablation and air temperature that is usually expressed in the form of positive temperature. The factor of proportionality is called the degree-day factor, involving a simplification of complex processes that are more properly described by the energy balance of the glacier surface and the overlaying atmospheric boundary layer. This means that the factor itself depends on the energy balance (Krenke and Khodakov, 1966; Ambach, 1988; Braithwaite, 1995). Therefore, there is a variation in degree-day factors resulting from the energy partitioning that varies with different climate, seasons and surfaces. Some studies suggest that spatial and temporal variations of degree-day factors largely affect the accuracy of modelling snow or ice melt (Quick and Pipes, 1977; Braun and others, 1993; Rigaudière and others, 1995; Schreider and others, 1997; Arendt and Sharp, 1999; Hock, 2003).

In western China, however, there is little research focusing on the variability of degree-day factors, especially in high-mountain regions. Therefore, this study provides a synthesis of the variation in degree-day factors essential for accurately estimating snow or ice melt processes, especially in the non-monitored mountain regions in western China.

DATA AND METHOD

Data collection

The 15 glaciers used in our study are located in western China (Fig.1) and were investigated or monitored during different periods in the past (Zhang and Bai, 1980; Mountaineering and Expedition Team of Chinese Academy of Sciences, 1985; Zhang and Zhou, 1991; Liu and others, 1992; Yao and Ageta, 1993; Li and Su, 1996; Su and others, 1998; Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1986-1993). The terminus elevations of these glaciers range from 2,640 to 5,450 m a.s.l.

In this study, the ablation data were measured using ablation stakes. Most of the ablation records span > 1 month (Table 1) and fortunately, on most of glaciers, the meteorological data were recorded over the entire period. The longest combined ablation-climate dataset exists on Urumqi No.1 Glacier (8 years, 1986-1993).

However, on four glaciers including Meikuang Glacier, Halong Glacier, Qirbulake Glacier and Yangbulake Glacier, there are no meteorological data. Hence, daily temperature on these glaciers was extrapolated from the closest national meteorological station using the vertical lapse rate (VLR). The distance between the glacier and national meteorological station varied considerably and ranged from several kilometers to a few hundred kilometers. The vertical lapse rate (VLR) of the different latitude and altitude zones over the Tibetan Plateau and surrounding regions can be taken from Li and others (2003) and ranges from -0.0054 to -0.006 °C m^{-1}. The equilibrium line altitude (ELA) for each of the 15 glaciers was taken from the China Glacier Inventory (CGI) and ranges from 4,000 to 7,000 m a.s.l. (Shi, 2005).

Method

The degree-day factor is an important parameter for the degree-day model, which is based on a linear correlation between snow or ice melt and the sum of daily mean temperatures above the melting point during a period. Commonly, the degree-day factor is computed either from direct measurements, using ablation stakes (e.g. Liu and others, 1996; Braithwaite and others, 1998) or snow lysimeter outflow (e.g. Kustas and Rango, 1994), or from melt obtained by energy balance computations (e.g. Braithwaite, 1995; Arendt and Sharp, 1999; Zhang, 2005).

In our study, degree-day factors are computed from direct measurements using ablation stakes distributed on different monitored glaciers. In general, the degree-day factor is given by

$$DDF = M/PDD \tag{1}$$

where DDF is the degree-day factor, different for snow and ice; M is the depth of meltwater in an N-day period; PDD is the sum of daily mean air temperatures above the melting point in the same N-day period. Commonly, PDD is given by (Braithwaite and Olesen, 1993)

$$PDD = \sum_{t=1}^{n} H_t \cdot T_t \tag{2}$$

where T_t is the daily mean air temperature on day t, and H_t is a logical variable, which can be defined such that $H_t = 1.0$ for $T_t \geq 0^{\circ}C$ and $H_t = 0.0$ for $T_t < 0^{\circ}C$. Strictly speaking, it might be better to define T_t as a function of a daily degree-day total, because daily mean temperatures can sometime be negative while temperatures are actually above freezing for part of the day. However, the familiar daily mean air temperature is used here for convenience in using conventional climatological data.

Based on the monitoring data of the 15 glaciers in different periods (Zhang and Bai, 1980; Mountaineering and Expedition Team of Chinese Academy of Sciences, 1985; Zhang and Zhou, 1991; Liu and others, 1992; Yao and Ageta, 1993; Li and Su, 1996; Su and others, 1998; Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1986-1993), the degree-day factors for ice and snow in western China can be obtained by equations (1) and (2) (Table 1). The results reveal a large variability from site to site. The values of the factors are derived from different integration periods ranging from a few days (e.g. Dagongba Glacier) to several years (e.g. Urumqi No.1 Glacier) which limit their direct comparison. In addition, the computed processes of degree-day factors involve two main sources of error:

(1) Possible errors in measuring snow or ice melt using ablation stakes distributed on different monitored glaciers; and
(2) Uncertainty in the vertical lapse rate (VLR) used to extrapolate air temperature from the nearest national meteorological station to the four glaciers where no

meteorological data exist.

RESULTS

Degree-day factors

Table 1 shows that there is a large variation in degree-day factors, which can be attributed to the difference in relative importance of individual energy components providing energy for melt. It is generally accepted that degree-day factors for snow are considerably lower than those for ice, due to the higher albedo of snow compared to ice. In western China, the mean value of degree-day factors for ice on the monitored glaciers is 7.1 mm d^{-1}°C^{-1}, whereas for snow it is 4.1 mm d^{-1}°C^{-1}. So the degree-day factor for snow reaches about 58% of that for ice in western China, while the corresponding percentage is about 40% and 70% on two Greenland glaciers and four Scandinavian glaciers (Hock, 2003).

Since the energy balance of the glacier surface varies considerably in space and time, the degree-day factor can be expected to vary seasonally and spatially. Some studies suggest that seasonal variations in degree-day factors for ice tend to be less pronounced because of low seasonal variations in surface albedo (Braithwaite and Olesen, 1993). In western China monthly variations of degree-day factors on Keqicar Baqi Glacier of southwestern Tianshan, given by Table 2, clearly show that monthly variations of the factor are less distinct. Similarly, seasonal variations during two summers are less pronounced over the ice on Qiongtailan Glacier, which only varies from -8% to 12% (Table 3). This finding is in agreement with that of Braithwaite and Olesen (1993), who detected no evidence of distinct seasonal variation in degree-day factors in their analysis of six years of summer data over ice on Qamanârssûp sermia in Greenland. Over snow, the seasonal variation in surface albedo is more pronounced due to metamorphic evolution, and hence degree-day factors also tend to be more pronounced (Kuusisto, 1980). In this study, however, we cannot discuss the variation in degree-day factors for snow due to lack of the long term monitoring data for snow in western China.

Spatial variation of degree-day factors

With different elevations, solar radiation and surfaces (albedo), degree-day factors will vary considerably in space. In addition, the degree-day factor is considerably affected by the topographic effects, such as slope, aspect and shape in mountain regions. Since temporal variations of degree-day factors on the observed glaciers of western China tend to be less pronounced, the spatial variation of the factors is discussed below.

For a single glacier, spatial variation is reflected by the relationship between the degree-day factor and the distance between the observed site of the factor and the ELA (Fig.2 and Fig.3). Figure 2 clearly shows that the degree-day factors for ice increase with decreasing distance to the ELA. It is concluded that on these monitored glaciers (Fig.2), the larger degree-day factors converge at a range of 500 m which is the distance below the ELA. It is evident from Figure 2 that the degree-day factor at higher altitude is larger than at lower altitude on these monitored glaciers where the ELA is very high, all above 4,000 m. This characteristic can be attributed primarily to ablation due to absorbed global radiation near the ELA where the positive degree-day (PDD) is low due to low air temperature (Kayastha and others, 2003). This means that glacier melt near the ELA (with small PDD) is mainly attributed to the absorbed global radiation, which results in a larger degree-day factor at higher altitudes than at lower altitudes, called “the low temperature effect” (Braithwaite, 1995). Nevertheless, an opposite trend of the degree-day factor is given by Fig.3, which clearly indicates that the degree-day factors for ice decrease with distance to the ELA on the glaciers in the central Tibetan Plateau and the Himalayas. On these glaciers, evaporation from ice, especially sublimation, plays a major role in the heat budget. Due to high energy consumption involved, evaporation from ice reduces considerably the energy available for melt, and thus reduces degree-day factors. In brief, the degree-day factors for a single glacier are subject to significant small-scale variations.

In western China the glaciers can be split into three types: extremely continental glaciers, sub-continental glaciers and maritime glaciers (Shi and Liu, 1999). For different glacier types, maritime glaciers are likely to have higher degree-day factors than sub-continental and extremely continental glaciers. The average values of degree-day factors for maritime glaciers, sub-continental and extremely continental glaciers are 10.9, 7.2 and 4.3 mm d^{-1} $°C^{-1}$, respectively. This finding is not in agreement with Hock (2003), who suggested that glaciers in maritime environments are likely to have lower degree-day factors than those in more continental climate regions due to relatively large turbulent fluxes, including condensation. Although the turbulent fluxes on maritime glaciers in western China account for more than 50% in the heat budget of the melt season (Xie, 1994), degree-day factors of maritime glaciers are higher than those of sub-continental and extremely continental glaciers. Besides the influence of different regional climate conditions, the fact that the ablation area of maritime glacier in western China is generally covered with a thin debris layer that accelerates glacier melt (Østrem, 1959; Rana and others, 1997; Zhang and others, 2005), should be emphasized among the most important reasons for this phenomenon. This debris layer has a strong influence on the surface energy balance and melting of the underlying ice, and the thermal conductivity and albedo are the main physical characteristics of a debris layer that control heat conduction to the ice-debris interface.

For the total glacier system of western China regional patterns of degree-day factors are clearly detectable (Fig.4). Figure 4 is a map of isolines for the degree-day factors for ice, which clearly shows that the factors increase gradually from the northwest to the southeast in western China. According to the values of degree-day factors, we can split the observed glaciers in western China into three categories: a high-value region ($\geq$ 9.0 mm d^{-1} $°C^{-1}$), a mid-value region (6.0-9.0 mm $d^{-1}$$°C^{-1}$) and a low-value region ($\leq$ 6.0 mm d^{-1} $°C^{-1}$) (Fig.4). It is evident that the high-value region ($\geq$ 9.0 mm d^{-1} $°C^{-1}$) is located in the southeast of western China; whereas, the low-value region ($\leq$ 6.0 mm d^{-1} $°C^{-1}$) lies in the northwest of western China. This distinct spatial variation of degree-day factors can mainly be attributed to the unique climatic environment and heat budget of the Tibetan Plateau and the surrounding regions.

Like the variation of degree-day factors, from the northwest to the southeast in western China, the climatic environment varies gradually from cold-dry to warm-wet; meanwhile, the type of heat budget varies from evaporation type to condensation-evaporation type (Shi, 2000). This shows that the regional climate conditions largely impact the spatial variation of degree-day factors in western China. Generally speaking, low degree-day factors can be expected for cold-dry areas where available ablation energy may be mainly consumed by evaporation, especially sublimation; whereas, high degree-day factors can be expected for warm-wet areas where the available ablation energy is mainly consumed by melting.

CONCLUSIONS

This study analyzes the spatial variation features of degree-day factors obtained from the investigated or monitored glaciers of western China over different periods. The mean value of degree-day factors for ice and snow is 7.1 mm d^{-1} $°C^{-1}$ and 4.1 mm $d^{-1}°C^{-1}$, respectively. Although temporal variations of degree-day factors are less pronounced, their spatial variations are significant. On a single glacier, degree-day factors are subject to significant small-scale variation. Considering different types of glaciers, maritime glaciers are likely to have higher degree-day factors than sub-continental and extremely continental glaciers. For the total glacier system, the regional patterns are detectable and significantly linked to the unique climatic environment and heat budget of the Tibetan Plateau and surrounding regions. In western China the high-value DDF region ($\geq$ 9.0 mm d^{-1} $°C^{-1}$) is located in the southeast; whereas, the low-value DDF region ($\leq$ 6.0 mm d^{-1} $°C^{-1}$) lies in the northwest; that is, the degree-day factors increase gradually from the northwest to the southeast in western China. Generally speaking, low degree-day factors can be expected for cold-dry areas where sublimation plays a major role in the available ablation energy; whereas high degree-day factors can be expected for warm-wet areas.

This paper describes the characteristics of the spatial variation of degree-day factors for degree-day models, used to estimate glacier melt on observed glaciers in western China. According to the China Glacier Inventory (CGI), there are 46,342 glaciers with a total area and volume of 59,415 km^2 and 5,601 km^3, respectively in western China. Due to the lack of money and time to monitor every glacier only 15 glaciers have been investigated or monitored during different periods in the past. The monitoring data of the 15 investigated or monitored glaciers are of vital importance for studying the change of non-monitored glaciers in China. Hence, based on the spatial variations of degree-day factors and the meteorological data of different observed glaciers in different periods, we can provide gridded degree-day models of the non-monitored glaciers for reconstructing gridded historical mass balance series in the different regions, which can then be used to predict the influence of glacier change on the water resources in western China.

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TABLE CAPTIONS

Table 1 Degree-day factors (*DDF*) on different monitored glaciers in western China.

Table 2 Monthly variation of the degree-day factors on Keqicar Baqi Glacier (2003).

Table 3 Seasonal variation of the degree-day factors on Qiongtailan Glacier during 1977–1978.

FIGURE CAPTIONS

Figure 1 Map of the study area, with locations of the 15 monitored glaciers in western China. The 15 monitored glaciers include 1. Urumqi No.1 Glacier; 2. Qiongtailan Glacier; 3. Keqicar Baqi Glacier; 4. Qirbulake Glacier; 5. Yangbulake Glacier; 6. Teram Kangri Glacier; 7. Meikuang Glacier; 8. Qiyi Glacier; 9. Halong Glacier; 10. Xiaodongkemadi Glacier; 11. Kangwure Glacier; 12. Hailuogou Glacier; 13. Dagongba Glacier; 14. Xiaogongba Glacier; 15. Baishuihe No.1 Glacier.

Figure 2 Increasing variations of the degree-day factors with decreasing distance to the ELA in western China.

Figure 3 Decreasing variations of degree-day factors with decreasing distance to the ELA in western China.

Figure 4 Map of *DDF* isolines for ice in western China.

Table1 Degree-day factors (DDF) on different monitored glaciers in western China. Units are mm d^{-1}°C^{-1}.

Mountain system	Glacier	DDF_{ice}	DDF_{snow}	Altitude（m a.s.l.）	Period	Reference
Tianshan Mountains	Urumqi No.1 Glacier	8.5		3831—3945	1986—1993	Liu and others,1996
		7.3		3754—3898	1986—1988	Liu and others,1996
			3.1	4048	1986－1993	Liu and others,1996
	Keqicar Baqi Glacier	4.5		3347	28 Jun—12 Sep 2003	Zhang and others, 2005
		7.0		4216	11 Jul—13 Sep 2003	Zhang and others, 2005
	Qiongtailan Glacier	4.5		3675	17 Jun—31 Jul 1978	this study
		7.3		4100	25 Jun—14 Aug 1978	this study
		8.6		4200	21 Jun—31 Jul 1978	this study
			3.4	4400	21 Jun—11 Aug 1978	this study
Hengduan Mountains	Hailuogou Glacier	5.0		3301	24 Aug 1982—Aug 1983	this study
	Baishuihe No.1 Glacier	13.3		4600	23 Jun—30 Aug 1982	this study
			5.9	4800	26 Jun—11 Jul 1982	this study
	Dagongba Glacier	13.2		4540	20 Sep 1982—22 Sep 1983	this study
	Xiaogongba Glacier	12.0		4550	15 Jul 1982—15 Jul 1983	this study

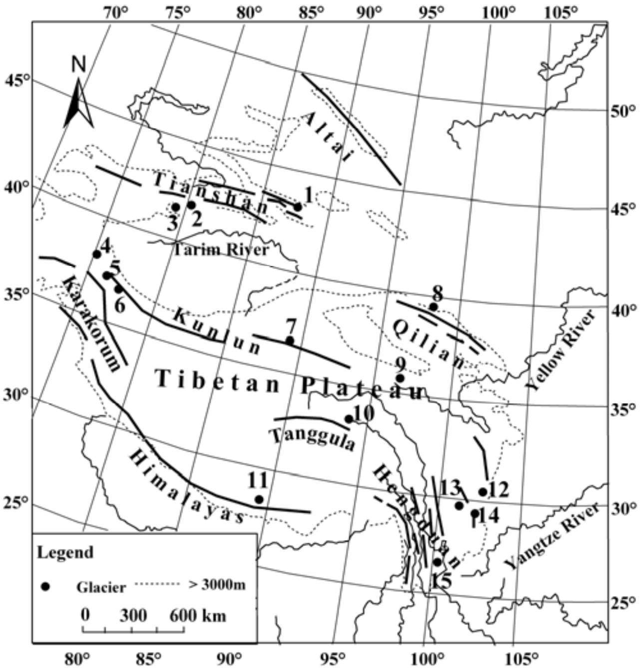
Mountain system	Glacier	DDF_{ice}	DDF_{snow}	Altitude（m a.s.l.）	Period	Reference
Karakorum Mountains	Batura Glacier	3.4		2780	Jun—Aug 1975	this study
	Teram Kangri Glacier	5.9		4630	25 Jun—7 Sep 1987	this study
		6.4		4650	24 Jun—7 Sep 1987	this study
	Qirbulake Glacier	2.6		4750	6 Jun—30 Jul 1960	this study
	Yangbulake Glacier	4.3		4800	1 Jul—5 Jul 1987	this study
Kunlun Mountains	Meikuang Glacier	3.0		4840	7 May—7 Sep 1989	this study
	Halong Glacier	4.7		4616	15 Jun—28 Jun 1981	this study
		3.6		4900	14 Jun—27 Jun 1981	this study
Tangula Mountains	Xiaodongkemadi Glacier	13.8		5425—5475	Jul—Aug 1993	Kayastha and others, 2003
Qilian Mountains	Qiyi Glacier	7.2		4305—4619	Jul—Aug 2002	Kayastha and others,2003
Himalayas	Kangwure Glacier	9.0		5700—6000	20 Jul—25 Aug 1993	this study

Table 2 Monthly variation of degree-day factors on Keqicar Baqi Glacier (2003).

Altitude of site (m a.s.l.)	DDF_{ice} (mm d^{-1}°C^{-1})		
	Jul.	Aug.	Sep.
3620	–	6.1	6.0
3742	5.1	5.3	4.9
3870	4.6	6.4	5.9
4113	8.7	8.9	8.6

Table 3 Seasonal variation of degree-day factors on Qiongtailan Glacier during 1977–1978.

Altitude of site (m a.s.l.)	DDF_{ice} (mm d^{-1}°C^{-1})		Variation range (%)
	1977	1978	
3675	4.9	4.5	-8
4100	6.5	7.3	12
Average	5.7	5.9	4



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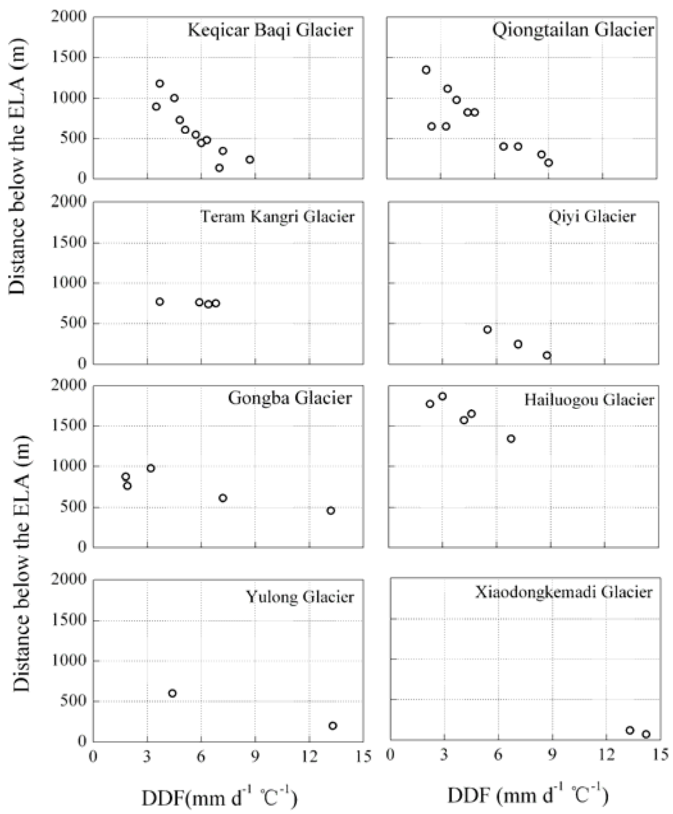

Figure 2 Increasing variations of the degree-day factors with decreasing distance to the ELA in western China.

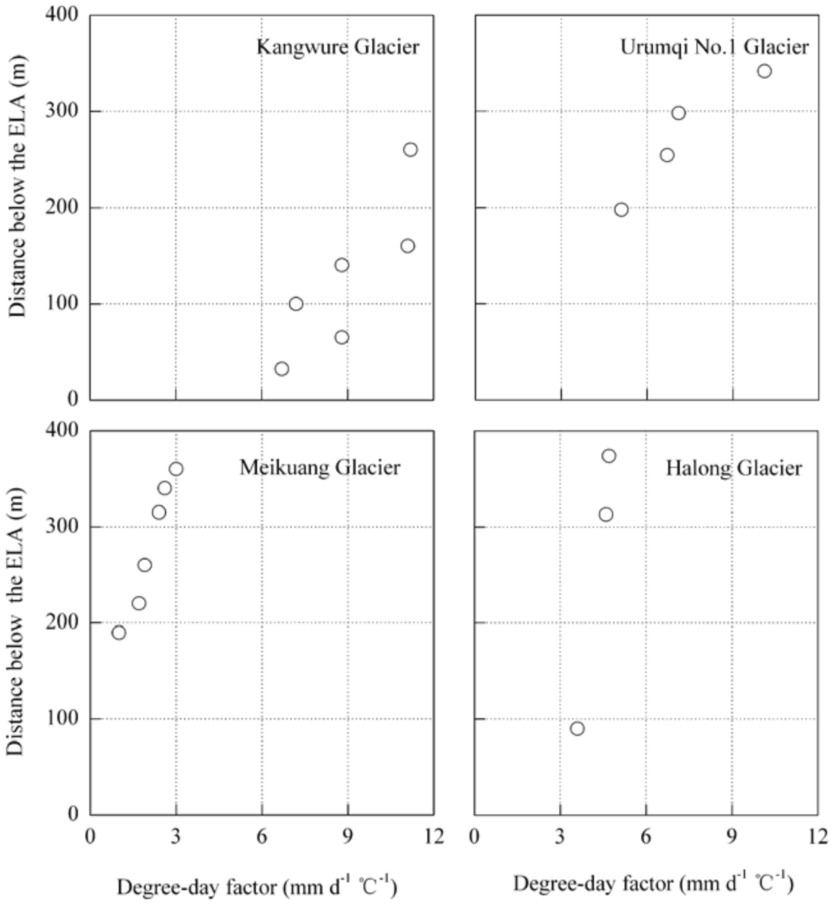

Figure 3 Decreasing variations of degree-day factors with decreasing distance to the ELA in western China.

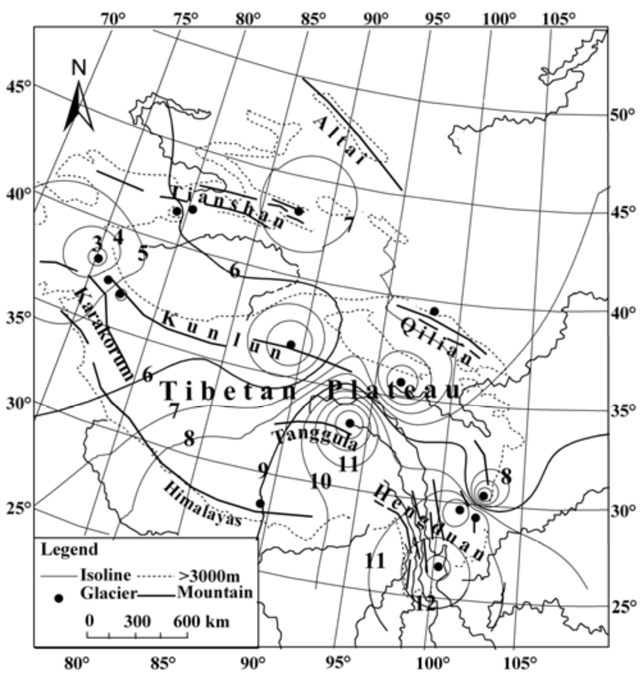

Figure 4 Map of *DDF* isolines for ice in western China.

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Snow Cover Distribution, Variability, and Response to Climate Change in the Western China

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ABSTRACT

A study is presented of geographical distribution, spatial and temporal variabilities of the western China snow cover in the past 47 years between 1951 and 1997. The data used consist of SMMR six-day snow depth charts, NOAA weekly snow extent charts, daily snow depth and number of snow cover days from 106 selected meteorological stations across the western China. Empirical Orthogonal Function was performed on SMMR dataset to better understand the spatial pattern and variability of the Qinghai-Xizang (Tibet) snow cover. A multiple linear regression analysis was conducted to show association of interannual variations between snow cover and snow season temperature as well as precipitation. Further, autoregressive-moving average model was fitted to the snow and climate time series to testing for their long-term trends. Results show that the western China did not experience continuant decrease in snow cover during the great warming period of 1980's and 1990's. It is of interest to note that no correlation was identified between temperature and precipitation in snow cover season. However year-to-year fluctuation of snow cover responds to both of snowfall and snow season temperature. About one-half to two-third of the total variance in snow cover are explained by the linear variations of snowfall and snow season temperature. The long-term variability of western China snow cover is characterized by a large interannual variation superimposed on a small increase trend. The positive trend of the western China snow cover is consistent with snowfall increasing, but in contradiction to regional warming. In addition, many constraints of the Qinghai-Xizang (Tibet) snow cover force us to challenge Blanford's hypothesis.

1. Introduction

Snow cover is a vital water resource in the western China. Major largest rivers of China, such as Yangtze River, Yellow River, etc. have their headwaters there. The agriculture and animal husbandry rely heavily on snowmelt water to be sustained. The crop failure and harvest have traditionally been tied strictly to the winter snow storage. Spring drought caused by snow scarcity represents potentially the most serious impact to agriculture and ecosystem. Sometimes it even results in flow break off of the Yellow river. On the other hand, heavy snowstorms often bring disaster to animal husbandry in Qinghai-Xizang (Tibet) Plateau, Xinjiang and Inner Mongolia. In the context of global warming changes in snow cover take on great significance and have clear economic impacts in western China.

The majority of climatic community convinced of pronounced reduction in seasonal snow cover in response to CO_2-induced global warming (IPCC, 1996a; Robinson et al., 1990; Groisman et al., 1994; Brown et al., 1996; Aizen et al 1997). However there are important regional exceptions (Moore et al, 2002; Ye et al 1998; Davis et al, 1998; Thompson et al, 1999; Vaughan et al, 1999; Ohmura et al, 1996; Li, 1995). Many studies have shown that higher snowfall is a characteristic of warming climate in cold regions (IPCC, 1996b; Karl et al, 1993; Leathers et al, 1993). Up-to-now global snow cover monitoring has not found any convincing evidence of the trend in snow cover variations on global scale. How snow cover will react to global warming is presently a controversial issue.

The South and the East Asia experience the monsoon climate that undergoes high-amplitude variability (Webster et al, 1998). The effect of the Qinghai-Xizang (Tibet) snow cover on the Asian monsoon is one of intriguing issue for climatologists (Blanford, 1884; Walker, 1910). Despite diagnostic and modeling investigations ascribed the importance to the Qinghai-Xizang (Tibet) snow cover (Hahn and Shukla, 1976; Barnett et al, 1988; 1989; Yasunari et al, 1991; Vernekar, et al, 1995), the efforts to support Blanfords hypothesis have left nothing but variant conclusions and sharp contrasts (Zwiers, 1993) for lack of ground truth of snow cover distribution and variability over the Qinghai-Xizang (Tibet) plateau. So far, the open questions about whether an apparent or a weak correlation (Li, 1994), a negative correlation or a positive correlation (Bamzai and Shukla, 1999) is in existence between the Qinghai-Xizang (Tibet) snow cover and the Indian monsoon rainfall, and whether albedo effect or hydrological effect of the Qinghai-Xizang (Tibet) snow cover is the key mechanism in affecting on Asian monsoon development, still elude us. Detailed and accurate information of Qinghai-Xizang (Tibet) snow cover is still essential to test Blanford's hypothesis.

The study area extends over the latitude-longitude domain from 70°to 105° east and from 27° to 50° north. Western China is physiographically divided into two regions: the Qinghai-Xizang (Tibet) plateau and northwestern China. The former, with an average elevation exceeding 4500m a.s.l, and area of more than two million square kilometer was acclaimed as the roof of the world. The Himalaya, the world highest mountain provides a natural screen in southern frontier of the plateau. The latter is an arid region of China and roughly encompasses by high mountains and large basins, such as Altai, Tianshan, Pamirs, Karakorum, Kunlun mountains and Tarim, Junggar Basins.

2. Datasets

2.1. SMMR six day snow depth data and their adjustment over western China

Assessment of spatial distribution and seasonal progress in snow mass requires reliable snow depth data with high-spatial resolution and covering a sufficient length of time. The microwave snow estimates have been recognized as an efficient means of large-scale mapping snow depth and snow water equivalent (SWE) with a high spatial density (Konig et al, 2001). The intensity of microwave radiation thermally emitted by snow cover is measured and expressed as brightness temperature. The scanning multi-channel microwave radiometer (SMMR), on board the Nimbus-7, is a five-frequency dual-polarized microwave radiometer. The frequency 37 GHz with a spatial resolution of 25km was the used sensor for snow cover observation. The brightness temperature was spatially averaged for each 0.5°×0.5°latitude-longitude grid cell and retrieved to snow depth by snow parameter retrieval algorithm developed by Chang et al (1987). The world SMMR snow depth charts were compiled for six-day period from 1978 to 1987 on a continuous basis and in a consistent manner. However employing a single global algorithm to extract snow depth from SMMR output significantly overestimates snow cover area in the Qinghai-Xizang (Tibet) plateau (Robinson, et al, 1984) for snow cover is predominantly shallow, patchy, and frequently of short duration. To calibrate SMMR estimates Chang et al (1992) thoroughly compared SMMR data with DMSP OLS short wave images and daily snow depths reported by 175 weather stations over western China. Then western China specific retrieval algorithms were developed under the support of GIS to account for the effect of the atmospheric conditions and snow cover extent adjustment for shallow and patchy snow area. The algorithms were expressed as:

for plateau $$SD = 2.0(T_{18H} - T_{37H}) - 8.0 \quad (1)$$

for high mountains $$SD = 2.0(T_{18H} - T_{37H}) - 6.0 \quad (2)$$

for rolling hills and basins $$SD = 1.59(T_{18H} - T_{37H}) - 3.0 \quad (3)$$

Where SD is the snow depth in cm; T_{18} and T_{37} are the horizontally polarized brightness temperature (K) for the SMMR 18GHz and 37GHz radiometers respectively.

In this study, NASA six-day SMMR snow depth data during the period between 1978 and 1987 have been adjusted by using the western china algorithms.

2.2. NOAA weekly snow extent charts

Weekly snow extent charts produced by NOAA from visible-band satellite imagery are the supplementary source of information for the Qinghai-Xizang (Tibet) plateau snow cover investigation. The charting improved considerably in 1972 with deployment of the AVHRR sensor and was digitized on an 89×89 cell northern hemisphere grid with spatial resolution ranging from 16000km^2 to 42000km^2. Presently NOAA weekly snow charts constitute the longest satellite-derived snow cover dataset available on a continuous basis and produced operationally. However they are limited by coarse resolution for regional scale study and by cloudiness which frequently obscures portions of the plateau. Since the Tibetan plateau has been one of the most difficult areas for snow cover monitoring, an efficient method to monitor the plateau snow cover is to utilize comparatively various satellite derived snow datasets and station snow cover data. To minimize discrepancies between datasets, NOAA weekly snow extent charts covering period from 1972 to 1989 were used to generate the plateau snow area time series for comparison with SMMR as well as station created snow time series.

2.3.In situ snow cover

To assess snow mass variability, particularly in light of long-term variation and trend the satellite data are still far from sufficient length. Ground station data could provide for longer time series generation. The meteorological network of western China consists of more then 200 synoptic stations. They report snow depth daily and number of snow cover days monthly. Snow density is measured at primary stations only per five days when snow depth≥5cm. The data span the period from 1951 to present. Considerable quality problems are inadequate spatial coverage and varying length. The former case does not refer to irregularity of station spatial distribution, but to high mountainous areas where snow cover is heavy and is affected by large interannual variability, and station is geographically sparse or virtually absent. For instance, over the Qinghai-Xizang (Tibet) Plateau the limited stations tend to be in inhabited river valley over the eastern plateau. Besides, it was only after 1956 that the Qinghai-Xizang (Tibet) network became the very least dense to ensure any adequate spatial coverage except for western Tibet (Figure 1). To minimize the defects of station data a subset of the network was created in northwestern China and the Qinghai-Xizang (Tibet) plateau respectively. The former consists of 46 stations. Of which 38 stations were selected in such a way that only one station was chosen from each grid cell of 2°×2° latitude-longitude. An additional 8 high elevation (2000m～4000m a s l) stations were added to account for orographic effects on snow cover distribution and to improve data coverage in high mountains. The station selection criteria included availability of a longest time series, few missing records, and without site relocation. The station records were used without further adjustments, and no attempt was made to fill a few missing data (Balling Jr. and Idso, 2002). After the strict quality control the station point records were integrated over the snow cover year (from September to next August) and space to derive regional time series. With regard to large scale area averages, biases and errors associated with specific point data were further minimized to such an extent that a homogeneous and meaningful signal can be extracted. Over the Qinghai-Xizang (Tibet) plateau, station network consisted of 60 primary stations. Of which 35 stations are located in Qinghai province and only 25 stations in Xizang (Tibet) Autonomous Region.

Figure 1

2.4. Climate data

Monthly temperature and precipitation from 1957 to 1992 for 60 stations over the Qinghai-Xizang plateau, and from 1951 to 1997 for 46 stations in northwestern China obtained from the Central Meteorological Bureau of China.

3. Methodology

The principal objective of this paper was to investigate spatial distribution and temporal variability of snow cover over western China, and particularly over the Qinghai-Xizang (Tibet) plateau. The Chief approaches used are briefly given below:

3.1.EOF analysis

Empirical Orthogonal Function (EOF) analysis is used for compressing an initial huge quantity of information and extracting the main dominant spatial-temporal modes that capture the maximum proportion of initial variance (Richman, 1986). The decomposition in EOF_S follows:

$$F(x,t) = \sum a_i f_i(x) g_i(t) \tag{4}$$

Where f_i and g_i are two sets of orthogonal functions in space and time; obtained by diagonalizing the covariance matrix. The corresponding eigevalues represent the portion of the variance. In this study we did not usw rotation in EOF analysis. The EOF_S are based on unnormalized SMMR snow depth data that are not converted to anomalies. It was performed on 10-year SMMR six-day snow depth field during the winter snow maxima (January and February) over the Qinghai-Xizang plateau. Compressing the original 90×875 matrix into 90×9 matrix, the first two take into account 60.4 percent of the total variance. The spatial distribution of loadings corresponding to the EOF_S represents the spatial pattern of snow depth distribution and variability.

3.2. Multiple linear regression

The linear regression used in this study is an ordinary regression approach. Since we are interested in diagnosing snow cover sensitivity to winter temperature and snowfall, a two-variable regression shortly described as the following:

$$S - S_0 = \frac{\sigma_S}{\sigma_P}\left(\frac{r_{SP} - r_{ST} r_{PT}}{1 - r_{PT}^2}\right)(P - P_o) + \frac{\sigma_S}{\sigma_T}\left(\frac{r_{ST} - r_{SP} r_{PT}}{1 - r_{PT}^2}\right)(T - T_o) \tag{5}$$

Where *S, P, T* denote snow cover, snowfall and temperature respectively. Other notations, such as means (S_O, P_O, T_0), standard deviations (σ_s, σ_p, σ_T), and regression coefficients (r_{SP}, r_{ST}, r_{PT}) are easy to understand. Their determinations can be found in any standard statistics book. For each regression coefficients a standard F-test was performed with degrees of freedom that two less than the number of years were used (Pollard, 1981).

3.3. Trend test

At the core of trend testing is to distinguish whether an observed trend in time series is a random trend or a deterministic trend. In this study, a statistical model consisting of a possible trend plus correlated noise is fitted to the snow and climate time series.

$$y_t = a + bt + E_t \tag{6}$$

where y_t represents snow and climate parameters in year t; E_t is the deviation from a straight line, and is assumed to be a stationary zero mean process.

When E_t is serially correlated, in order to detect a deterministic trend for time series due to random trend presence an autoregressive-moving average (ARMA) model is appropriate for adopting (Woodward and Gray, 1993). The statistical significance of the trends is evaluated by using the Students t-test with following significance parameter:

$$t = r[(n-2)/(1-r^2)]^{1/2} \quad (7)$$

Where n is the total number of years, and r is correlation coefficient.

4. Spatial pattern of snow depth over western China

Figure 2 shows spatial pattern of average snow depth (cm) during the winter snow maxima (January and February) between 1978 and 1987 estimated by SMMR covering 2500 cells of 0.5°×0.5° latitude-longitude grid over western China. It is characterized by uneven geographical distribution. Altitudinal variation is surprisingly pronounced. Snow depths vary spatially between large mountains and basins in northwestern China. The highest snow depth is seen in Altay mountain, the second highest occurs in Tianshan, Pamirs, Karakorum and Kunlun mountains. Besides, an appreciable snow cover is also noted in the Elgis valley and the Ili valley. In contrast, snow cover is rare in the Tarim basin, Lop Nur and Badain Jaran desert. In Junggar basin snow is predominantly thin, and frequently of short duration. Aside from the great distance to moisture sources, the blocking mountains keep the basins very dry in snow cover.

Figure 2

Snow cover is far from a pervasive feature over the Qinghai-Xizang (Tibet) plateau. It was about 59% snow covered in winter. Only in the peripheries, including Himalayas, Pamirs, Nyainqentanglha and estern Tanggula mountains there is heavy snow cover present. In the vast interior, such as Qaidam basin, Yarlung Zangbo valley, snow cover is rare, and in the North of Qinghai-Xizang (Tibet) plateau snow cover is thin and short duration.

In order to better understand and interpret the structures of the SMMR data, Figure 3 shows the first EOF_s pattern of 10-year SMMR six-day snow depth data during the winter snow maxima from 1978 to 1987. It contains 44.7% of the total variance and has uniform negative loadings over the Tibetan plateau, which are beyond the domain of China territory, The two largest loadings occurred along the east periphery and the west periphery of the plateau that represents the two heavy snow cover areas. An apparent similarity between Figures 3 and 4, indicates the first EOF_s represents an average of the original 10-year SMMR snow depth during the winter snow maxima. It is convinced that over the Tibetan plateau only in the peripheries, particularly in the east and the west peripheries, was any heavy snow cover noted. Unfortunately, many diagnostic and modeling investigations ascribed the importance to the Qinghai-Xizang (Tibet) snow cover acting as a huge elevated cool source on atmosphere but paid no attention to this key feature of snow cover distribution.

Figure 3 **Figure 4**

5. Annual cycle of snow cover

The regularity of annual cycle of snow cover seems to be ideal for agricultural practices. Large changes in timing, for instance, late or early spring snow cover dissipation and ill-timed snow peak would have the potential for significant societal consequences.

The normal annual cycle of snow water equivalent in northwestern China derived from the SMMR six-day snow depth averages during the 10-year observation and pentad snow density area-averages based on 36 primary weather stations in northwestern China (Figure 5a) demonstrated that snow begins accumulating in the mid November. Increases to a late February or early March peak, follows by a rapid decline until early April. The late peak and short ablation duration are beneficial to humans for overcoming spring droughts. In some winter the peak was delayed by about one mouth, and sometimes appeared earlier by half a month. The broad peak lasted for 72 days, while the sharp peak for only 30 days. The peak amounts of snow storage (snow water equivalent) between the heavy snow winter and the light snow winter have difference of $70\times10^{8}m^{3}$.

Figure 5

Over the Qinghai-Xizang (Tibet) plateau snow season normally begins in the mid September (Figure 5b). Snow cover growth is rapid in first half of winter with the maximum occurring in January. This is followed by a slow decline until June. The long snow season, early snow peak, rapid snow growth and slow snow decay are evident. Of all snow seasons, winter (Dec. Jan. Feb) has the greatest snow storage. The winter, spring (Mar., April, May.) and autumn (Sep., Oct., Nov.) are represented by 45.2%, 28.0% ad 21.2% of the annual snow storage respectively. The largest variability of peak snow amount is the most striking feature with great difference as many as $300\times10^{8}m^{3}$ between the heavy snow winter and the light snow winter.

The highly variable nature of annual cycles is principally responsible for the anomalies in spring runoff as well as seasonality of river flow in western China.

6. Interannual variability of snow cover

6.1.Station-derived snow cover time series verification

Over the northwestern China snow cover time series were created from 46 best stations over the past 47 year from 1951 to 1997. First, daily snow depth and monthly number of snow cover days summed over the snow cover season (September-August) respectively at single station. Then northwestern China snow cover time series were generated by averaging annual snow cover data of 46 stations. To verify station-derived snow cover time series we compared time series of annual number of snow cover days developed from the 46-selected station network with annual cumulative six-day snow storage estimated by SMMR in northwestern China during overlap period between 1978 and 1987 (Figure 6).

Figure 6

It is of interest to note that any year-to-year fluctuations experienced by the snow cover duration time series derived from station data showed up in the SMMR snow storage time series as well. A strong correlation (r=0.59) exists between the two. The same also holds true for station generated two time series of annual number of snow cover days and annual cumulative daily snow depth with correlation coefficient being 0.72. It argues that long-term snow cover time series constructed from station data have ability to represent the ground truth of interannual variation of snow cover in northwestern China. Over the Qinghai-Xizang (Tibet) plateau three snow cover time series were generated from area-averaged annual cumulative daily snow depths based on 60 primary stations, the SMMR six-day snow depth charts and NOAA weekly snow cover area charts respectively (Figure 7). It can be seen that Tibetan station data do not have the ability to perfectly represent the ground truth of snow cover. Despite there are major similarities between the station and satellite derived time series, for instance heavy snow cover in 1977/78 and 1988/1989. light snow cover in 1984/85, etc., some discrepancies could be found. 1985/1986 was an apparent example. While both SMMR and NOAA recorded a very heavy snow winter, the stations failed to report it.

Figure 7

6.2. Characteristics of spatial and temporal variations of snow cover

From the ten year SMMR 6-day snow depth data, we computed the anomaly, which is the difference in snow depth during the snow pick period between the maximum (1985/1986) and the minimum (1984/1985) snow cover years for every grid cells.

The spatial pattern of SMMR snow depth ranges showed that large interannual variability of snow depth is the most striking feature over the Qinghai-Xizang (Tibet) plateau. The maximum and minimum of area-average snow depths were 21.3cm (1985/1986) and 10.4 cm (1984/1985) respectively during the period of SMMR operation. In fact, only eastern part of the Qinghai-Xizang (Tibet) Plateau is affected by the most substantial year-to-year fluctuation in snow depth (Figure 8). It is here that turns to be one of the largest variation areas of China snow cover as well as Eurasian snow cover (Vernekar, et al, 1995). Most of the anomaly is about 30cm in snow depth and larger than 50cm is in a relatively small region over eastern Tibet plateau. In Figure 9 we display the second EOF_s of 10-year SMMR six-day snow depth data during the winter snow maxima (January and February), which accounts for 15.7% of total variance with a broad maximum negative loadings extend over the eastern Tibet and a weaker positive loadings are located over the western Tibet. The striking analogue between the Figure 8 and the Figure 9 suggests that the second EOF_s of SMMR snow data represents east-west difference of snow variability over the Tibetan plateau (Moron, 1997). From Figure 8 and Figure 9 it is well established that the plateau snow cover fluctuation almost always exhibited in such a regional pattern. Snow depth fluctuation in eastern part of the Qinghai-Xizang (Tibet) Plateau not only dominates interannual variability of snow cover over entire Qinghai-Xizang (Tibet) plateau, but also is out of phase with that in western Tibet. Contrast with the Qinghai-Xizang (Tibet) plateau, snowy areas affected by substantial year-to-year variation in snow depth are scattered in six large mountain systems, Ili basin, Elgis basin and Junggar basin over northwestern China. Variability of snow depth is not as large as in the Qinghai-Xizang (Tibet) Plateau. It would be remiss not to mention another notable feature that snow depths display the largest variability in the coldest months (Table 1) and they could dominate annual variation over the Qinghai-Xizang (Tibet) plateau.

Figure 8

Figure 9

Table1

Figure 10 depicted time series of annual and spring ablation season (March and April) numbers of snow cover days and annual cumulative daily snow cover depth over northwestern China from 1951 through 1997. As will be readily seen from visual inspection, it demonstrated that long-term variability of snow cover is characterized by normal oscillation. Snow cover fluctuated around the mean. Heavy and light snow winters occurred alternatively. Neither abrupt changes nor continuation of snow minima from the late 1980’s and early disappearance of spring snow cover were found. Only from the end of 1980’s a longer-lived decrease in snow cover was evidenced but not so great as the three previous snow deficits. In the 1960’s and early 1970’s snow cover was the lowest in second half of the 20th century.

Figure 10

Over the Qinghai-Xizang plateau long-term variability of snow cover is characterized by the largest interannual variability superimposing on a continuous increase trend. Furthermore, the annual amplitude of snow cover variability has increased significantly since 1980's (Figure 11). Both extremely heavy snow cover year and light snow cover year occurred more frequently. The anomalies did not appear to be outside the range of natural variability.

Figure 11

7. Response of snow cover to climate change

7.1. Association between interannual variabilities of snow cover, temperature and precipitation in snow cover season

Snowfall and low temperature are full conditions to meet formation of snow cover. To find a clue to the response of snow cover to climate change, it is necessary to understand linkage of variations between snow cover, snow season temperature and snowfall.

In China, the meteorological observation practices have not used independent method for snowfall measurement. We have to use snow season precipitation data. It should not have a qualitative effect on the conclusions since the snow season temperature is well below the freezing over the western China (see Figure 12). Monthly average temperature and monthly total precipitation were used from 46 selected stations and from 60 primary stations to develop area-averaged time series of snow season temperature and precipitation over northwestern China and over the Qinghai-Xizang (Tibet) plateau respectively. What Figure 12 interested us is that in northwestern China the snow season temperature fluctuated in a fairly similar manner as the global temperature (Jones et al, 1999) over the past half century. The warming trend is most apparent. The snow season temperature rose by 1.7℃ over the past 47 years being one of the strongest warming regions all over the world. However temperature increase has not been monotonic. Most of the warming occurred after 1976. It increased by 4.1℃ during the five winters between 1976 and 1981. 1990's exhibited the warmest decade during the past 47 years. The warmest winters were 1996/1997, 1994/1995, 1988/1989 and 1980/1981. The first three occurred on a global basic, and the last one occurred in the Arctic (Przybylak, 2000). Moreover, the variation is characterized by an alternating occurrence of warm period and cold period. The same is true for snow season precipitation. Here we lay special emphasis on that the precipitation variability exhibits little relationship to the temperature ($r=+0.008$) in snow season from 1951 to 1997. It is evident that cause and effect relation between them is not in existence. Both of them are controlled by different atmospheric circulations. A major control on interdecadal variation in winter temperature over northwestern China is the North Atlantic Oscillation (NAO) (Clark, et al, 1999, Kushnir, 1999). From 1960's until the early 1970's when the NAO index exhibited a downward trend to the minimum the wintertime temperature was lower than normal and cold winters lasted for the longest period over the northwestern China. The sharp warming has occurred with unprecedented strongly positive NAO index values since the end of 1970's (Hurell, 1995). In contract, the NAO's impact on the winter precipitation is limited for the precipitation primarily determined by availability of moisture bringing by the southwest flows.

Figure 12

To diagnose the climate influences on western China snow cover, we conducted a multiple linear regression analysis. The area-averaged time series of annual snow duration and annual cumulative daily snow depth were related to area-averaged snow season precipitation and temperature time series. The resulting regression equations are given by

$$S_n = 0.4975\ P_s - 4.5142\ T_s + 35.2 \qquad (8) \qquad (1951\text{-}1997)$$

$$S_d = 20.8551\ P_s - 150.2840\ T_s - 738.8 \qquad (9) \qquad (1956\text{-}1997)$$

$$S_d = 1.9950\ P_s - 14.2090\ T_s - 121.1 \qquad (10) \qquad (1957\text{-}1992)$$

where S_n and S_d are the annual number of snow cover days (day) and annual cumulative daily snow depth (cm) respectively; P_s represents the total precipitation (mm) in snow cover season. T_s denotes the surface air temperature (℃) during snow cover season. The first two equations are for northwestern China, and the third one is for the Qinghai-Xizang (Tibet) plateau. The multiple regression coefficients are 0.70, 0.81 and 0.67 respectively and significant at the 95% confidence level (Table 2). The results highlight the important influences of both temperature and precipitation on snow cover. The year-to-year fluctuation of snow cover is fundamentally tied to the snowfall and snow season temperature variabilities while positive snowfall and negative temperature relationships were found. About one-half to two-third of the total variation in the snow cover could be explained by the linear relationship of corresponding precipitation and temperature variabilities.

Table2

Figure 13 shows comparison of calculated time series of annual number of snow cover days from snow season temperature and precipitation by using the multiple linear regression equation (8) with the measured result. The similarity between the two is striking except for the difference in trends. While observed time series exhibit a positive trend, the calculated one turned out to be a negative trend. The clear message of this discrepancy is that while much of the year-to-year fluctuation can be explained as snow cover response to precipitation and temperature variations in snow season, the long-term trend of snow cover is by no means predictable by the regression equation (8). It is obvious that important limitation may affect the validity of the equation (8). Three possible explanations are presented: standard raingauge currently being used worldwide at meteorological networks undercatch snowfall due to wind-induced turbulence. For instance, number of snow cover days, snow season temperature and precipitation rose by 9 day, 1.7℃ and 5.3mm respectively in northwestern China over the past 47 years. However the equation (8) predicts that the precipitation should rise by 12.3mm. In other words, the observed precipitation is much smaller than that it should be. Another reason is that all regression models, except those with r=1, underestimate the variance in the observed values. In the case of a time series with monotonic trend, this feature can cause the model to underestimate the magnitude of the trend. In addition, snow cover variability exhibits a very small trend which embedded in a large year-to-year fluctuation that makes long-term trend more difficult to detect. Confirmation of the inability of the statistical models to accurately represent true trend is vital for projecting future behavior of snow cover. This comparison addresses the question of where we now stand with respect to prediction of snow cover based on snowfall data. At present, it is not possible to make a confident statement about reliable trend of snow cover by using the regression equation because actual relationship between snow cover and temperature as well as precipitation in snow season could not be obtained. One of the main reasons is large bias in snowfall measurements (Goodison, et al., 1992)

Figure 13

7.2. Testing for trends in the time series of snow cover, temperature and precipitation in snow season

Searching for long-term trend in snow cover variation forced by climate change may provide a starting point for understanding future behavior of snow cover. Results of trend estimates for standardized time series of snow cover, snow season temperature and precipitation are listed in Table 3. They reveal a general and uniform positive trend of snow cover over the western China. Increase in snow cover is a systematic development as evidenced by the presence of deterministic trends. Both snow depth and snow cover duration exhibited a gradual increase. Although increasing rates are small, they are statistically different from zero. The increase in snow cover is more evident over the Qinghai-Xizang (Tibet) plateau. The annual cumulative daily snow depth increased by 2.3 percent per year during the period between 1957 and 1998. The long-term trends of western China snow cover are in good agreement with the snowfall trend but in contradiction to regional warming. It is an unexpected result that apparent unprecedented warming of the 1990's and 1980's was accompanied by an increase in snow cover over the western China. A persistent and misleading question is that the global warming would decrease the snow cover since snow cover has a strong negative relationship to temperature. Our study suggests that the global warming may have various impacts on snow cover depending on different correlations between local winter temperature and snowfall. In a warming world, negative correlation corresponds to snow cover decrease. Positive correlation corresponds to snow cover increase, Zero correlation means snow cover is more vulnerable to changes in snowfall. Snow cover trend is dependent on snowfall trend rather than on temperature trend, if winter temperature is well below freezing. In other words, even if global warming there is no reason for snow cover to be decreased when snowfall is increasing and temperature is still to remain well below freezing in the region.

Table 3

8. Summary and concluding remarks

Western China snow cover has been a long-standing gap in our knowledge despite many diagnostics and modeling studies ascribed the importance to it. Accurate monitoring of the snow cover still remained a tough question since the Qinghai-Xizang (Tibet) plateau is marked by the highest terrain and complex mountain ranges.

In this paper geographical distribution, spatial and temporal variability of western China snow cover has been investigated for the past 47 years between 1951 and 1997. The data used consists of 10-year SMMR six-day snow depth charts which revised by the regional retrieval algorithms, NOAA weekly snow extent charts, daily snow depth and number of snow cover days recorded at 106 selected meteorological stations. Empirical Orthogonal Function was performed on SMMR dataset. A multiple linear regression was conducted between snow cover, snow season temperature, and snow season precipitation. An autoregressive-moving average model was fitted to the snow and climate time series to testing for trends. The major findings are summarized below:

Snow cover distribution is far from a pervasive feature over the Qinghai-Xizang (Tibet) plateau. Only in the peripheral mountains is any appreciable snow cover noted. In the vast interior snow cover is rare or very thin, patchy, and short of duration. The blocking mountains keep the interior of the Qinghai-Xizang (Tibet) plateau very dry in snowfall. Annual cycle of Qinghai-Xizang (Tibet) snow cover is characterized by early peak occurring in January, very slow snow decay, and long snow dissipation progress from February to June. More than half of snow mass was lost by sublimation in winter. Although the Qinghai-Xizang (Tibet) plateau is one of the largest year-to-year variation areas of Eurasian snow cover, only eastern Plateau, one quarter part of the plateau in area, is affected by substantial interannual variability in snow depth and it is out of phase with western Plateau. Above-mentioned characteristics constrain the Qinghai-Xizang (Tibet) snow cover to be a key variable influencing the Asian monsoon, and challenge Blanford’s hypothesis that a simple inverse relationship between Tibetan snow cover and Indian monsoon rainfall could provide a plausible explanation for the monsoon variations.

Western China did not experience continuant decrease in annual snow storage and early disappearance of spring snow cover, even if during the great warming periods of 1980’s and 1990’s. Over northwestern China long-term variability of snow cover is marked by a stochastic oscillation superimposed on a small increasing trend over the past 47 years. No any abrupt change in snow cover was found. Over the Qinghai-Xizang (Tibet) plateau, large interannual variability of snow depth is the most striking feature, and annual amplitude has increased significantly since 1980’s. Increase in snow depth is more evident over the Qinghai-Xizang (Tibet) plateau than in northwestern China. The annual cumulative daily snow depth increased by 2.3 percent per year over the Qinghai-Xizang (Tibet) plateau during the period between 1957 and 1998. The increasing trend of western china snow cover is in good agreement with the snowfall positive trend but in contradiction to the regional warming.

The study highlights the importance of both low temperature and snowfall influence on snow cover. The year-to-year fluctuation of western China snow cover is fundamentally tied to the precipitation (snowfall) and temperature in snow season. About one-half to two-third of the interannual variation in snow cover could be explained by the linear relationship of the precipitation and temperature variabilities. In contrast, the long-term trend of snow cover is by no means predictable by the multiple linear regression equation between snow cover, temperature and precipitation. The main reason is large biases in snowfall measurement. Further, the authors argued that the precipitation variability exhibits little relationship to the temperature ($r=+0.008$) in snow season over northwestern China. This is evident that cause and effect relation between the two is not in existence. The results address the question of where we now stand with respect to prediction of future behavior of snow cover based on snowfall data.

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Figure 1. Distribution of stations used for creating long-term time series of snow cover, temperature and precipitation in snow season over the western China
Red-Tibetan Plateau; Green-northwest China

Figure 2. Spatial pattern of average snow depth (cm) in winter snow peaks during the period between 1978 and 1987 estimated by SMMR over western China.

Figure 3. The first EOFs of 10-year SMMR six-day snow depth data during the winter snow maxima between 1978 and 1987 over the Qinghai-Xizang (Tibet) plateau.

Figure 4. Spatial pattern of average snow depth (cm) during the winter snow maxima between 1978 and 1987 estimated by SMMR over the Qinghai-Xizang (Tibet) plateau.

Figure 5. Annual cycles of snow storage (SWE) over northwestern China (a) and Qinghai-Xizang plateau (b) based on the SMMR derived 6-day snow depth charts during the period between 1978 and 1987.

ⓐ—normal snow year; ⓑ—heavy snow year; ⓒ—light snow year;

Figure 6. Comparison of the SMMR estimated snow cover time series (ⓐ) and station derived snow cover time series (ⓑ) during the overlapped period from 1978 to 1987 in northwestern China

Figure 7. Comparison of three time series created from SMMR six-day snow depth charts, NOAA weekly snow area charts and annual cumulative daily snow depth data at 60 weather stations respectively over the Qinghai-Xizang (Tibet) plateau

(a)—SMMR; (b)—NOAA; (c)—station;

Figure 8. Distribution of snow depth ranges (cm) during the winter snow peaks between the maximum (1985/86) and the minimum (1984/85) snow cover years estimated by SMMR from 1978 to 1987 over the Qinghai-Xizang (Tibet) plateau

(contour interval is 10cm)

Figure 9. The second EOFs of 10-year SMMR six-day snow depth data during the winter snow peaks from 1978 to 1987 over the Qinghai-Xizang (Tibet) Plateau

Figure10. Variability of snow cover over the northwestern China, 1951—1997

ⓐ—annual number of snow cover days; ⓑ—annual cumulative daily snow depth; ⓒ—spring ablation season (March and April) number of snow cover days;

Figure 11. Variation of annual cumulative daily snow depth over the Qinghai-Xizang (Tibet)

plateau, 1957—1998.

Figure 12. Variabilities of temperature and precipitation in snow seasons over northwestern China,1951—1997

T—temperature;　P—precipitation;

Figure 13. Comparison between calculated annual number of snow cover days by using the multiple regression equation and observed result over the northwestern China

Fig. 1

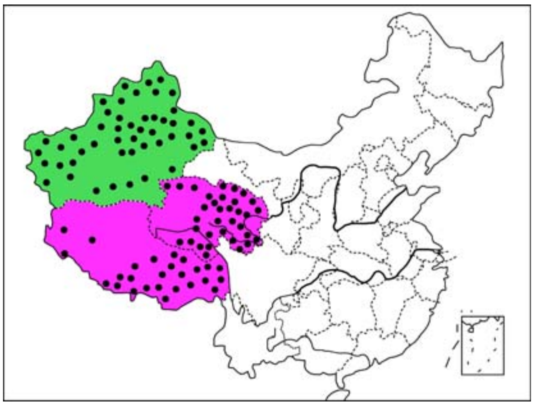
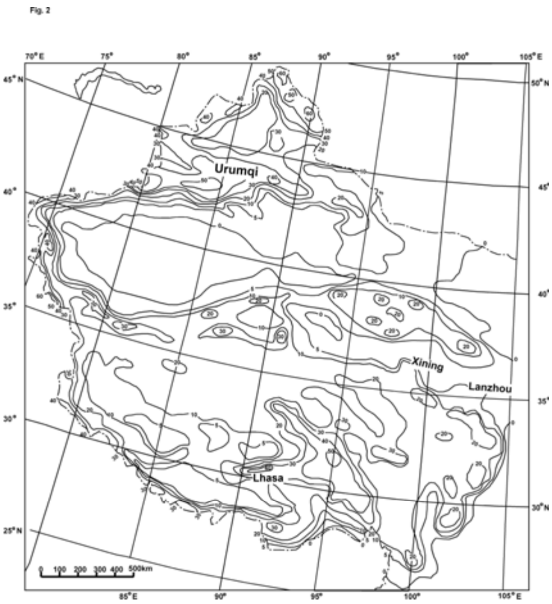


Fig. 2



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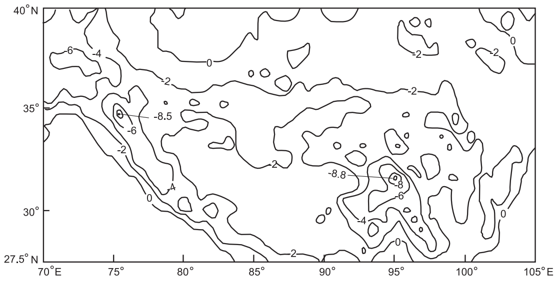

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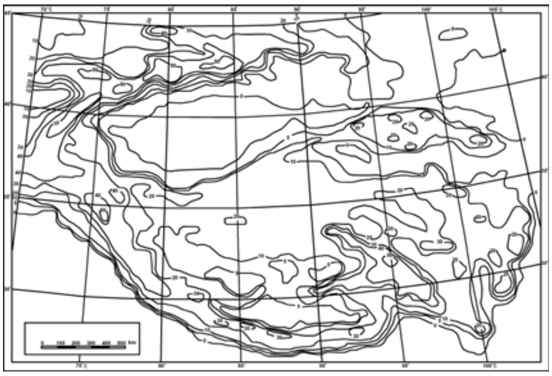

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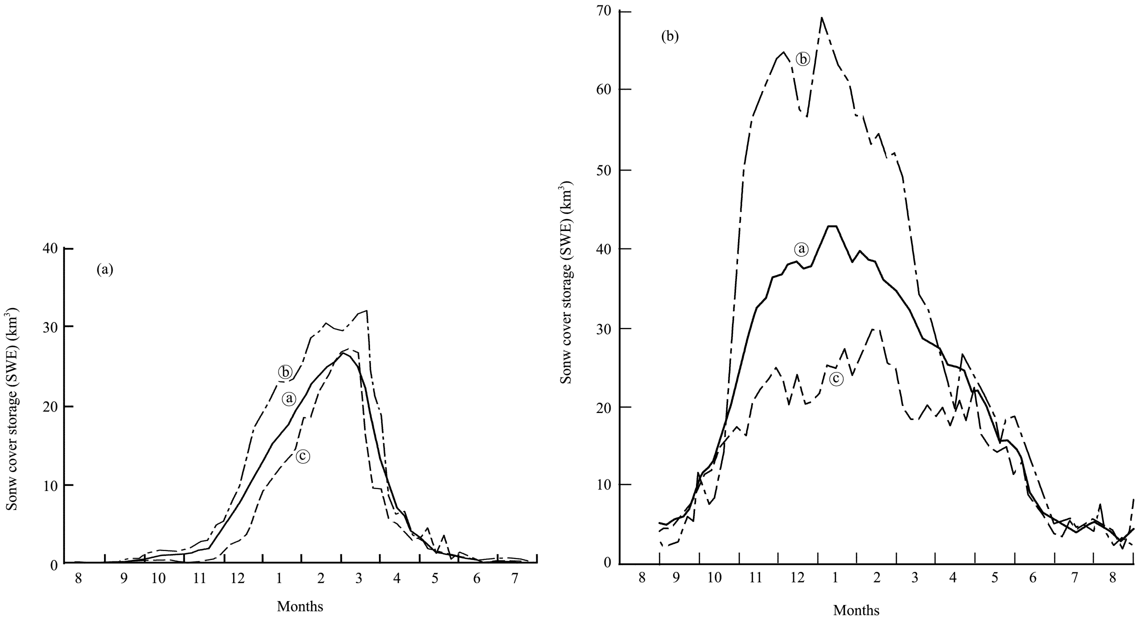

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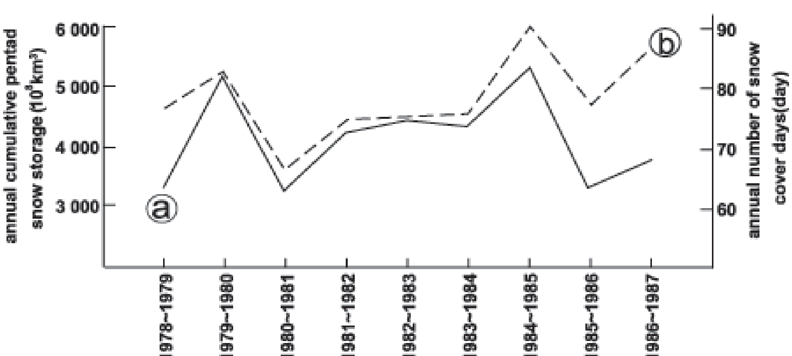

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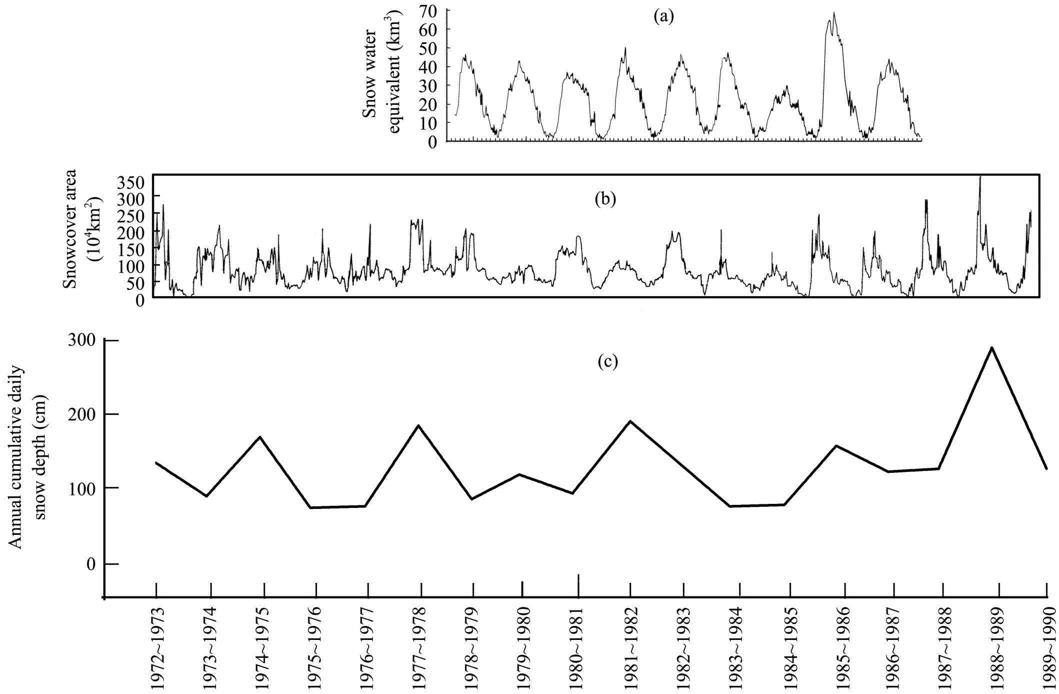

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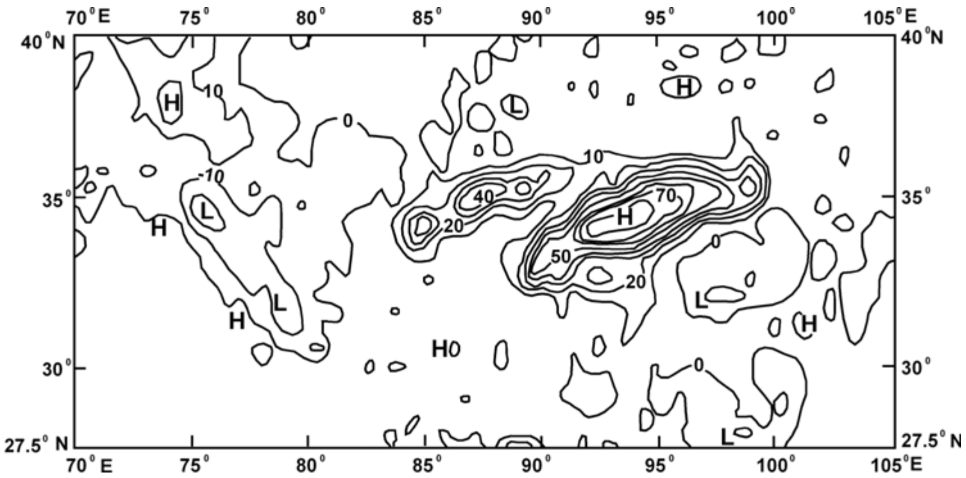

Fig. 9

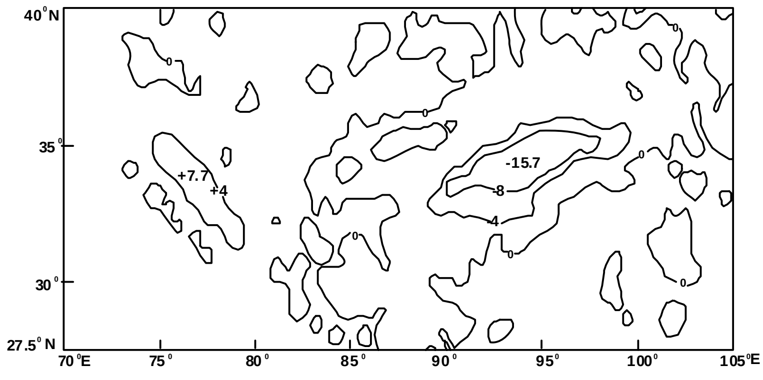

Fig. 10

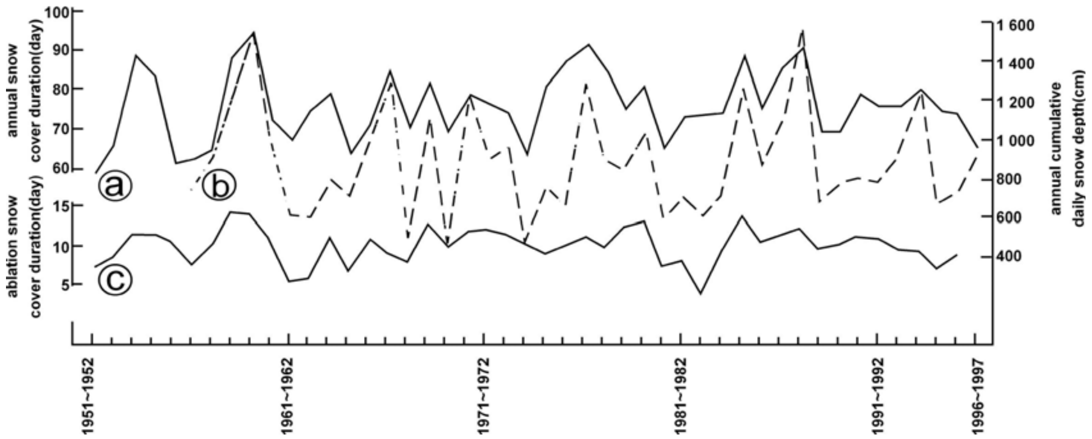

Fig. 11

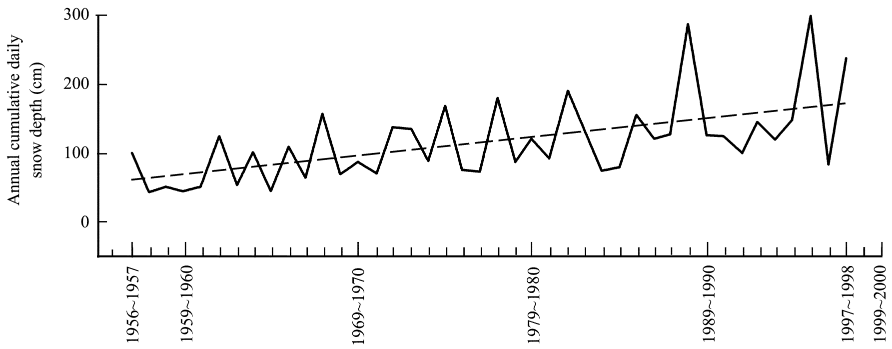

Fig. 12

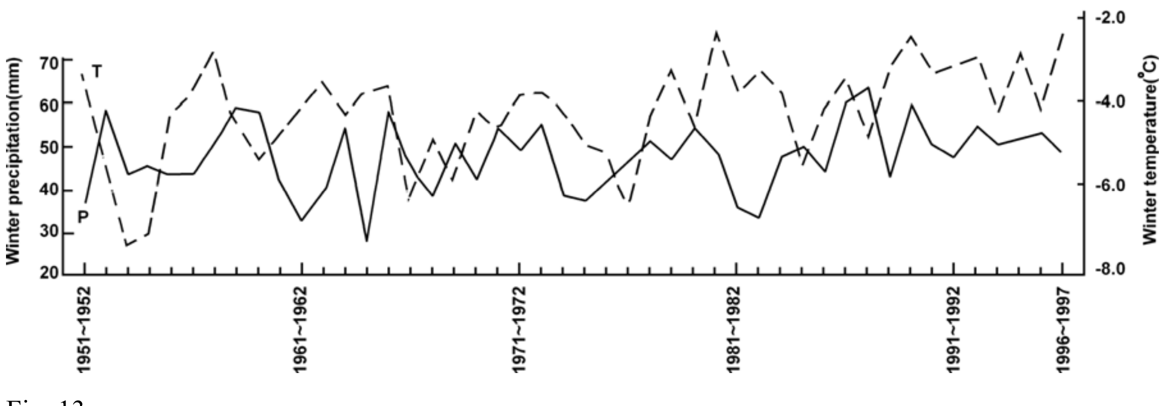

Fig. 13

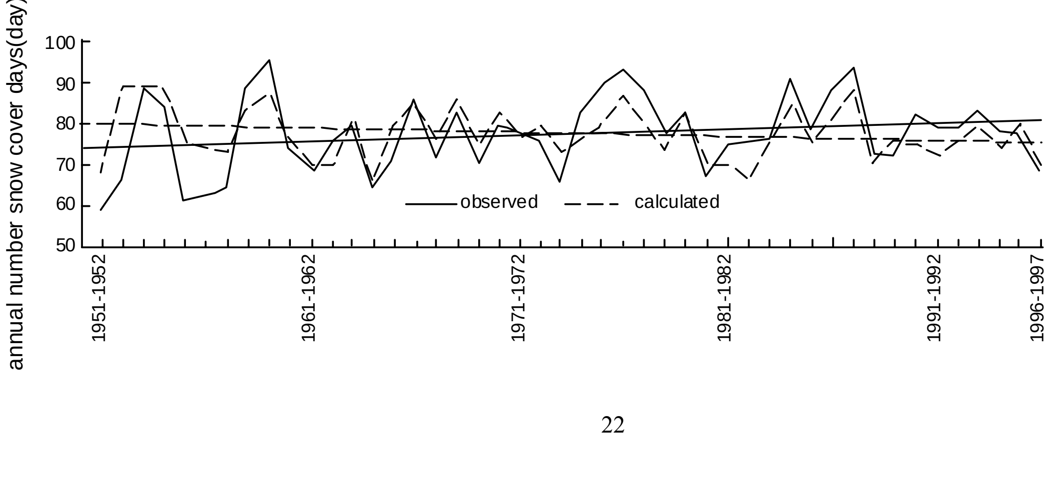

Table 1 Interannual variability of area-average monthly cumulative daily snow depth based on 60 primary stations from 1957 through 1992 over the Qinghai-Xizang (Tibet) plateau

Mouth	S	O	N	D	J	F	M	A	M	J	Round year
C_v*	0.41	0.58	0.81	0.82	0.96	0.74	0.69	0.42	0.32	0.38	0.47

* Cv is the coefficient of variation and is defined as $C_v = \frac{\sigma}{Y_0}$; where σ-standard deviation; Y_0-average

Table 2 Linear correlation coefficients between snow cover, winter temperature, and winter precipitation in northwestern China from 1951 to 1997. Significance at 0.05 level are underlined

	Winter temperature	Winter precipitation	Both temperature and precipitation	Time series length
Annual number of snow cover days	<u>-0.55</u>	<u>+0.42</u>	<u>0.70</u>	1951—1997
Annual cumulative daily snow depth	<u>-0.51</u>	<u>+0.62</u>	<u>0.81</u>	1951—1997
Winter temperature		+0.008		1951—1997
Winter precipitation	+0.008			1951—1997

Table 3 Trend estimates of snow cover, snow season temperature and precipitation based on ARMA over the western China.
**** and * indicate trends that are statistically significant at the 0.01 level and 0.05 level respectively**

Regions	Time series	Trend estimates	Autocorrelation	Time lengths
Northwestern China	Annual number of snow cover days	+0.0221**	0.2821	1951～1997
	Ablation season number of snow cover days	+0.0153*	0.1972	1951～1997
	Annual cumulative daily snow depth	+0.0018	0.0200	1956～1997
	Snow season temperature	+0.0318**	0.4182	1951～1997
	Snow season precipitation	+0.0147*	0.1919	1951～1997
Qinghai-Xizang Plateau	Annual cumulative daily snow depth	+0.0380**	0.4991	1957～1998
	Snow season temperature	+0.0270**		1957～1992
	Snow season precipitation	+0.0240*		1957～1992

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ESR dating of glacial tills and glaciations in the Urumqi River headwaters, Tianshan Mountains, China

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Abstract

Electron spin resonance (ESR) dating of the Shangwangfeng, the Xiawangfeng, and the Gaowangfeng tills in the headwaters of the Urumqi River was carried out using Ge centers in quartz grains. The Shangwangfeng till is dated at 35±3.5 ka BP. Three dates from the lower portion of the Xiawangfeng till are 171.1±17, 176±18, and 184.7±18 ka BP, respectively, and the age of the Gaowangfeng till is 459.7±46 ka BP. Considering the available ages (i.e. ^{14}C, TL and ESR) and the principles of geomorphology and stratigraphy, the Shangwangfeng till is determined to be deposited in marine isotopic stage 2–3 (MIS2–3). The upper part of the Xiawangfeng till was formed in MIS4 and the lower part was deposited in MIS6. The Gaowangfang till is the oldest at the head of the Urumqi River, corresponding to MIS12. The age of the Gaowangfang till also demonstrates that the Tianshan Mountains lay at a suitable altitude for a glacial climate at that time, when the glaciers on this segment of the mountain began to develop.

1. Introduction

In recent decades, methods utilizing radiation-defects in quartz (i.e. electron spin resonance (ESR), thermoluminescence (TL), and optically stimulated luminescence (OSL) dating techniques) have developed rapidly and are well suited to determine the ages of terrestrial sediments. ESR has advantages compared to the others: a wider dating scope (from several thousand to several million years); ubiquitous datable materials (fossils, oceanic and terrestrial deposits, meteorites, etc); small samples required (less than 1 g quartz for some special samples) and simple preparation. It is also a nondestructive method, and the samples may be reused for other purposes. An ESR age can be derived from the following formula:

$$\mathrm{TD} = \int_0^t D(t)\,\mathrm{d}t,$$

where TD is the total dose the sample has accumulated over time and D is the annual dose rate that is generated by the radioactive elements (U, Th, and K_2O) in the sample (internal dose rate) and its surroundings (external dose rate) as well as cosmic rays. TD is determined by the additive artificial dose method, and the annual dose is derived from the concentration of the radioactive elements (U, Th, and K_2O) in the sample and its surroundings.

ESR dating has been applied in geology (Hennig and Grün, 1983; Grün, 1989; Ikeya, 1993; Rick, 1997). Dating of unconsolidated sediment by ESR was proposed by Yokoyama et al. (1985). Tanaka et al. (1986) chose Ge centers to date sun-bleached sediment and obtained reasonable geological results. Grün (1991) proposed that Ge centers should be used in future ESR dating studies. Schwarcz (1994) suggested that glacial till was suitable for future ESR studies. Many scholars (Kuang et al., 1997; Shi et al., 2000; Wu et al., 2001; Yi et al., 2001; Zhou et al., 2002b) have applied the ESR technique to investigate glacial tills, and obtained

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period, which caused glacial advance (Shi and Yao, 2002). The investigations carried out on the south slope of Himalayas indicated that the extent of glaciation during MIS3 is greater than the general Last Glacial Maximum (LGM) (Owen et al., 2002a, b; Zech et al., 2003; Kamp Jr. et al., 2004). Two other ESR ages of the Shangwangfeng till determined by Yi et al. (2001) showed that the upper till's age is 37.4 ka BP, which is coincident with our result, and the underlying one is 27.6 ka BP. Thus, our measured age of the Shangwangfeng till should be believable. It is reasonable to infer that the Shangwangfeng tills were deposited in MIS2–3 based on the above ages. The great debate about the Xiawangfeng till has not been fully solved. Wang (1981) inferred it was formed in MIS6, but Li (1995) thought it was deposited in a later period of the Last Glaciation. Yi et al. (2001) concluded that it was deposited in MIS4 on the basis of ESR ages (50–70 ka BP). We found that the Xiawangfeng group could be divided into an upper and lower portion. The lower portion was poorly preserved, most of it was destroyed, and only a section around the station of the Wangfeng road maintenance squad was well preserved. Three samples were collected from this section and the dating results were consistent. Two circumstantial pieces of evidence confirm the believability of the ages: Zhou et al. (2002a) determined the ESR age of the second outwash terrace around Erying in the Houxia wide valley is 125.6 ± 13 ka BP and the TL age of the bottom of the loess which covers the outwash terrace is 90.0 ± 7.5 ka BP. The ESR age of the third outwash terrace which developed at the exit of the Urumqi River Valley is 114.4 ± 11 ka BP. These outwash terraces and their ages show the presence of MIS6 glaciation. Thus, the upper Xiawangfeng till should have been deposited in the early period of Last Glaciation, corresponding to MIS4, and the lower portion around the station of the Wangfeng road maintenance squad was formed in MIS6.

The Gaowangfeng till was distributed in the upper U-shaped valley, about 150–200 m above the lower valley and 200–300 m above the river. The position of the till means an older age of its formation. The other available ESR age is 477.1 ka BP dated by Yi Chaolu (Zhou et al., 2001). These two results are consistent, indicating that the Gaowangfeng till was formed in MIS12.

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Response of Melt-Water Runoff To Air Temperature Fluctuations on Keqikaer Glacier, South Slope of Mt.Tuomuer, Western China

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ABSTRACT: Flow records of melt-water runoff provide information about the movement of water through the ice and about glacial ablation. This study indicates that the lag time required for a maximum correlation between daily discharge and air temperature, and the sensitivity of melt water response to air temperature, changes during the ablation period for different proportions of the base-flow. To examine how glaciers respond to climatic changes and the hydrological characteristics of the large glaciers in Mt.Tuomuer area, observations have been undertaken in this region since June 2003. By means of correlation and cross-spectral analysis, the relationship between air temperature and melt-water runoff in different months of the ablation period (May-Sept) on Keqikaer Glacier in 2004 has been evaluated. Data have been selected from the 1st to the 30th for every month, and the calculated hourly discharges of the melt-water runoff for each day were utilized. From these data we conclude that for Keqikaer Glacier the melt-water runoff has a greater sensitivity to air temperature in May, July and August compared to June and September; however, the lag time is shorter in June, July and August than it is in May and September.

Keywords: Melt-water runoff; Air temperature; Cross-spectral analysis; Keqikaer Glacier

INTRODUCTION

Flow records of melt-water runoff provide some information about the movement of water through the ice and about glacial ablation. In summer, the discharge has a notable diurnal variation superimposed on a base flow whose volume changes more slowly. In addition, the peak discharge comes a few hours after the peak in glacial ablation. As summer advances, however, the daily rise and fall in discharge becomes more rapid and the lag time decreases. Total daily discharge usually reaches its maximum in late July or early August. When summer snowfall

In May and September, the bare ablation area is small; the water provided by the snow-cover area is large, which needs more time to drain from the glacier. However, in July and August, the proportion of the melt water provided by the snow-cover area is small and the lag time is short in these months. June is a special month that calls for further discusion. Melt-water runoff is small and air-temperature is low in June, however, the ice melt water in the ablation area has produced most water, because snowmelt water of the ablation area has drained away in May. The proportion of the rapid flow is small, so the melt-water runoff has small sensitivity to the fluctuation of air temperature. The melt water provided by the snow-cover area is small, so the lag time is short in this month.

In this paper, cross-spectral analysis has been used to analyse the fluctuation of the glacial melt-water runoff and its response to the air temperature, and the method is successfully applied to evaluate the sensitivity of the discharge to air temperature and calculated the lag time in different months. Compared with a physical-math model, the theory is simple and the conception is clear and the parameters are few. From Keqikaer Glacier, we arrived at the conclusion that the melt-water runoff has greater sensitivity to air temperature in May, July and August than that in June and September. The lag time is shorter in June, July and August than in May and September.

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Mass balance and recession of Glacier No.1 at the Headwaters of the Urumqi River, Tianshan Mountains, China over the last 45 years

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ABSTRACT. Observations from 1959-2003 of Glacier No. 1 at the headwaters of the Urumqi River in the Tianshan Mountains show remarkable changes. The cumulative mass balance of the glacier is -10,032 mm, equivalent to 11.1 m of glacier ice, or 20% of the glacier volume, showing particular sensitivity to temperature change. The speed of glacier flow has gradually declined, especially from the 1980s from when it is even more evident. The flow speed of the east and west branches of the glacier have decreased from 1980 to 2003 by about 21% and 43%, respectively. The glacier has continuously retreated from 1962 to 2003. Its length has decreased by about 180m (7.5%) and its area reduced by 0.23 km^2 (11.8%). Analyses show that summer precipitation is negatively correlated with mass balance and positively associated with runoff. These relationships are reasonable, as higher precipitation leads to higher runoff and lower glacier melt. On the other hand, summer temperature is negatively correlated with mass balance and positively associated with runoff, as higher temperatures lead to higher glacier melt and thus higher runoff - summer temperatures controlling mass balance variation. It is important to note that over the past 45 years the negative mass balance, caused by higher ablation than accumulation, is associated with precipitation increase and temperature warming over the study area.

INTRODUCTION

Annual or periodic changes in temperature and precipitation in glacial regions can be detected from mass balance and snow line measurements. If there is a change in the trend of regional climate then evidence from glaciers may directly reflect adaptations to such climate changes. Previous research has shown that not only is such a small glacier sensitive to mass balance and positively associated with runoff, as higher temperatures lead to higher glacier melt and thus higher runoff. The summer temperature controls glacier mass balance variation. It is important to note that, over the past 45 years, the negative mass balance, caused by higher ablation than accumulation, is associated with both a precipitation increase and temperature warming over the study area.

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Recent progress of glaciological studies in China

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Abstract: Glacier inventory compilation during the past 20 years and modifications of that for the Eastern Pamir and Banggong Lake indicate that there are 46,342 modern glaciers with a total area and volume of 59415 km^2 and 5601 km^3 respectively in China. These glaciers can be classified into maritime and continental (including sub-continental and extremely continental) types. Researches show that glaciers in China have been retreating since the Little Ice Age and the mass wastage was accelerated during the past 30 to 40 years. Being an important part of glaciological studies in China, ice core climatic and environmental studies on Tibetan Plateau and in the Antarctica have provided abundant, high resolution information about past climatic and environmental evolution over the Tibetan Plateau and Antarctica. Except for different parameters recorded in ice cores relating to climate and environment changes on Tibetan Plateau, records from ice cores extracted from different glaciers show that the discrepancies in climatic and environmental changes on the north and south parts of the plateau may be the consequence of different influencing effects from terrestrial and solar sources. Glaciological and meteorological phenomena imply that Lambert Glacier valley is an important boundary of climate in the east Antarctica, which is thought to be connected with cyclonic activities and Circum-polar Waves over the Antarctica.

Key words: glacier; Tibetan Plateau; ice core; Antarctica; China

1 Introduction

In the early 1960s, glaciers in western China were classified into maritime- and continental-types by different glacial environment and physical characteristics (Shi and Xie, 1964). With extensive glaciological investigations in the western regions (Lanzhou Institute of Glaciology and Geocryology of CAS, 1988), Lai and Huang (1990) suggested a new classification of temperate, subpolar and quasipolar glaciers, corresponding to the maritime-, subcontinental- and extremely continental-type glaciers (Shi and Liu, 2000). The maritime-type glaciers, accounting for 22% of the total area of the Chinese modern glaciers, are primarily distributed in the southeast of Tibet, west of Sichuan and northwest of Yunnan, where the glaciers are influenced by Asian monsoons and have abundant precipitations. For this kind of glacier, annual precipitation over the ELA (Equilibrium Line Altitude) can reach 1000-3000 mm, and summer mean temperatures vary between 1℃ and 5℃ while ice temperature fluctuate between -1℃ and 0℃. The subcontinental glaciers are located in the Mts. of Altay, Tianshan, Qilian, eastern Kunlun, eastern Tanggula, western Nyainqentanglha, Gangdise, northern slope of the middle and western Himalaya and northern slope of the Karakorum Mountains, with an area of 46% of the total. Annual precipitations over ELAs of these glaciers vary between 500 mm and

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乌鲁木齐河源空冰斗径流增大的原因分析

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摘　要：天山乌鲁木齐河源区空冰斗径流量自20世纪80年代中期以来增大趋势明显，尤其是1996年以来径流量一直维持在较高水平，远大于前十几年的平均值. 分析其主要原因为：河源区降水自1985年以来呈增加趋势，1996年以来降水明显增多；气温自20世纪80年代以来总体呈上升趋势，其中1997—1999年气温升高显著，河源区处于一个明显的向暖湿阶段的转变过程中. 同时，冻土活动层内温度的升高，导致冻土活动层内地下冰和地下埋藏冰强烈消融，也是径流量增大的重要原因之一.

关键词：空冰斗；径流增加；降水；温度
中图分类号：P343.6　　**文献标识码**：A

1　引言

自1987年以来，新疆以天山西部为主的地区，出现了气候从暖干到暖湿转型的强劲信号[1]，降水量、冰川消融量、径流量连续多年增加，导致湖泊水位显著升高，洪水增加，植被改善、沙尘暴减少，新疆其它地区也有降水量、径流量增加的趋势. 根据天山乌鲁木齐河源近十几年来冰川进退和雪线变化、水文气象纪录变化的事实，河源区及乌河流域气候环境也有由暖干向暖湿突变（转型）的信号，年平均气温呈现升温趋势，山前平原区年均温升温幅度远大于山区，冬季升温非常明显[2]，河源区降水及径流有较为明显的增加趋势[3].

2　研究区概况

空冰斗位于天山乌鲁木齐河源1号冰川东北侧（43°04′N，86°30′E），海拔介于3 803～4 393 m，斗口朝向南. 为对比观测研究高山区积雪、多年冻土融水径流，中国科学院天山冰川观测试验站在空冰斗口处（海拔3 805 m）设有水文监测断面，控制流域面积1.68 km²，同时在空冰斗口还安置有空冰斗气象场，观测气温、降水、湿度等气象要素. 自1982年以来，对空冰斗裸露山坡降水、积雪、冻土融水径流及其各气象要素进行了连续观测研究.

3　径流变化特征

多年观测资料的分析研究表明（图1），以降水、高山积雪和多年冻土融水径流为主的空冰斗径流，20世纪90年代年平均径流深较80年代增加了约96%，比1982年以来的多年平均径流深多出了28%. 更为明显的变化发生在90年代中后期，1996—2001年径流的年平均值（873 mm）远大于80年代平均（364 mm）和多年平均（556 mm），与90年代前期（1991—1995年）相比，平均径流深增加了约68%.

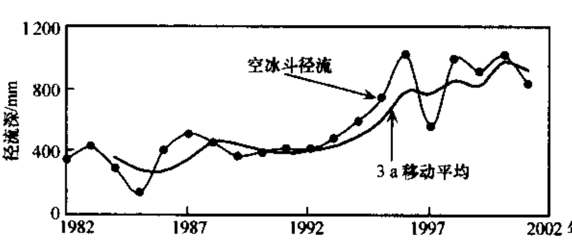

图1 乌鲁木齐河源区空冰斗径流变化趋势

Fig. 1　Runoff changing with time in the Ice-free Cirque at the headwaters of the Ürümqi River

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天山南坡台兰河流域冰川物质平衡变化及其对径流的影响

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摘 要：应用控制流域的径流及相关降水资料，通过模型重建了台兰河流域平均冰川物质平衡序列. 结果显示，1957—2000 年流域冰川平均年物质平衡为 -287 mm，累计冰川物质平衡 -12.6 m；44 a 来由于气温升温引起的冰川净消融相当于每年补给河流径流 $1.24\times10^8 m^3$，占河流年径流量的 15%. 1982 年以后，流域冰川物质平衡一直呈负平衡，1957—1981 年平均物质平衡为 $-168\ mm\cdot a^{-1}$，1982—2000 年平均为 $-445\ mm\cdot a^{-1}$. 随着气候由暖干向暖湿转型，降水量增加，但冰川对气温的敏感性更大，冰川消融加快，冰川融水量持续增加. 气温和降水量的变化与北大西洋涛动和北极涛动变化一致，其突变年份都在 1986—1988 年左右.

关键词：冰川物质平衡；气候变化；NAO/AO 指数；台兰河

中图分类号：P343.6　　**文献标识码**：A

冰川水资源是我国西部干旱区重要的水资源，稳定着河流水文的变化，夏季气温升高引起的冰川融水猛烈增加也是洪水的主要根源. 冰川是固体高山水库，气候的变化对河流水资源的产生和洪水的发生具有重要作用. 冰川变化、冰川水资源变化及其冰川洪水研究对塔里木河的治理及供水安全防范是必须的和迫切的. 塔里木盆地内陆流域共有现代冰川14 285 条，面积 23 628.98 km^2，冰储量2 669.435 km^3，冰川融水年径流量达 $150\times10^8 m^3$，约占流域地表总径流量的 40%，冰川融水在本区的水资源组成中占据重要的地位[1].

1 流域基本概况

台兰河流域位于天山最高峰托木尔峰(海拔 7 435.3 m)南坡，河流最终注入塔里木盆地. 以台兰河水文站控制的流域面积 1 324 km^2，流域最高点为托木尔峰，最低点为台兰水文站(海拔 1 550 m). 台兰河流域共发育现代冰川 115 条，冰川总面积 431 km^2，冰川储量 73.132 km^3，平均雪线海拔 4 290 m. 流域内长度超过 10 km 的冰川有 4 条，总面积达 307.7km^2，占流域冰川总面积的 71.2%，流域内最大冰川为琼台兰冰川，长度为 21.4 km，冰川面积达165.4 km^2. 流域内冰川末端最低海拔 3 080 m，最高海拔 5 800 m，冰川覆盖度32.6%[2].

根据气象观测和 1977—1978 年的科学考察，本区山区的降水主要来自大西洋和北冰洋的暖湿气流补给，6～8 月的降水量占全年的 50%左右，而 5～9 月占 70%左右，因此，冰川的补给主要发生在暖季[3]. 流域山区的降水量与其北侧天山的昭苏站和天山内部的巴音布鲁克站比较接近，其月季变化趋势也比较一致[4].

近 40 a 来本区气温呈升温的变化趋势，天山山区平均气温在 4 个 10 a 中升高了 0.6 ℃. 各季的气温变化也呈现出波动特征，夏、秋、冬三季均呈明显的上升趋势，其中秋季上升幅度最大，为 1.1 ℃，冬、夏两季上升幅度同为 0.7 ℃，春季变化不大[1]. 秋冬升温使得冰川冷储减少，冰温升高，夏季很短的升温都会使冰川大量消融. 夏季急剧的升温可能引起冰川洪水的发生，产生严重的灾害.

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西北地区空中水汽时空分布及变化趋势分析

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摘 要：使用 NCEP/NCAR1958 2000 年再分析格点资料，分析了西北地区空中水汽和水汽输送的时空分布特征和变化趋势. 结果表明：1)西北地区空中水汽地域分布主要集中在西北地区东部和西部的天山北部以及塔里木河流域盆地，而西北地区中部水汽含量较少，尤以青海的西部和北部为最；2)西北地区空中水汽主要来自印度洋孟加拉湾、南海以及阿拉伯海的水汽输送，北面还有一支来自西伯利亚和蒙古方向的水汽输送；3)西北地区空中水汽含量自 50 年代末至 80 年代中期呈明显下降趋势，而从 80 年代后期开始水汽又呈波动上升趋势. 水汽增加地区主要在新疆北部沿河西走廊至甘肃中部祁连山区中段以及南疆盆地西部，而其它地区近年来水汽明显减少，其中减少幅度最大的地方位于西北中部的甘肃、青海、新疆交界处以及东部的陕西省；4)从空中水汽年代际变化趋势看，60～70 年代西北大部分地区呈现减少趋势，而 80～90 年代全区普遍呈现增多趋势，以西北地区西部水汽增多趋势最为明显. 最后讨论了影响西北地区水汽分布及输送的气候动力因子.

关键词：西北地区；空中水汽；输送；时空分布；变化趋势

中图分类号：P426.1+5 **文献标识码**：A

1 引言

西北地区幅员辽阔，处于北半球亚非干旱带，属中亚和中蒙干旱区. 区内涵盖了高山、湖泊、冰川冻土、森林植被、季风气候和西风带气候等气候系统的所有成员，是我国主要的干旱和半干旱区. 全区年降水量平均小于 200 mm，水资源十分缺乏，严重制约着社会经济建设和生态建设的发展，是我国目前正在实施的开发大西北战略中迫切需要解决的一个重大问题. 20 世纪末期以来，全球气候变暖幅度加大，尤其是中高纬度地区最为明显，对全球气候变暖的研究更迫切需要了解空中水汽在气候系统中的作用. 西北干旱研究与水资源问题密切相关，大气中的水分含量和水汽输送不仅与大气环流有着密切的内在联系，而且作为能量和水分循环过程的重要一环，对区域水分平衡起着重要作用，对其正确估计能对大气环流的形成和演变有更深入的了解，从而有助于进一步了解西北地区天气和气候变化过程以及水文循环过程. 此问题多年来备受国内外水文学家和气象学家的广泛关注[1～8]. 最近，施雅风等[9]研究指出，中国西北部从 1987 年起以新疆天山西部为主地区出现了气候由暖干向暖湿转型的强劲信号，即降水量、冰川消融量和河流径流量连续多年增加，湖泊水位显著上升，植被改善，沙尘暴减少，新疆其它地区以及祁连山中西段的降水和径流也有增加趋势. 本文从西北地区空中水汽分布特征及其变化趋势这一角度进行分析，从而使西北气候由暖干向暖湿转型的信号评估由地表水、地下水扩展到大气水，丰富对西北地区水资源状况的认识，为正确评价西北气候转型提供依据.

2 资料和计算方法

本文使用美国 NCEP/NCAR 公布的 43 a(1958—2000 年)再分析网格点(2.5°×2.5°)资料以及国家

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新疆近 50 a 来的气温和蒸发变化

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摘 要：根据 77 处国家水文、气象站点观测资料，分析了新疆不同地区近 50 a 来气温和蒸发两个气候要素的变化. 结果表明，新疆近 50 a 来的气温呈上升趋势，平均增长率为 0.27 ℃·10 a^{-1}. 1987 年以后的平均气温较 1986 年以前有明显升高，尤其是北疆西部、北部和东疆地区增幅较大，达 0.6～1.6 ℃. 新疆各季平均气温的变幅以冬季为最大，夏季最小，但各季总体上均呈上升趋势. 新疆年蒸发量和干旱指数的变化总体呈下降趋势，反映出气候转湿的信号.

关键词：气温；蒸发；气候转型；信号；变化趋势

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近几十年来，温度升高，气候变暖，水循环加快，导致降水、河川地表径流和洪水的增加，引起了国内外专家学者和全社会的普遍关注. 施雅风等人[1]提出了 1987 年以来西北地区的气候从暖干向暖湿转型，降水、冰川消融量和径流量连续多年增加，导致湖泊水位显著上升，洪水灾害猛烈增加，出现气候转向暖湿的强劲信号. 林学椿等人[2]也指出，从 1951—1989 年的 40 a 来，全国年平均气温以 0.04 ℃·10 a^{-1}的倾向率上升，西北地区降水亦略有增加. 本文对新疆不同地区 50 a 来气温和蒸发两个气候要素的变化分析.

1 基础资料及分析方法

为分析不同自然条件下水文气象记录中的新疆气候转型情况，选取了 77 处代表性较好和资料系列较长的国家水文、气象站作为分析依据. 其中山区站 37 处(北疆 18 处,南疆 19 处)，海拔 620～3 507 m；平原站 40 处(北疆 16 处,南疆 24 处). 77 处站点中，有 75 处资料系列达 40 a(1961 年起)以上，8 处达 50 a(1951 年起)以上，4 处达 60 a(1941 年起)，所有资料均截止到 2000 年. 在蒸发分析中，均采用 ϕ20 cm 蒸发皿的水面蒸发资料. 所采用的分析方法主要有 5 a 滑动平均和距平和线性趋势等，地区平均值是根据该地区所选各站点的算术平均推求而得.

2 近 50 a 来的气温变化趋势

2.1 年均气温变化

根据观测资料统计以及绘制的年平均气温过程线、5 a 滑动平均曲线和距平柱状图得出了新疆近 50 a 来的气温变化情况，总体上呈上升趋势(图 1).

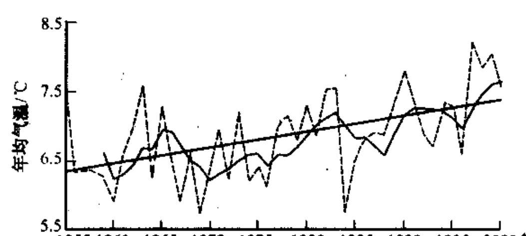

图 1 全疆年平均气温过程线

Fig. 1 Annual mean temperature changing with time in Xinjiang Region

为反映其平均增长水平，采用下式计算线性增长率[2]：

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西北气候环境转型信号在新疆河川径流变化中的反映

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摘 要：对新疆不同区域、不同补给类型的26条河流年平均径流量变化趋势分析研究，结果显示：大多数河流年径流量从1987年起出现增加趋势，天山山区增加尤其明显，其它地区有不同程度的增加，昆仑山北坡略微有减少．从径流变化来分析，天山山区的气候变化已出现由暖干向暖湿转型的信号，其它地区也正处在转型过程中．

关键词：年径流量；气候转型；新疆河流

中图分类号：P339 **文献标识码：**A

全球大幅度变暖，水循环加快，增强了降水和蒸发．中国西北部从19世纪小冰期左右处于波动性变暖变干过程中，1987年起新疆以天山西部为主地区，出现了气候转向暖湿的强劲信号，降水量、冰川消融量和径流量连续多年增加，导致湖泊水位显著上升，洪水灾害猛烈增加，植被改善，沙尘暴减少[1~6]．本文选用新疆不同自然地理条件的地区代表河流26条，根据1956—2000年年径流量资料，分析气候转型信号在新疆河流径流量变化中的反映．

1 新疆河流年径流量趋势变化分析

从新疆26条河流出山径流量资料分析，其中有16条河流年径流量呈增加的趋势，9条河流通过了信度为0.01显著性检验．16条河流年径流量平均年增加的变率为0.0007~0.0115，其中天山南坡河流年径流量增加趋势最明显，平均年增加的变率为0.0027~0.0115，如库玛拉克河协合拉站的年径流量平均年增加变率达0.0066(图1)，阿拉沟站为0.0115；帕米尔高原平均年增加的变率为0.0047~0.0055；天山北坡为0.0007~0.0047．10条河流呈下降趋势变化，年均下降的变率为0.00006~0.0037，在呈下降趋势的河流中仅有2条河流通过了信度为0.1显著性检验，其它河流下降趋势不明显．呈下降趋势的河流主要分布在昆仑山北坡，如玉龙喀什河同古孜洛克站年径流量年平均下降率为0.0037(图2)．呈下降趋势的河流与增加趋势的河流相比下降变化率要小得多．

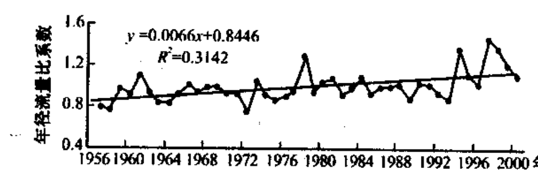

图1 协合拉站年径流量模比系数年际变化过程

Fig. 1 Frequency factor of annual runoff at Xiehela Station in Kumalik River changing with time

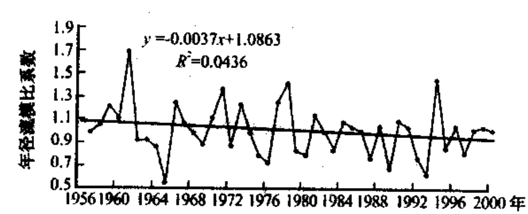

图2 同古孜洛克站年径流量年模比系数年际变化过程

Fig. 2 Frequency factor of annual runoff at Tongguziluok Station in Yulongkashi River changing with time

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新疆河流洪水与洪灾的变化趋势

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摘 要：在西北气候由暖干转向暖湿的过程中，新疆河流的洪水和洪灾反映明显. 对新疆 29 条河流选取年最大洪水，统计出超标准洪水、20 a 一遇、50 a 一遇洪水的出现频次进行分析，结果显示 1987 年后洪水量级、洪水频次呈增加的变化趋势. 通过 20 世纪 90 年代以来灾害性洪水出现的频次、灾害损失的变化比较分析，90 年代以来灾害性洪水尤其是灾害性暴雨洪水和突发性洪水呈现增加的态势，1987—2000 年的灾害损失与 1950—1986 年相比增加了 30 倍.

关键词：洪水与洪灾；变化趋势；新疆河流

中图分类号：P333.2 **文献标识码**：A

自 20 世纪 80 年代中、90 年代初以来新疆气温持续增暖，降水增加，气候出现了明显暖湿迹象，对气候变化响应敏感的新疆大多数地区，呈现河流径流量增加、若干湖泊水位上升和湖水面积扩大、山区植被覆盖率增加[1]. 河流大洪水和洪灾出现频次和强度的增大，是气候由暖干向暖湿转型的重要特征. 选取不同地区 29 条河流年最大洪峰流量，分析新疆洪水的变化趋势，统计 90 年代以来新疆各类洪灾平均发生的频次和洪灾损失，以此反映西北气候向暖湿转型过程中出现的洪水和洪灾问题，为防灾减轻提供科学依据.

1 河流洪水概况

新疆地域辽阔，气候复杂，河流源于山区，洪水类型多种多样，按成因有 4 种主要类型的洪水：冰雪融水洪水、暴雨洪水、冰雪融水和暴雨混合洪水和各种类型的突发洪水. 对全疆主要河流 1950—1990 年有实测资料的 1 953 次年最大洪水的统计，融水洪水占 39%，暴雨洪水(包括暴雨泥石流)占 24%，融水和暴雨混合性洪水占 34%[2]. 近 50 a 来，新疆每年都有不同类型的洪水和洪灾发生，洪水灾害成为新疆最严重的灾害，给新疆的国民经济建设和人民生命财产安全造成了不同程度的危害.

2 洪水变化

2.1 洪水频次变化

超标准洪水是指超过年最大洪峰流量多年平均值的洪水，统计出现的频次可以反映出洪水发生的频繁程度并进行年际与地区间比较分析. 统计 29 条河流年最大洪峰流量 1956—2000 年超标准(年最大洪峰流量的平均值)洪水出现的频次(图 1)，50 年代、60 年代是超标准洪水多发期，70 年代、80 年代在 1987 年前是超标准洪水少发期，自 1987 年以来超标准洪水明显增多，尤其是 1993—2000 年连续 8 a 出现高频次的超标准洪水. 这里采用 1987 年为界统计，计算 1987—2000 年与 1956—1986 年年平均频次变率(表 1)，从表中可明显看出发源于天山山区的大多数河流在 1987 年后，年平均频次变率高达 20% ~ 700%，其中天山南坡、帕米尔高原的河流变率最高为 77% ~ 700%，发源于这些地区的河流洪水以暴雨成因为主；其次为天山北坡，中段变率 7% ~ 107%，伊犁地区为 20% ~ 60%，发源于准噶尔西部和阿尔泰山南坡雨雪混合性洪水的河流变率为 14% ~ 93%. 昆仑山北坡的河流洪水频

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渭干河流域‘2002·7’特大洪水分析

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3．新疆 水文水资源局，新疆 乌鲁木齐 830000)

摘 要：渭干河是塔里木河流域第六大源流，位于天山西部南麓，渭干河干流起点有新疆最大的流域性控制工程——克孜尔水库．2002年7月下旬天山中西部山区出现大暴雨(雪)过程，渭干河流域山区降水持续时间长达30 h以上，山区降水量50 mm左右，导致5条支流和渭干河干流出现有水文记录以来的最大洪峰，流量超过警戒流量和危险流量的2～3.5倍，暴雨(雪)过程结束之后，融雪型洪峰长时间居高不下．洪水过程中，各支流以及暴雨与融雪等多种洪峰遭遇现象很明显．克孜尔水库入库洪峰流量达3 660 $m^3 \cdot s^{-1}$，经水库调洪错峰，出库峰值流量为1 000 $m^3 \cdot s^{-1}$，削峰率72.7%．

关键词：渭干河；暴雨(雪)；融雪；洪水遭遇；水库调洪

中图分类号：P333.2 **文献标识码**：A

在全球变暖，水循环加快的背景下，新疆以天山中西部为主的山区近十几年来明显增湿，冰川消融量加大，径流量也连续多年增加，出现了气候转向暖湿的强劲信号[1]．新疆洪水出现的频率和强度及其灾害损失也猛烈增加，1999年塔里木河曾出现全流域特大洪水，当时渭干河流域的洪水为有水文资料以来第1位，仅仅在3 a之后，2002年7月下旬该流域又发生有水文记录以来的特大洪水，最大洪峰流量是1999年最大洪峰流量的1.58倍．

1 流域基本情况

1.1 流域概况

渭干河位于新疆天山中西段南麓，是塔里木河流域第六大源流，由木扎提河、卡普斯浪河、台勒外丘克河、卡拉苏河、黑孜河5条支流汇合而成．经拜城、库车、新和、沙雅四县，最后消失于塔里木河北岸附近．渭干河全长约452 km，流域面积72 420 km^2，介于80°40′～84°10′ E，41°06′～42°42′ N之间．

渭干河上游主要支流为木扎提河，发源于哈尔他乌山的汗腾格里峰东侧的喀拉库勒冰川东坡，流经拜城盆地后，又汇集了卡普斯浪河、台勒外丘克河、卡拉苏河、黑孜河四条支流后始称渭干河，渭干河出秋里塔克山峡后分为沙雅河与英达亚河．其中木扎提河长282 km，克孜尔水库以下渭干河河长170 km．干流木扎提河上游山势高峻，右侧除汗腾格里峰(海拔6 995 m)外，还有托木尔峰(海拔7 435 m)等，由于高山降水丰沛，年降水量可达900 mm以上[2]，这里是中国天山最大的冰川作用中心 \ + [3]，木扎提河破城子水文站以上冰川面积覆盖率达42.6%，为新疆主要河流中冰川面积覆盖率最大的河流[4]．

天山山区是新疆暴雨常发区，暴雨中心常沿天山自西向东移动，有的始发于喀什、阿图什以北地区，有的始发于伊犁河谷上游或阿克苏北部山区，然后东经渭干河、开都河上游、巴仑台和天池到北塔山出境[5]．渭干河流域山区地形险峻，西高东低，常发生暴雨型洪水．

1.2 水文站网

渭干河流域5条支流和干流上共设有水文站7

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西北地区近年来内陆湖泊变化反映的气候问题

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摘 要：内陆湖泊是气候变化敏感的指示器，高山湖泊处于自然状态，受人类活动影响较小，能够较真实地反映气候状况，而内陆河尾闾湖变化是自然和人类活动共同作用的结果．利用 NOAA/AVHRR、EOS/MODIS 卫星资料和相关文献资料研究分析了祁连山哈拉湖和大、小苏干湖，黑河下游东居延海、新疆博斯腾湖、塞里木湖和艾比湖面积变化．结果表明，近年来祁连山哈拉湖面积呈逐渐扩大趋势，大、小苏干湖面积变化稳定；2002 年是黑河流域降水较多的年份；2002 年新疆内陆和高山湖泊面积显著增加，预示着这些地区降水增多，冰雪融化加快．内陆湖泊变化应引起人们的关注．

关键词：哈拉湖；卫星资料；湖面积；变化

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1 引言

内陆湖泊是气候变化敏感的指示器，高山湖泊处于自然状态，受人类活动影响较小，能够较真实地反映气候状况，而内陆河尾闾湖变化受自然和人类活动共同影响．利用内陆湖泊变化研究其反映的气候问题已有许多研究，施雅风[1]利用青海湖和伊塞克湖水位变化等资料分析其所指示的气候干暖化趋势；胡汝骥等[2]利用天山湖泊变化分析其所示的气候趋势；王树基[3]研究了我国干旱区湖泊受人类活动的影响．由于内陆湖区人烟稀少，自然条件恶劣，受到自然和物质因素的约束，难以经常获得湖泊变化数据．卫星遥感技术为监测湖泊变化提供了有效手段，早在 20 世纪 70 年代，美国 NESDIS 就利用 NOAA/AVHRR 可见光和红外图像监测五大湖湖冰的变化[4]，中国国家卫星气象中心气象卫星水情监测已形成业务产品[5]．本文利用 NOAA/AVHRR、EOS/MODIS 卫星资料和相关科技文献资料研究分析了近年来祁连山区哈拉湖、苏干湖、黑河下游东居延海、新疆博斯腾湖、塞里木湖和艾比湖面积变化，从中分析这些地区的气候变化．

2 资料与方法

2.1 资料

本文选用 1989 年、1994—2002 年 NOAA/AVHRR 资料、2002 年 8～9 月 EOS/MODIS 资料和相关科技文献[1～3]资料．

2.2 监测原理

NOAA 系列气象卫星上携带的改进的甚高分辨率扫描辐射仪(AVHRR－2)有 5 个通道，其中通道 1 位于可见光波段(0.58～0.68 μm)、通道 2 位于近红外波段(0.725～1.1 μm)，它们接收来自地气系统的反射辐射．由于水在整个反射红外波段相对与植物或土壤来说具有很突出的低反射特征[6]，在通道 1 和通道 2 图像上，水体的色调非常暗，与周围陆地有很大差别，这在通道 2 图像上尤其突出，水陆界限十分明显，很容易将其识别出来．

美国对地观测系统计划 EOS (Earth Observing System)是通过发射一系列对地球观测卫星获取的数据来解决全球环境和气候变化问题．中分辨率成像光谱仪 MODIS(Moderate－resolution imaging Spectrora－diometer)是 EOS 中计划最有特色的仪器之一，

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20 世纪下半叶开都河与博斯腾湖的水文特征

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摘　要：开都河属于雪冰融水和雨水混合补给的河流，流域共有冰川 722 条，冰川总面积为 445 km^2，冰川总储量为 22.4 km^3. 开都河年径流补给源中，积雪和冰川及地下水补给占有相当大的比例. 开都河是博斯腾湖的主要补给源，对博斯腾湖生态与环境起着至关重要的作用. 1987 年以来，由于开都河天然年径流量的大幅度增加，博斯腾湖水位不断持续上升回复到上世纪 50 年代水平，目前，已达到历史最高水位.

关键词：开都河；博斯腾湖；冰川；径流量；矿化度

中图分类号：P343.3　　**文献标识码**：A

1　开都河的水文特征

1.1　基本特征

开都河位于新疆天山南坡焉耆盆地北缘，介于 82°58′~86°55′ E、41°47′~43°21′ N 之间. 开都河发源于天山中部艾尔宾、依连哈比尔尕、那拉提、科克铁克等山脉，属雪冰融水和雨水混合补给为主的河流，亦属新疆巴音郭楞蒙古自治州境内最大的一条河流.

开都河上游主源哈尔尕特沟发源于哈尔尕特大坂，主流自东向西经小尤勒都斯盆地至巴音布鲁克水文站，而后折转东南，经大尤勒都斯盆地至呼斯台西里，再经峡谷段至大山口水文站后流出山口，山口以上流域集水面积 18 827 km^2，山区流域平均海拔 3 100 m.

开都河流域山区降水丰富，诸河源冰川积雪主要集中分布在海拔 4 000~4 500 m 的艾尔宾、依连哈比尔尕、科克铁克和那拉提等山脉.

据《中国冰川目录》[1] 统计，开都河流域诸河、沟共有冰川 722 条，冰川总面积为 445 km^2，冰川总储量达 22.4 km^2. 据 1984 年统计，该河多年平均雪冰融水补给量约 $5.08\times10^8 m^3$，占开都河多年平均径流量的 15.2%. 丰富的雪冰水资源，造就了开都河稳定的基流补给源. 开都河流域和天山西部山区其它河流一样，自 20 世纪 90 年代开始，径流量明显增大，2000 年达到历史最丰值[2].

1.2　开都河枯水年份水文特征

根据开都河 1956—2000 年 45 a 水文资料分析，1957 年是开都河较为典型的枯水年份，该年径流总量为 $28.0\times10^8 m^3$，较多年平均年径流量偏少 18%，其中春季(3~5 月)径流量为 $5.6\times10^8 m^3$，较多年平均春季径流量的 $7.8\times10^8 m^3$，偏少 28%；夏季(6~8 月)径流量为 $13.6\times10^8 m^3$，较多年平均夏季径流量的 $15.5\times10^8 m^3$，偏少 12.2%；秋季(9~11 月)径流量为 $5.9\times10^8 m^3$，较多年平均秋季径流量的 $7.1\times10^8 m^3$，偏少 16.9%；冬季(12~2 月)径流量为 $2.8\times10^8 m^3$，较多年平均冬季径流量的 $3.7\times10^8 m^3$，偏少 24%.

该年开都河山区地下水稳定补给量为 $10.5\times10^8 m^3$，较多年平均补给量的 $13.0\times10^8 m^3$，偏少 19.2%. 雪冰补给量约为 $2.73\times10^8 m^3$(图 1).

1.3　开都河平水年份水文特征

1973 年年径流量为 $35.1\times10^8 m^3$，属平水年份.

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近40 a来新疆河流洪水变化

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摘 要:随着全球变暖,水循环加快,降水量、冰川消融量和径流量连续多年增加,导致20世纪90年代以来新疆河流各类洪水频繁发生,且呈现出峰高量大的特征. 近40 a来洪水灾害的频次呈逐年增加趋势,尤其是1987年以来,洪灾发生的频次增高,灾害损失成10倍增加. 其原因主要是由于天山中西部为主的地区气候由暖干向暖湿转型所致.

关键词:新疆河流;洪水;洪峰流量;气候转型;信号
中图分类号:P333.2 文献标识码:A

1 洪水成因和类型

新疆地处中国西北边陲,位于亚欧大陆腹地,是典型的内陆干旱区,但由于新疆境内耸立着许多高大山体,截获了较多的水汽,因而在山区形成较多降水[1]. 高山区在低温条件下,降水形成冰川和积雪,融化后产生冰雪洪水;中低山带多暴雨,常形成暴雨洪水和泥石流,同时在各种特殊自然地理条件下还会形成各种类型突发性洪水. 这种独特自然地理条件,使得新疆河流具有径流补给多样,洪水成因复杂的特点. 新疆共有大小河流570多条,其洪水按成因[2,3],可分为4种主要类型:融水洪水、暴雨洪水、融水和暴雨混合洪水以及各种类型的突发性洪水.

2 新疆河流洪水近40 a来的变化

2.1 年最大洪峰流量均值

统计了南北疆26条代表性河流不同年代最大洪峰流量均值(资料系列从建站至2000年),结果显示:20世纪60—80年代洪峰流量均值虽有波动,但变化不大;进入90年代以后大多数河流10 a平均值都远比60—80年代大,尤其是雨洪型河流增加更多,如:阿拉沟站60—80年代平均值分别为73.0 $m^3 \cdot s^{-1}$、60 $m^3 \cdot s^{-1}$、65 $m^3 \cdot s^{-1}$、而90年代10 a平均值166 $m^3 \cdot s^{-1}$;卡拉贝利站60—80年代分别为454 $m^3 \cdot s^{-1}$、444 $m^3 \cdot s^{-1}$、425 $m^3 \cdot s^{-1}$、而90年代10 a平均值719 $m^3 \cdot s^{-1}$(表1).

2.2 年最大洪峰流量模比系数

计算历年洪峰模比系数,挑选出各年代最大模比系数进行比较. 历年最大模比系数大多数河流出现在90年代,有些出现在80年代末,说明实测最大洪水大多出现在90年代(表1).

2.3 年最大洪峰流量5 a滑动平均曲线

图1、图2绘出26条河流5 a滑动平均曲线,可见历史洪水变化趋势:各河虽洪水水源不同,但大多数河流都从80年代末90年代初明显呈上升趋势,新疆西部尤为明显.

2.4 超定量洪水和超标准洪水发生频次分析

选择21条河流的21个断面,统计超过历年最大洪峰流量平均值(标准)和历年最大洪峰流量平均值的一半(定量)的洪水频次. 其统计结果以柱状图来表示(图3),可看出:

(1)以高温和暴雨叠加成因为主的河流发生超定量的频次最高的年份大多出现在1987年以后,以1988、1998、1999、1997、1994年较多. 如:玛纳斯河、特克斯河、哈什河、昆马力克河、叶尔羌河、台兰河等. 尤其是以暴雨成因为主的河流自1987年以来发生超定量的洪水的频次明显增高,如

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塔里木河流域近40 a来气候、水文变化及其影响

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摘 要:塔里木河流域平原地区在近10 a明显变暖,较明显的增湿出现在近20 a,大部分平原地区近10 a反而略有变干的迹象;20世纪90年代是流域山区近40 a来最暖阶段,在天山南麓中西部山区和帕米尔高原一带90年代增湿幅度大,西昆仑山北坡一带近20 a降水变化很小. 塔里木河流域4条源流出山口多年平均径流量为224.9×10^8 m^3(1957—1999年),年代际尺度上,50—80年代基本接近多年平均值,而90年代由于受山区增暖变湿影响,4条源流径流量达241.9×10^8 m^3,增幅7.6%. 由于源流区人类活动的影响和粗放型农业,补给塔里木河源流条数减少,塔里木河干流上中游区间耗水量严重,中下游水量来水量在近40 a中持续减少,导致下游生态环境急剧恶化.

关键词:塔里木河流域;变暖增湿;径流量增加
中图分类号:P339 文献标识码:A

1 塔里木河流域四源一干概况

塔里木河流域总面积102×10^4 km^2,由阿克苏河、叶尔羌河、和田河、开都河-孔雀河4条源流和塔里木河干流组成. 塔里木河从阿克苏河、叶尔羌河、和田河3河汇合口肖夹克至台特马湖全长1 321 km,其中肖夹克至英巴扎为上游,河长495 km;英巴扎至恰拉为中游,河长398 km;恰拉至台特马湖为下游,河长428 km. 由于人类活动的影响,补给塔里木河水量急剧减少,台特马湖于1974年干涸. 2000—2001年的3次向塔里木河下游'绿色走廊'应急输水工程,于2001年11月16日成功地把水输到了台特马湖,从而结束了28 a塔里木河下游320 km河道滴水未见的历史,生态环境开始恢复.

塔里木河流域四源一干共有主要水文站19个,其中源流13个站,包括源流出山口径流控制站、区间重要节点站和入塔里木河径流控制站,基本上控制了源流入、出径流量. 在塔里木河干流共设有6个站,分布在上、中、下游重要径流变化节点处.

2 塔里木河流域近40 a气候变化趋势

全球气候在过去100 a中变暖了0.3~0.4 ℃,近40 a中变暖了0.2~0.3 ℃[1];中国气候的研究表明,1951—1990年间年平均气温升高了0.3 ℃[2]. 50 a来,新疆气温呈上升趋势,北疆变暖幅度大于南疆,而且变暖主要季节在冬季;降水呈明显的增湿趋势,南疆降水偏多幅度大于北疆,各季降水均有增加趋势[3~6]. 塔里木河流域是一个相对独立的生态环境系统,与全球气候变化同步,流域内的气温、降水等气象要素近40 a来也有变化.

2.1 站点资料选取

选取流域内的山区和平原共8个气象台站,山区站有代表西昆仑山北坡的塔什库尔干气象站(区站号51804,下同)、帕米尔高原上的吐尔尕特气象站(51701)、代表西天山南麓山区的阿合奇气象站(51711)和代表中天山南麓一带的巴音布鲁克气象站(51542);平原站有和田河流域的和田气象站(51828)、喀什噶尔河流域的喀什气象站(51709)、阿克苏河流域的阿克苏气象站(51628)、开都河-孔雀河流域的库尔勒气象站(51656). 各站海拔及地

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塔里木河中游滞洪区的形成及其对生态环境的影响

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摘 要：塔里木河位于我国新疆内陆干旱区，是我国最大的内陆河，全长 1 321 km. 近 40 a 来，在阿克苏河、叶尔羌河、和田河、开都河-孔雀河四条源流出山口天然来水量未减少，且在 20 世纪 90 年代增加 7%的情况下，由于源流区人类活动的影响和粗放型农业，补给塔里木河水量以年平均 2 500×10^4 m^3的速率减少，加之中游区新生滞洪区耗水严重，进入下游的水量锐减. 20 世纪 70 年代以来又被大西海子水库几乎全部拦蓄，导致最下游 320 km 河道断流近 30 a，地下水位下降，植被衰退，沙漠化进程加快，“绿色走廊”危在旦夕，生态环境恶化，已影响到流域人类的生存安全.

关键词：塔里木河；滞洪区；区间耗水；生态环境
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1 流域概况

1.1 基本情况

塔里木河流域位于我国西北干旱区内陆盆地，新疆维吾尔自治区南部，包括发源于天山、昆仑山、帕米尔山区和阿尔金山的九大水系 144 条河流和塔里木河干流、塔克拉玛干沙漠、东部荒漠三大区，流域总面积 102×10^4 km^2，其中沙漠面积达 37.04×10^4 km^2. 1998 年统计总人口为 826×10^4 人，水资源总量 429×10^8 m^3，现有灌溉面积近 133×10^4 hm^2，水土资源量相对丰富. 目前流域人均耕地约 0.133 hm^2，人均水资源达 5 200 m^3，高于全国平均水平.

塔里木河是我国最长的内陆河，也是世界上最大的内陆河，历史上开都河-孔雀河、迪那河、渭干河、阿克苏河、喀什噶尔河、叶尔羌河、和田河、克里雅河、车尔臣河九大水系都与塔里木河干流相通. 随着上游人类活动影响和用水量的不断增加，到 20 世纪初车尔臣河、克里雅河、迪那河已断流，20 世纪 40 年代以后喀什噶尔河和渭干河已与塔里木河失去地表水联系，现今与塔里木河有地表水自然联系的只有阿克苏河、和田河、叶尔羌河和开都河-孔雀河四条源流. 四条源流多年平均地表水径流量为 224.9×10^8 m^3，占塔里木河河流域地表总径流量 398.0×10^8 m^3的 56.5%. 目前的状况是叶尔羌河自 1964 年后大部分水量引入小海子水库和永安坝水库，自 1986 年至 2002 年的 17 a 间，仅有 1994 年、1999 年和 2000 年有少量水汇入塔里木河外，其余 14 a 断流无水输入塔里木河，该河实际已处于基本断流；开都河-孔雀河 1952 年因在轮台县塔里木河汊河拉因河口修建塔里木大坝，与塔里木河分离，从 1980 年起孔雀河通过库塔干渠向塔里木河下游灌区输水，而实际进入塔里木河的水量仅约 1.0×10^8 m^3；和田河是塔里木河第二大水量补给源流，又是一条季节性河流，每年只有在 7～9 月 3 个月有水量汇入塔里木河，其余时间断流；阿克苏河是塔里木河流域四条源流中最大的源流和补给塔里木河最大的河流，入塔里木河水量占四条源流入

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冰川学开拓与气候环境变化研究的回顾

Deploitation of Glaciology in China and Retrospect of Studies on Climatic and Environmental Change

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1 前言

人生征途中,大学生活数年是很重要的甚至关键性的一个环节,在基础学识的成长,独立能力的形成,以至人生观的树立中都有重要作用. 我于1919年出生于江苏海门市农家,仰仗父母异常勤劳刻苦支持上学,有幸于1937年考入杭州国立浙江大学,适值抗日战争开始,随校转移内迁(其中有8个月不在校),1940年初到达贵州遵义,尽管物质生产极其艰苦,但在杰出的科学家、教育家竺可桢校长领导下,以《求是》为校训,依靠一批好教授,培养成勤奋、朴实、自由、民主、努力向上的好学风. 我所在史地系在系主任人文地理学家张其昀教授组织下,汇集了一流学者包括地质学家叶良辅、气象学家涂长望、地貌学家任美锷、自然地理学家黄秉维、历史地理学家谭其骧等,每人开设二、三门以上课程,并由学生自愿选择为导师,指导学生撰写毕业论文. 我选请叶良辅先生为导师,三年级结束时已将规定的学分课程读完,四年级得全力进行论文准备,对遵义附近地形,做了3个月实地调查,每有发现就向叶先生报告和讨论,特别高兴的是发现和证实一处河流劫夺和一处削平构造的古侵蚀面,写成6万字的论文,甚得叶师赞赏,经学校上报教育部得奖,论文主要内容以《遵义附近之地形》为名发表[1]. 1942年大学毕业后,接着当研究生,开始时研究生津贴,除膳费外还有点零用钱,但随着物价猛涨,津贴不够吃饭了,做论文的费用也无处着落,幸承已转到重庆资源委员会工作的黄秉维教授推荐,到重庆一个挂名研究单位兼任助理研究员,拿一份工资,承担整理、分析华中区水文资料任务,在黄先生指导下,以一年时间撰写成4万字的《华中水理概要》论文发表[2]. 即以此为研究生毕业论文,于1944年取得了硕士学位. 1942年初,浙大发生了倒孔(祥熙)学生运动,我参加了这个运动并在以后的活动中结识了一批思想进步、热诚、品德优秀的同学,特别是吕东明同志(1938年入党)的长期引导帮助,促进我政治思想和思维方法转变,参加革命组织,1947年在南京加入中国共产党.

1944年夏季研究生毕业离校,到现在已60年了,工作单位和地点有几次变动. 1944—1949年在中国地理研究所(重庆北碚与南京),1950—1958年在中国科学院地理研究所(南京,北京),并于1954年后担任中国科学院生物学地学部副学术秘书,在社会工作与学部工作中拓宽了视野,培养了能力,但研究任务不稳定,每项研究浅尝辄止. 1958年起在兰州开始新创建的冰川考察研究,并负责建立冰川冻土研究机构. 研究方向的长期性,导致研究工作的逐步深入与扩展,1984年我已65岁,解除了冰川冻土研究所所长行政职务,改任名誉所长;1985年,兼任南京地理与湖泊研究所研究员. 从此如候鸟般的夏季在兰州、冬季在南京,考虑自己体力,已不能攀登高山冰川,一方面继续某些室内能进行的冰川研究;另方面转向气候环境变化研究,也作出了一定贡献. 本文即上述冰川学与气候环境变化二方面工作的回顾.

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基于 RS 与 GIS 的冰川变化研究
——青藏高原北侧新青峰与马兰冰帽变化的再评估

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摘 要:应用遥感(RS)与地理信息系统(GIS)技术,分析了位于青藏高原东北部,可可西里地区、昆仑山脉中段的新青峰和马兰冰帽近30 a来的冰川变化.1971—2000年间新青峰冰帽总面积呈减小变化,马兰冰帽面积有所增加;结合以往研究结果,发现新青峰冰帽面积变化在1979年前后为突变点,1979年前冰帽总体面积扩大,之后面积迅速减小,期间经历了1989—1994年相对稳定的时期.进一步分析新青峰冰帽东南侧新青峰冰川和西北侧西新青峰冰川长度变化过程,发现新青峰冰帽面积变化在很大程度上取决于这两条冰川的变化.研究时段内两条冰川末端进退变化有较大差异,西新青峰冰川在1971—1976和1994年之后为退缩期,1976—1994年间为前进,而新青峰冰川则有所不同,该冰川1971年以来一直处于退缩之中,但不同时段退缩速率不同,且1994年后有加速退缩的趋势.根据马兰冰帽冰芯$\delta^{18}O$记录所反映的夏季气温变化,近50 a来研究区在1976年之前为相对高温期,之后为相对低温期,两冰川不同的长度变化趋势可能与两冰川对气候变化具有不同的动力响应特征有关.根据两条冰川冰面地形特征分析认为,受地形条件制约,两条冰川可能具有不同的冰川表面物质平衡梯度,这也可能是两冰川具有不同的动力响应特征的影响要素之一.

关键词:新青峰冰帽;冰川变化;遥感与地理信息系统
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1 前言

近期大量文献报道世界各地山地冰川纷纷处于退缩状态,通过不同方式估算的全球山地冰川在过去数十年中物质亏损速率年均在数百毫米的量级上[1~13].这些研究表明目前观测到的冰川物质加速亏损的状态很好地反映出与人类活动有关的温室效应所带来的影响[14].

在上述各类分析与计算中,针对中国西部冰川近数十年来的变化因缺乏分布合理的监测冲川的数据,而主要参考从1959年开始的乌鲁木齐河源1号冰川(以下简称1号冰川)的物质平衡观测结果,以及根据短期观测资料结合气象-水文数据恢复的物质平衡,如祁连山中段“七一”冰川,贡嘎山东坡的海螺沟冰川等.因此,有关对中国西部冰川近数十年来变化估计的合理性,因对无观测资料地区冰川状态缺乏认识而无从评价.近期对祁连山西段1956—1990年间冰川的遥感分析提出该地区的冰川仍以退缩为主[15];黄河源区阿尼玛卿山地区在1966—2000年间的冰川变化呈现出加速萎缩的趋势[16],而处于青藏高原内部、位于长江源格拉丹冬地区的冰川虽然在1969—2000年中总体上表现出

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近期气温变暖叶尔羌河冰湖溃决洪水增加

An Increasing Glacial Lake Outburst Flood in Yarkant River, Karakorum in Past Ten Years

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水是整体环境的一部分, 它的可用性对于生物圈的有效运转是不可替代的, 人类和经济的发展如果没有安全、稳定的供水是不可想象的. 另一方面, 水也具有破坏性, 极端的事件不仅对人类和社会而且也对陆地环境产生影响. 随着全球变暖, 不稳定天气出现的频率增多, 新疆冰川退缩, 融水增大, 使雪崩、冰川泥石流和冰湖洪水等冰雪灾害发生频率也呈上升趋势. 近年来新疆洪灾发生的频次有如下特点: 1) 90年代洪灾发生的频次高于80年代, 并有逐年增加的趋势; 2) 90年代暴雨洪水仍然是成灾的主要洪水, 年均发生的频次为14.4次, 冰川、泥石流、滑坡阻塞洪水成灾的频次有明显的增加, 冰川和泥石流阻塞洪水分别由80年代的平均0.5、0.7次提高到了1.0、0.9次, 这是因为气温升高, 冰川融水增多使冰湖突发洪水的发生机率增大.

发源于喀喇昆仑山叶尔羌河源的突发性洪水是上游分布在喀喇昆仑北坡一系列与克勒青河河谷呈正交的冰川, 由于有4、5条冰川下伸到主河谷阻塞冰川融水的下排, 包括克亚吉尔冰川、特拉木坎力冰川、迦雪布鲁姆冰川等, 经常形成冰川阻塞湖, 当冰坝被浮起或冰下排水道打开, 就会发生冰湖溃决洪水. 在经历了1986年的冰湖溃决洪水后, 由于冰川排水道打开, 直到1996年再没有发生溃决洪水. 当时张祥松等根据喀喇昆仑山冰川进退变化, 认为克勒青河上游的克亚吉尔冰川和特拉木坎力冰川等20世纪10 a时间尺度的冰川前进脉动已经过去, 目前处于相对稳定和退缩、变薄的阶段, 预计在21世纪初气温持续升高的情况下, 多数冰川必将后退变薄, 冰川阻塞湖溃决(突发)洪水的规模也相应减小, 出现数千秒立米流量的溃决(突发)洪水的可能性很小, 叶尔羌河流域冰川洪水的危害将日益减轻. 但在90年代的剧烈增温过程, 冰川消融加剧, 冰川融水量增加, 冰温升高, 冰川流速加快, 冰川再次阻塞河道形成冰湖, 发生频繁的大冰湖溃决洪水(表1), 并且冰湖溃决洪水的洪峰流量和洪水总量越来越大, 冰湖的规模相应扩大, 溃决的危险程度也增加. 随着全球气温的持续变暖, 叶尔羌河的冰川湖溃决洪水的频率和幅度将会继续增加, 对下游人们的生命财产和社会经济发展带来严重威胁.

表1 近20 a卡群站冰湖突发洪水纪录

Table 1 Glacial lake outburst flood recorded in Kaqun Station, Yarkant River

日期 /(年-月-日)	洪峰流量 /($m^3 \cdot s^{-1}$)	净洪量 /$10^8 m^3$
1971-08-02	4 570	0.699
1978-09-06	4 700	1.037
1980-10-21	802	0.226
1982-11-16	856	0.299
1983-10-28	854	0.425
1984-08-30	4 570	1.027
1986-08-14	1 980	0.392
1997-08-03	4 040	0.850
1998-11-05	1 850	0.854
1999-08-11	6 070	1.410
2002-08-13	4 550	

冰川湖溃决洪水变化对全球变暖的响应机理主要是: 1)冰床变软, 变形加大, 冰底部滑动量大, 加快冰川流动和融化; 2)冰川流速加大, 阻塞河谷, 冰川湖形成; 3)冰温升高, 冰川软化, 冰湖水更易打开排水通道; 4)气温升高, 冰川消融加剧, 径流量增大, 洪水发生频率加快; 5)冰川后退, 冰川湖库容增大, 冰川湖面积扩大; 6)洪水洪峰增大, 洪水量增多.

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中国喀喇昆仑山、慕士塔格-公格尔山典型冰川变化监测结果

Monitoring Results of Glacier Changes in China Karakorum and Muztag Ata-Konggur Mountains by Remote Sensing

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以世界第二高峰乔戈里峰(K2, 海拔8 611 m)闻名的喀喇昆仑山, 发育着规模巨大的山地冰川. 国内、外科学工作者曾对喀喇昆仑山进行过许多次科学考察和探险活动. 中国于1974—1980年与巴基斯坦合作考察了喀喇昆仑山南坡的巴托拉冰川, 1985—1987年对喀喇昆仑山叶尔羌河流域进行的冰川与洪水科学考察, 取得丰硕的成果. 然而, 由于其地理位置独特, 自然环境恶劣, 对喀喇昆仑山冰川变化进行常规的监测存在诸如需耗费大量的时间、人力和财力的不足等因素的限制. 号称"冰山之父"的慕士塔格山海拔7 509 m, 而最高峰公格尔山主峰海拔7 649 m, 其主峰周围和山脊两侧发育了数量较多、规模较大的冰川. 本区近50多年有过数次国内外科学考察活动, 2001年还曾对慕士塔格山西侧的洋布拉克冰川进行了考察[1]. 而这些考察只是区域性、针对单条或几条冰川的考察.

在全球气候变暖的大背景下, 大部分地区的冰川处于萎缩减薄状态, 但在喀喇昆仑山北坡、慕士塔格-公格尔山的冰川发生了怎样的变化, 我们目前还不清楚. 因此, 有必要在前人工作的基础上对2000年前后的冰川状态进行调查.

遥感(RS)与地理信息系统(GIS)技术为开展大范围的冰川变化监测提供了技术支持. GLIMS(全球陆地冰监测计划)计划正是在这种背景下诞生的, 该计划为我国监测山地冰川的变化提供了大量高分辨率的遥感影像数据. 作为参与该计划的"区域中心(RC)"之一, 我们利用ASTER、Landsat ETM+遥感数据, 进行了包括几何纠正、辐射纠正、空间锐化增强、普间关系法、叠加DEM等处理, 对喀喇昆仑山北坡、慕士塔格-公格尔山地区的遥感数据进行解译, 得出2000/2001年的冰川边界范围, 并与中国冰川目录资料进行对比, 典型冰川变化结果如表1和表2所示. 几何纠正的精度为ASTER:0.83像元(±12.5 m);ETM:1.4像元(±21.3 m).

表1结果显示, 慕士塔格-公格尔山典型冰川中有5条处于前进状态, 8条冰川处于明显退缩状态, 尤其是5Y663D99冰川, 目前已经分成东西两支;而克拉牙依拉克冰川处于稳定状态, 其原因可能是因表碛覆盖抑制了下伏冰的消融, 对冰川起保护作用;另有5Y663B17(面积0.41 km^2)消失. 对该区域379条冰川监测表明, <1.0 km^2的冰川面积减少了11.6 km^2, 占该级冰川面积的12.6%.

表2显示, 喀喇昆仑山典型冰川中有8条保持稳定状态;而5Y654D42(木斯塔)与5Y654D48、5Y654D96与5Y654D97俩俩合并, 并且有趣的是它们分别都是前进的冰川爬到后退的冰川上. 5Y654D77与5Y654D78都处于冰川前进中, 但却合并到一起. 在监测的过程中, 还发现5Y653M1、5Y653M2、5Y654C1、5Y654C159、5Y654C2、5Y654C21、5Y654D124、5Y654D69、5Y654E1、5Y654E3、5Y654E32等面积<1 km^2的冰川消失.

根据冰川规模越小, 对气候变化的响应越敏感

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天山南坡科其卡尔巴契冰川消融期气候特征分析

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摘 要: 通过分析天山南坡科其卡尔巴契冰川区的气候变化特征及其对冰川消融变化过程的影响, 研究了冰川对气候变化的响应机理及其对塔里木河水资源的影响规律. 科其卡尔巴契冰川区夏季气温比较高, 基本处于正温, 日较差较小; 气温直减率较小, 平均值为 0.60 ℃·$(100m)^{-1}$, 冰川冷效应不明显; 对流性降水较多, 降水量的75%发生在白天; 冰川区局地环流——山谷风发育, 海拔3 900 m以上冰川受西风环流影响显著; 净辐射在7月和8月中上旬均较大, 在8月下旬后净辐射开始逐渐减小, 与冰川消融是一致的. 7月初至7月下旬是消融较强的两个时段, 冰川平均消融速率为 38.66 mm·d^{-1}, 到8月中旬消融速率略有降低, 平均为 34.79 mm·d^{-1}, 至9月中旬降至 28.83 mm·d^{-1}.

关键词: 科其卡尔巴契冰川; 气温; 局地环流; 太阳辐射; 冰川消融

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1 前言

在全球变暖大背景下, 我国西北受西风环流影响为主体的地区气候正在发生由暖干向暖湿转型的趋势[1]. 在这种背景下, 西北地区特别是天山山脉的冰川发生了显著变化, 目前冰川退缩成为主导趋势, 造成这种现象的主要原因是冰川表面物质收支状况即冰川物质平衡发生较大变化. 从冰川物质平衡构成——积累和消融来看, 在气候处于暖湿条件下, 冰川消融势必增加, 而冰川积累未必同步扩大, 原因在于尽管降水有所增加, 因气温升高, 高山带降水中雨雪比例也随之变化, 更多的降水可能以液态形式发生. 因此, 研究冰川物质平衡, 既要考虑物质平衡各分量的变化特征, 同时, 也必须考虑导致物质平衡各分量变化的气候状况的变化. 本文通过分析典型冰川区的气候变化特征及其对冰川消融变化过程的影响, 获取冰川物质平衡各分量的变化特征以及冰川气候状况等方面的变化信息, 从而研究冰川对气候变化的响应机理.

塔里木盆河是我国冰川融水补给最大的一条内流河, 该流域分布有现代冰川11 711条, 面积19 889 km^2, 冰储量2 313 km^3[2]. 据估算塔里木河流域冰川年融水总量 139.51×10^8 m^3, 占河川径流的40.2%[3], 是塔里木河流域社会经济发展的重要水资源. 研究表明20世纪80年代中后期以来, 西南天山南坡各流域出山径流呈增加变化的趋势, 如阿克苏河1986年之后径流量较之前增加了15.1%, 台兰河增加了18.6%[4]. 这一方面说明, 这些河流的水资源形成区即山区的降水可能增加显著; 另一方面, 由于气温升高, 高山带冰川区的消融强度也可能有较显著的增加. 这种解释是否合理, 还需要进行高山带气象、水文、冰川等观测来检验. 如果气候暖湿转型变化对冰川作用流域的影响的确表现为降水、冰川消融同步增加的现象, 那么在此背景下, 冰川的物质平衡状况如何, 冰川规模如何变化等是值得关注的重要问题.

2003年6~9月, 我们对塔里木河流域内的科其卡尔巴契冰川进行了冰川物质平衡、冰川运动、冰川径流与气象等过程的观测. 根据野外观测资料, 并结合已有研究, 分析科其卡尔巴契冰川消融期气候特征及其对冰川消融的影响, 为进一步研究气候变化与冰川波动间的关系奠定基础.

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高山冰川区大降水带的成因探讨

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摘 要：在中纬度高亚洲的高山冰川带，由于下垫面的温度场和湿度场与周围环境的差异，形成冷岛和高湿中心. 其结果造成水平湍流加强，并影响内部场的湍流加剧，使冰川区成为湿岛和局地对流加强，形成多降水过程，增加降水量. 当过境气流通过时，冰川区形成阻岛，气流活动加强，产生降水天气. 这种作用使高山冰川带成为高降水带，并且山地越高，冰川面积越大，对于气流影响越强烈. 其结果形成青藏高原外围区冰川分布广，降水量大，而内部降水少的格局. 大降水带的成因主要归于冷下垫面和高湿度场的作用.

关键词：高山冰川区；大降水带；冷下垫面；成因
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高山冰川区，尤其是中纬度的高亚洲高大的山脉，存在着大降水带的事实. 这些地区往往位于内陆干旱区，河谷中年降水量仅几十至一、二百毫米，但在高山区却发育着大量的冰川，冰川区的降水量为河谷地的数倍至十几倍. 在青藏高原及其周围山地冰川考察中，人们注意到高山冰川区降水量随高度递增，成为高降水中心，它们为山地冰川的发育提供了丰富的物质基础，也为干旱区的发展提供了水源[1]. 在我国西部干旱区，高山冰川区高降水带的存在，对于这些地区的社会经济发展具非常积极的意义.

大降水带存在的事实

从1859年以来，在珠穆朗玛峰北坡绒布河谷进行的气象和冰川考察中[2,3]，人们发现高山冰川区降水随海拔增加，在雪线以上的海拔6 500～7 000 m出现大降水带，其年降水量为谷地的二倍多. 在喜玛拉雅山南坡，据Ageta的观测[4]，1974年8月21～31日期间位于莫加河谷的拉均(Lahjung，海拔4 200 m)总降水量为37 mm，同期在高于900 m的冰川上(海拔5 300 m)则记录到107 mm的降水，后者大于前者3倍之多. 在西昆仑山的南坡，位于谷地海拔4 900 m的甜水海，年降水量仅为20.6 mm，而在高山的崇测冰帽6 350 m的雪坑，我们测到的冰雪水当量折合成年降水量达600～700 mm. 位于巴基斯坦喀喇昆仑山的巴托拉冰川，在冰川末端河谷(海拔2 563 m)的年降水量仅100 mm左右，而在海拔5 100 m的冰川上其年降水量达1 000～1 300 mm[5]. 1986年中国-联邦德国乔戈里峰联合考察队在喀喇昆仑山乔戈里(K_2)峰北坡考察中，各高度同期观测到的降水量如表1所示，可以看到从冰川末端河谷到高山粒雪盆区降水量剧增.

以上事实说明，在中纬度高山冰川区存在大降

表1 1986年喀喇昆仑山北坡K_2冰川区不同高度降水比较(mm)

Table 1 Precipitations at different altitude on K_2 Glacier of the Karakorum, 1986(mm)

海拔/m	9月13日	9月14日	9月22日	9月27日	合计
4 150	0.1	0.0	0.0	0.1	
4 600	8.5	0.9	2.0	6.8	
5 150	24.3	4.3	6.8	21.5	

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玉龙喀什河源区 32 年来冰川变化遥感监测

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摘要：根据航空相片、地形图、遥感影像数据分析了玉龙喀什河源区的冰川变化，结果表明，1970~2001 年本区冰川总体上以稳定冰川的数量占多数，但由于部分冰川的退缩使得整个研究区的冰川表现为萎缩的趋势。1970~1989 年冰川规模有扩大的趋势，冰川面积、储量分别增加了 1.4 km^2、0.4781 km^3，约占 1970 年研究区相应总量的 0.12%、0.19%；而 1989~2001 年的冰川面积、储量分别比 1970 年减少了 0.5%、0.4%，是西北干旱区冰川面积变化幅度最小的区域。分析认为该区域 1970~1989 年冰川扩大可能与该地区的冰川对 20 世纪 60 年代末温度降低、降水量增加有 10~20 年滞后响应有关；1989~2001 年冰川退缩，主要受温度快速上升影响，而丰富的降水对冰川退缩起到缓冲的作用。

关键词：玉龙喀什河源区；冰川；遥感；GIS

1 引言

“中国西北部可能由暖干向暖湿转型”这一科学论断已经引起研究者广泛重视[1,2]。在全球气候日益变暖的背景下，作为我国淡水资源的冰川储量是增大还是减少，已备受社会各界关注[3,4]。地处地球中低纬地区的冰川与人类密切相关，被誉为高山“固体水库”的冰川不仅对河川径流有直接的影响，而且可以揭示气候波动的响应特征[5]。监测冰川变化规律，尤其是代表性冰川或典型区域冰川变化是冰川学研究的重要内容之一，具有重要的理论和应用价值[3,6]。玉龙喀什河是和田河的两大支流之一。而玉龙喀什河源区是昆仑山西段主峰现代冰川分布规模最大、最集中的地区[7]。冰川融水补给是和田河内流区的主要补给来源。因此对该区域的冰川变化进行监测是研究和田河冰川融水补给及其变化的重要方面。传统的冰川研究是以野外考察为主，结合航空照片进行的。随着遥感 (RS) 在冰冻圈变化研究中的应用，3S 技术为研究冰川变化提供了有效的手段[8-14]，为冰川变化研究提供了新视角。GLIMS (Global Land Ice Measurements from Space) 计划的实施更是推动了 3S 支持下的冰川学研究[14]。正是基于这样的背景，本文利用遥感与地理信息系统技术，选取 1970 年航空相片和 1989 年及 2001 年 Landsat TM/ETM＋影像资料为信息源，综合雪盖指数与目视判断方法，提取不同时期玉龙喀什河源区的冰川分布，研究流域尺度的冰川变化；结合气候特征分析，探讨该区近 32 年来冰川波动的一般规律，为研究该流域冰川变化对水资源的影响提供基础数据。

2 冰川发育状况

玉龙喀什河源区位于西昆仑山的北坡，地理位置大致介于北纬 80°~82° 和东经

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托木尔峰南坡冰川水文特征及其对径流的影响分析①

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摘 要：托木尔峰地区冰川消融和冰雪融水径流对温度和降水变化有很好的响应，冰面消融与同期温度之间呈线性相关性，冰川年消融深与消融期6～8月份平均气温呈指数关系。过去40年来托木尔峰地区年冰雪融水量增加了8～10×10^8m^3左右，而在区域温度持续升高的趋势下，冰雪融水补给量将会持续增加。冰雪融水对河流补给的季节集中性和多年变化的稳定性，造成水资源量高度季节集中和平稳的年际变化。通过对本地区河流月流量持续性分析表明，本地区河流月径流量持续性很差，并且冰雪融水补给越高，持续性越差，对充分利用区域内水资源产生了不利影响。

关 键 词：冰川消融 融水径流特征 河道径流 托木尔峰南坡
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1 引 言

冰川水资源在我国西北干旱区水资源组成、波动和变化中扮演着十分重要的角色。西北地区对社会经济发展有决定作用的内陆河水资源构成和变化中，冰川水资源的影响不容忽视。在西北地区众多内流水系中，塔里木河流域冰川数量最多，在面积约$102\times10^4km^2$的塔里木河流域中，集中了全国冰川面积的34%、冰川储量的41%，内流区冰川面积的56%和储量的65%，每年冰雪融水对河川径流的补给平均可占到河川径流总量的40%左右。随着国家西部大开发战略的实施，塔里木河流域已成为新疆经济社会发展和我国西部开发潜力巨大的地区之一[1]。自20世纪70年代以来，塔里木河下游出现了长达近30余年的断流现象，流域水质恶化、生态退化、沙漠扩大，严重危及中下游地区的经济发展和社会进步。历史上曾经汇入塔里木河的九大水系中现今与塔里木河有地表水联系的只有阿克苏河、和田河和开都河－孔雀河三条源流[2]。阿克苏河不但是四条源流中补给塔里木河最大的河流，也是惟一常年向塔里木河输水的河流，汇入塔里木河的水量占四条源流总水量的70%，阿克苏河－塔里木河已成为相对独立的流域系统[3,4]。冰雪融水较高的补给比重，是阿克苏河径流量多年来保持稳定并在近年来略有增长的主要原因之一。明确天山高山区冰雪的消融和变化趋势，将会对阿克苏河流域乃至塔里木河流域水资源的利用和生态环境建设做出指导，对本地区社会经济建设将产生影响。

2 研究区概况

托木尔峰是天山最高峰，海拔7 483.5m，位于我国天山西段。这里不但是天山最大的冰川作用中心，而且也是世界上著名的山岳冰川区之一。托木尔峰地区的冰川面积是珠穆朗玛峰地区冰川总面积的2.4倍，比整个祁连山冰川总面积（1 979.8km^2）大2倍。平均每年山区产生的径流量约为$63.4\times10^8m^3$，其中56%为冰雪融水[5]，是我国新疆阿克苏地区和伊犁地区重要的水资源，也是塔里木盆地北侧塔里木河主要支流的源区。

托木尔峰地区的降水主要靠来自大西洋和北冰洋的潮湿气流补给，降水量主要集中在夏季和冬季，春秋两季降水量相对较少。其中6～8月份降水量约占全年的50%左右，而5～9月份占70%左右，冷季降水量约占30%；托木尔峰南坡冰川区的降水梯度为30mm/100m[5]，冰川积累区气候严寒，降水丰沛，多年平均降水估计可达1 000mm以上，冰川末端估计在400～600mm，山前平原区多年平均降水不足80mm（阿克苏站）。山区丰富的降水和冰雪融水共同成为山前河流主要的水量来源。

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新疆阿克苏地区耕地变化分析及驱动因子研究①

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摘 要:据新疆阿克苏地区各市、县的统计数据,分析了阿克苏地区50年代以来耕地面积的总体变化趋势、变化速度、区域差异和驱动因子。分析表明:阿克苏地区的耕地面积呈现波动增加的态势,但人均耕地面积经历了从增加到减少的变化过程;耕地空间变化区域差异较明显;影响阿克苏地区耕地变化的8个因子可归纳为经济发展因素、人类行为因素和城市化发展水平;通过模型计算,人类行为对耕地变化的影响尤其显著。研究结果和分析结论对于阿克苏地区农业可持续发展具有重要的意义。

关 键 词:阿克苏地区 耕地 驱动因子 影响强度 新疆
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1 引 言

随着人口、资源和环境问题的日益突出,土地利用/土地覆盖变化研究成为全球环境变化研究的前沿和热点领域[1],耕地更成为了土地利用/土地覆盖变化研究中的热点。位于天山南部、塔里木盆地北缘的阿克苏地区是一个农业大区,也是新疆少数民族聚居较集中的地区。农业经济占据国民经济主导地位,在全疆占有举足轻重的地位。1998年,地区农业总产值占全疆的12.3%,排位第二位,粮食占总产占全疆的12.0%,排位第三位。近年来,由于社会经济发展迅速、人口剧烈增长和非农业用地等原因,导致阿克苏地区耕地面积逐年波动变化,尤其是人均耕地面积呈现减少的趋势,人均耕地面积已由1958年的0.40hm^2减至2001年的0.17 hm^2,44年间净减了3/5。而人口逐年增加,2002年总人口达214万人,相当于1949年的3.2倍。随着西部大开发战略的实施,阿克苏地区不仅加大了农业发展的投入,同时也加大了城市基础设施建设,耕地面积面临着巨大的挑战。因而,该地区耕地面积的变化对于区域经济发展的影响是显著的。但对于阿克苏地区耕地变化的研究是很少的,因此可通过本项研究,掌握该区域耕地现代变化的空间格局及其驱动因素,不仅可以为该区域合理利用耕地资源、控制耕地的剧烈变化以及与环境协调发展提供科学依据,还可以为耕地变化研究提供一个案例,更有利于地区的可持续发展[2]。

2 研究区概况

2.1 自然环境概况

阿克苏地区地处新疆中部,天山山脉中断南麓、塔里木盆地北缘。位于39°30′~42°40′N,78°02′~84°05′E之间,地势北高南低,由西北向东南倾斜。该区地处亚欧大陆深处,远离海洋,为暖温带干旱型气候;年均气温在9.9~11.5℃,年降水量在42.4~94.4mm,具有冬季干冷和夏季干热的气候特点。全区年总日照达2 800~3 831.35h,仅次于青藏高原,居全国第二位。高山区有常年冰川积雪,是区内众多水系的发源地,区内主要水系有阿克苏河、塔里木河、木扎尔特河、渭干河、库车河等,本区是南疆水资源最丰富的地区。

2.2 社会经济概况

阿克苏地区辖包括库车、拜城、温宿、乌什、柯坪、沙雅、新和、阿瓦提8个县和阿克苏市以及兵团农1师的大部分团场;总面积13.25×10^4km^2,占新疆总面积的8%,总人口214万人其中少数民族占75.3%。地处天山南麓由东往西,排列着库车、拜城、温宿、乌什和柯坪5县;地处塔克拉玛干沙漠北缘由东往西,排列着沙雅、新和、阿克苏和阿瓦提。阿克苏地区农牧业发达,占据国民经济的主导地位,是新疆主要的灌溉绿洲农业区和重要的粮食、棉花和瓜果生产基地之一,也是新疆的主要水稻产区,素有“塞外江南”、“鱼米之乡”之美誉。图1是新疆阿克苏地区地理位置示意图。

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2002年塔里木河流域四条源流区间耗水分析

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摘 要：2002年塔里木河四条源流出山口天然径流量273.9×10^8 m^3，比多年平均值多46.9×10^8 m^3，偏多20.7%，属丰水年.其中发源于天山山脉的阿克苏河和开都河-孔雀河径流增幅大，水量充沛，属丰水年，而发源于昆仑山脉的叶尔羌河和和田河径流量保持多年均值年.2002年度，四条源流区总耗水量219.1×10^8 m^3，占出山口天然径流量的80.0%.其中阿克苏河流域总耗水量为65.90×10^8 m^3，占出山口天然径流量的60%；叶尔羌河流域耗水量61.92×10^8 m^3，年内无水量进入塔里木河干流；和田河流域耗水量36.45×10^8 m^3，占出山口天然径流量的80.9%.开-孔河流域内耗水54.76×10^8 m^3，占出山口天然径流量的95.9%.

关键词：塔里木河；源流；区间耗水；2002年
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塔里木河流域由阿克苏河、叶尔羌河、和田河和开都河-孔雀河四条源流和塔里木河干流组成.近十几年来，我国西北部分地区气候出现了明显的由暖干向暖湿变化的趋势[1~4]，塔河流域的各源流区也发生了不同程度向暖湿方向变化的特征[5~10]，引起了各源流出山口径流量也呈现上升趋势[11~13].从塔里木河各源流出山口到入塔河干流的区间内，孕育着南疆的各片绿洲，也是南疆人类活动的集中区，合理客观地分析各源流区间内的耗水情况，对于科学合理地调配塔河水量，保持塔河流域内人类社会生产和自然生态环境的和谐发展有着极其重要的意义.

1 四条源流出山口天然径流量

2002年塔里木河流域四条源流出山口天然径流量273.9×10^8 m^3，较历年平均值多46.9×10^8 m^3，距平百分率为20.7%，属丰水年，在45 a水文系列中仅次于1994，1999和1978年，排名第4位.阿克苏河和开都河-孔雀河发源于天山山脉，2002年为丰水年.而位于昆仑山山脉的叶尔羌河和和田河，均为平水年(表1).

阿克苏河年径流量109.8×10^8 m^3，比多年平均值多28.4×10^8 m^3，距平百分率为34.8%，属丰水年；叶尔羌河61.92×10^8 m^3，比多年平均值少5.28×10^8 m^3，距平百分率为−8.0%，属平水年；和田河为45.03×10^8 m^3，比多年平均值少0.09×10^8 m^3，距平百分率为−0.002%，属平水年；开都河-孔雀河为57.10×10^8 m^3，比多年平均值多22.24×10^8 m^3，距平百分率为63.8%，属丰水年(表1).

2 源流区耗水分析

2.1 阿克苏河

阿克苏河流域总灌溉面积为29.27×10^4 hm^2，包括克州的阿合奇县；阿克苏地区的乌什县、温宿县、阿克苏市、阿瓦提县；新疆生产建设兵团农一师的15个农牧团场.年耗水量为54.42×10^8 m^3.占出山口天然径流量的60%(图1，表2).

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近百年来青藏高原冰川的进退变化

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摘 要：近百年来，青藏高原的冰川虽然出现过两次退缩速率减缓或相对稳定甚至小的前进阶段，但总的过程仍然呈明显的波动退缩趋势. 随着全球气候的波动变暖，特别是进入20世纪80年代以来的快速增温，使高原冰川末端在近几十年间出现了快速退缩. 以高原东部和南部边缘山地的冰川变化幅度最大，而高原中北部山区和羌塘地区的冰川变化幅度较小，相对比较稳定. 显示出青藏高原冰川对气候变化响应的敏感性在边缘山区较中腹地区更为敏感.

关键词：冰川变化；变化幅度；青藏高原

中图分类号：P343.6 **文献标识码**：A

青藏高原是中低纬度地区现代冰川最发育的地区. 根据最新中国冰川目录资料统计，青藏高原中国境内有现代冰川36 793条，冰川面积49 873.44 km^2，冰储量约4 561.3857 km^3，分别占中国冰川总条数的79.5%，冰川总面积的84%和冰储量的81.6%. 在高原南缘的喜马拉雅山、西部的喀喇昆仑山和北部的昆仑山西段等边缘山系冰川分布最集中，冰川数量多，冰川作用规模大. 高原中部的冰川总面积和冰川规模都不及高原边缘山地大. 在羌塘高原内流区域，突起于高原面之上的一些高大山体，如普若岗日发育了中低纬度地区最大的冰原. 藏色岗日、布若岗日、马兰山等，则发育了许多较大的冰帽形冰川.

进入20世纪以来，随着全球气候的明显波动变化和进入80年代以来的快速增温，青藏高原气候也发生着显著的变化. 高原冰川响应气候变化过程而发生着一系列的进退变化.

本文试图通过对近百年来前人对冰川变化的研究资料和近数十年的实际观测资料分析研究，揭示高原冰川变化的区域特征.

1 冰川变化记录

青藏高原冰川近百年来的进退变化研究，不像小冰期时那样，利用冰川前进遗留下来的终碛垄作为佐证[1~6]，而是要通过直接的监测对比和文献资料记录的分析等方法获得. 高原上能够连续系统观测的冰川为数不多，大多数冰川的变化仍然是利用航片、地形图和文献记录与实地考察对比观测获得的一定时段内或两次考察时段内的总变化. 20世纪早期的研究比较少而且较零散. 20世纪中期以来，随着青藏高原资源与环境研究的广泛开展和不断深入，青藏高原冰川研究也取得了丰硕成果，冰川变化的研究也积累了大量资料，70年代以来，实际考察监测资料也不断增多. 20世纪50—80年代拍摄的航空相片、已出版的航摄地形图和专业冰川图等，是研究冰川近期变化的重要基础资料.

青藏高原近百年来的气候波动和近几十年来的气候变暖，在其冰川末端的变化中均有明显的反映.

在喀喇昆仑山区，K. 马森(1926)和A. 德西奥(1929)先后考察克亚吉尔冰川时，其冰舌横切克勒青河谷地，末端紧靠北岸阻塞主谷形成克亚吉尔特索湖，表明1926—1929年间，克亚吉尔冰川仍然处于前进或相对稳定. 1935年荷兰人韦塞夫妇考察时，冰舌仍旧阻塞河谷，阻塞湖依然存在，和

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2002年塔里木河流域“四源一干”地表径流情势

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摘 要：2002年塔河流域内平原及山区气温都明显偏高，平原降水偏多，山区降水略偏多. 3～10月0 ℃层高度接近常年. 塔里木河4条源流出山口天然径流量273.9×10^8 m^3，比多年平均值227.0×10^8 m^3多46.9×10^8 m^3，偏多20.7%，属丰水年. 其中发源于天山山脉的阿克苏河和开都河-孔雀河径流增幅大，水量充沛，属丰水年；而发源于喀喇昆仑山脉的叶尔羌河和源于西昆仑山的和田河径流量保持多年均值年. 4条源流入塔里木河水量为54.82×10^8 m^3. 在塔里木河干流上游段耗水量25.42×10^8 m^3，是干流最大的耗水区段，中游段耗水量24.55×10^8 m^3，下游段耗水量7.38×10^8 m^3. 上、中游区间耗水量49.97×10^8 m^3，占阿拉尔站年径流量的90.8%. 从7月20日至11月10日共计114 d由博斯腾湖向塔里木河下游生态应急输水，从博斯腾湖调水12.67×10^8 m^3，恰拉水库分水闸向塔里木河输水2.339×10^8 m^3，大西海子水库下泄3.313×10^8 m^3，年内台特玛湖形成了28.74 km^2的水域面积，下游沿河地下水位普遍回升，影响范围达800 km^2，生态效益十分显著.

关键词：塔里木河；气象条件；河川径流；运行分析；区间耗水；下游输水
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塔里木河流域是我国最大的内陆河流域，流域总面积102×10^4 km^2，由阿克苏河、叶尔羌河、和田河和开都河-孔雀河四条源流和塔里木河干流组成. 近50 a来，由于人类活动影响和粗放型农业，塔里木河生态环境急剧恶化，已影响到整个西北地区[1,2]. 2002年7月20日至11月10日共计114 d进行了第4次输水，从博斯腾湖调水12.67×10^8 m^3，恰拉水库分水闸向塔里木河输水2.339×10^8 m^3，大西海子水库出库3.313×10^8 m^3输向台特玛湖，年度内台特玛湖形成28.74 km^2的水域面积.

1 气象条件分析

选取了塔里木河流域内的山区和平原8个气象台站，各站的地理位置以及气温、降水气候平均值的计算规则等内容同文献[3]. 由于塔里木河的几条主要源流区海拔高，夏季冰雪补给的地表径流有较大比例，因此，在分析8个站点的气温降水资料基础上，又分析了盆地周边和田、喀什、阿克苏、库尔勒4个探空站3～10月的0 ℃层高度，取1991—2002年12 a平均值作为多年平均值.

1.1 2002年塔里木河流域气象条件

2002年度，塔里木河流域内平原及山区气温都明显偏高，平原降水偏多，山区降水略偏多. 3～10月0 ℃层高度接近常年.

1.1.1 平原气象条件

(1) 气温明显偏高. 2002年塔里木河流域平原4站平均气温为12.6 ℃，较历年偏高1.0 ℃，自1961年以来，仅次于1999年，与2001年并列第2. 年内仅7月、9月、12月偏低；其中，12月偏低幅度为1.5 ℃，其余9个月均偏高，其中，3月、8月、10月、11月均偏高2 ℃以上，6月偏高近2 ℃，1月、2月、4月、5月偏高0.3～1.4 ℃. 年平

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0 ℃层高度与夏季阿克苏河洪水的关系

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摘 要：应用阿克苏河两条支流的出山口水文站日流量资料，以及流域及其周边3个探空站的0 ℃层高度资料，分析了1999年夏季阿克苏河流域特大洪水期间0 ℃层高度与日流量的关系. 阿克苏等3站的0 ℃层高度逐日变化与阿克苏河两条支流逐日流量之间有显著的相关关系. 托什干河日流量与超前2~3 d、持续3~4 d的0 ℃层高度累积值之间的相关系数最大；库玛拉克河日流量则与超前3~4 d、持续4~5 d的0 ℃层高度累积值之间的关系最为密切. 阿克苏河流域东部库车站的0 ℃层高度与托什干河日流量之间的关系最密切；中部的阿克苏站、西部的喀什站的0 ℃层高度与库玛拉克河日流量之间的关系更加显著. 1999年特大洪水中，阿克苏河日流量与0 ℃层高度之间呈指数函数关系. 以0 ℃层高度为因子，建立了阿克苏河两条支流4个日流量序列的非线性多元回归模型.

关键词：日流量；0 ℃层高度；洪水预报；阿克苏河；新疆
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引言

我国对七大江河流域（黄河、长江、淮河、海河、辽河、松花江、珠江）的洪水研究较多[1~5]. 由于气候背景、地理位置、海拔高度等影响，新疆塔里木河流域的洪水特点完全不同于我国东部地区，其气象因子更加复杂，随监测手段的改进，对该区域洪水类型的认识也在提高[6~8]. 阿克苏河是塔里木河水量最大的一条源流，也是天山南坡径流量最大的河流，多年平均年径流量$78\times10^8 m^3$. 在干旱区中纬度高海拔流域的河流中，阿克苏河具有典型的代表性，从流量的年、月变差系数，以及月流量的年分布等特征，都明显地呈现出融雪（冰）补充为主的特点[9]. 有实测水文记录以来到2001年底，阿克苏河洪水按洪峰流量排列在前列的绝大多数是融雪（冰）叠加山区降水的混合型洪水或融雪（冰）型洪水[9]. 陆帼英分析了新疆1999年特大混合型洪水的气象成因之后，强调了积雪监测的重要性[10]，王建等分析了基于遥感信息的春季融雪模型后指出，精确地获取雪盖面积是影响模拟结果的关键[11]. 在考虑阿克苏河流域的洪水问题上，除积雪监测外，还要更多地考虑与融雪（冰）径流有关的一系列技术问题，如融雪（冰）气象条件分析及预测、面融雪量分析和预测等.

关于我国内陆干旱地区的融雪（冰）水文过程研究，杨针娘等[12]在月、旬、日时间尺度上研究过祁连山区、东天山山区、昆仑山区等流域平均温度、冰川附近科学考察站点的地面温度等气象要素与融雪（冰）径流的关系，在月、旬等时间尺度上，径流量与同期平均温度呈指数函数关系. 在定量分析祁连山、天山东段等地的冰川融雪径流时，应用了附近探空站600 hPa的旬平均温度为因子，建立旬融雪径流量的指数回归模型[12]. 蓝永超对同属西北干旱、半干旱地区的河西走廊一带的河流径流模型有系统深入的研究，特别是针对黑河流域，建立了不同时间尺度的多种径流模型[13]. 冯学智等研究了天山北坡的玛纳斯河春季的季节性融雪问题，建立了该河春季2~5月的日流量融雪模

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新疆喀什噶尔河流域水资源质量保护及对策

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摘 要：喀什噶尔河流域水环境系统十分脆弱，运用环境容量总量控制、水质模型等方法进行了重点河段污染物控制量计算，合理的划分水功能区，拟订可行的水资源保护目标，确定了污染物总量控制方案，为水资源保护、水资源的可持续利用提供依据.

关键词：水资源保护；污染物总量控制；对策；喀什噶尔河流域

中图分类号：X522 **文献标识码**：A

水是人类生存和发展不可缺少、不可替代的自然资源. 水资源匮乏和水污染日益严重所构成的水危机已成为流域实施可持续发展战略的制约因素[1]. 喀什噶尔河流域属于塔里木盆地内陆干旱地区，水资源时空分布不均，生态环境十分脆弱[2]. 合理的划分水功能区，拟订保护目标；防止地表水和地下水进一步恶化，以满足水体功能对水质的要求；保证水资源的永续利用对流域社会经济发展至关重要[3, 4].

1 流域概况

1.1 自然地理

喀什噶尔河流域位于我国西部边陲新疆维吾尔自治区的西南部，介于 73°03′～80°25′ E，38°10′～40°55′ N，流域面积81 800 km^2.

流域地势西高东低，地形起伏大，天然地形按高度分为三级. 山区内有世界著名的公格尔山和慕士塔格峰，海拔分别为7 719 m 和7 546 m. 该流域地处欧亚大陆腹地，远离海洋，受帕米尔高原及各山体的层层阻隔，西风环流及印度洋水汽难以侵入. 大陆性干旱气候特点显著，平原和山区水文气候特点各异.

构造影响形成了喀什噶尔水文地质坳陷，盆地边缘第四系松散堆积物厚达数百米，为良好的地下水储存空间，由于冲洪积扇交替沉积，地层结构由单一向多层次变化，粒径渐细，为砂、砾石、亚粘土等多层含水结构. 接受山区降水、冰雪融水、基岩裂隙水的补给，另有沟谷和山前雨洪潜流的侧向补给、平原河、渠、田灌的转化补给，形成了流域的地下水. 一般而言，表层潜水受地表水影响较大，水质亦差；深层承压水水质相对较好.

喀什噶尔河流域行政区属喀什地区、克孜勒苏柯尔克孜自治州两地州，辖 9 县(市)5 团场. 有维吾尔、汉、柯尔克孜、回、哈萨克等 14 个民族，总人口 200.12×10^4 人(1999 年).

1.2 水系河流

喀什噶尔河流域有 7 条较大河流，如表 1 所示.

表 1 喀什噶尔河流域水系河流一览表

Table 1 Water systems of the Kaxkar River drainage basin

河名	河流全长/km	评价河长/km	控制站	控制河长/km	控制面积/km^2
克孜河	481	379	卡拉贝利	203	13700
盖孜河	408	373	克勒克	177	9212
库山河	200	167	沙曼	93	2169
布谷孜河	110	110	阿俄	65	2112
恰克马克河	167	167	恰其嘎	137	3788
依格孜牙河	95	70	克孜勒他克	70	1340
吐曼河	55	46			

1.3 水资源

流域地表水资源量为 45.92×10^8 m^3，其中国

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天山天格尔山南北坡降水特征研究

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摘　要：对新疆天山天格尔山南北坡乌拉斯台河和乌鲁木齐河流域及其山前平原不同高度气象(水文)站近40 a降水实测资料的统计分析，研究天山天格尔山南北坡不同坡向及高度的降水特征. 结果表明：山区降水远大于山前平原，南北坡降水均呈现为增加趋势，冬季和夏季降水的增加趋势明显；山前平原区降水的年际变化幅度大于山区；冬、春季降水变率大于夏、秋季，南坡降水变率远大于北坡，冬、春季表现地尤为突出. 年际降水的减少趋势出现在乌鲁木齐河流域中山峡谷地带的英雄桥水文站，其春季3月份的降水量减少趋势非常显著；乌鲁木齐河源大西沟气象站4～5月和6～8月月降水呈明显的反相关变化.

关键词：天山；南北坡；降水变化；趋势；相关
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1　引言

近数十年来，全球气候温暖化趋势十分明显. 气候变暖，水循环速度及频率加快，导致了全球降水量有明显的减少趋势[1]，降水时空变率增大；同时又明显表现出降水强度、月(日)等时段降水的差异[2~5]和区域降水的差异性变化. 这种差异性在地处中国西北内陆干旱区的新疆却呈现了降水的明显增加趋势，尤其是1987年以后，上升趋势非常明显[6,7]. 由于区内水汽来源和地形的特点，降水在平原区和山区差异较大，山区降水远大于平原区[6,8,9]. 本文就新疆天山天格尔山南北坡降水变化的区域性特征进行研究，主要分析天格尔山南北坡降水的年(月)际变化及降水变率特点，分析其与全球降水变化、西北气候转型过程中降水效应的关系，及其降水在天山不同坡向及高度的响应特征.

2　资料

选取天山天格尔山南北两坡乌拉斯台河和乌鲁木齐河流域及山前平原不同海拔高度气象站(水文站)的降水实测资料，运用趋势和相关分析等方法，分析天山南北坡降水的高度变化及季节(年)变化特点，结合不同季节环流型式，探讨降水变化差异的原因. 所选资料系列从1950年代至2000年不尽一致. 南坡台站有：巴仑台(1958—2000年)、黄水沟(1958—2001年)、和静(1960—1995年)和库尔勒(1959—2000年)；北坡台站：英雄桥(1959—2001年)，乌鲁木齐(1951—2000年)、昌吉(1953—1996年)、蔡家湖(1959—2000年)和天山乌鲁木齐河源大西沟气象站(1958—2002年). 所选台站资料系列均超过20 a以上，其均值基本趋于稳定[10]，其趋势分析可以代表其长系列的变化趋势.

3　不同坡向及高度年降水特征

3.1　降水的年变化趋势

图1结果显示，天山南北坡各站降水基本表现为明显的增加趋势，尤以20世纪80年代中后期以来，年降水的增加趋势非常明显. 其中，蔡家湖、乌鲁木齐、大西沟、巴仑台及和静等站的降水增加

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冰川系统高度结构计算研究
——以塔里木盆地水系冰川为例

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摘 要：冰川面积随高度的分布(即高度结构)具有重要的水文学及冰川学意义. 在分析中低纬冰川作用区(冰川系统)特征的基础上，着眼于特定冰川系统的全体，依托概率理论，提出计算冰川系统高度结构的统计学公式. 与普遍使用的经验公式相比，它具有计算所需参数少，结果不存在系统误差的特点，并且二者计算结果的总差异程度在0.1～0.3之间. 用内天山的实测资料验证显示，统计学公式计算的结果与实测值的总的差异程度仅为0.045.

关键词：冰川系统；高度结构；统计学公式

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冰川面积随高度的分布(高度结构)具有重要的冰川学及水文学意义，如成冰作用带的划分及其面积统计，冰川消融和冰川径流的计算等往往需要冰川面积按高度带分布的数据[1]. 冰川各高度带面积由于量算量大，计算繁琐，大多数国家的冰川编目未进行该项统计. 冰川高度结构数据的获取一般是通过计算获得，本文就其计算方法进行探讨.

1 理论分析

中心极限定理表明：若影响某随机变量分布的因子可表示为大量独立随机因子之和，其中每一个别随机因子对该随机变量分布的影响只起很小的作用，则可以认为这个随机变量实际上是服从正态分布的.

在中低纬山地某冰川作用区(即某冰川系统[1])，多年平均背景气候条件(主要指气温和降水)一定，则该冰川作用区冰川的具体位置以及具体位置上冰川的多寡，主要受控于非气候因素即局地因子(设为 ξ)所控制，如地表状况、坡度、坡向、山体高度、山体面积等(设为 ξ_i). 而这些局地因子在同一冰川作用区的不同地方，不同山头，以及不同山头的不同高度又是千差万别的，这些千差万别的局地因子综合作用实际上决定着该冰川系统内冰川具体分布，即有：

$$\xi = \sum_{i=1}^{n} \xi_i \tag{1}$$

式中：ξ 为影响冰川系统内冰川具体分布的综合因素；ξ_i 为主导冰川系统内单个冰川的某一特定因子；n 为特定因子的个数.

一般而言，对于某特定的冰川系统(即背景气候条件一定)，其内部单个冰川的具体分布，有因某高度山体面积大而增大，有的因某部位凹陷而增厚，有的因坡度陡峭而下滑，有的因位于阳坡而减缩等. 但对于冰川系统整体而言，无论哪一种局地因子都只作部分贡献，可近似地认为，千差万别的局地因子中，任何单一局地因子对冰川系统中冰川分布的总体状况而言，都仅起很小的作用，即可以认为对某特定冰川系统而言，冰川的分布总体上应该近似地服从正态分布或接近正态分布.

2 高度结构的统计特征

冰川的均值高度(H_{me} 即冰川的最高高度与最低高度的平均值)与平衡线高度(ELA)一样，能综

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天山乌鲁木齐河源 1 号冰川物质平衡特征*

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摘 要:统计了天山乌鲁木齐河源 1 号冰川自 1980 年以来冰川表面的单点物质平衡,分析了不同季节物质平衡及其冰川变化特征。研究表明,1 号冰川厚度较之 1959 年平均减薄了 9 599 mm;1997—2002 年为实际观测以来连续的强负物质平衡时段,平均物质平衡为 −739.6 mm /a。物质平衡与气温、降水的相关分析显示:1 号冰川物质平衡主要取决于夏季平均气温的高低,二者具有较好的反相关关系(相关系数为 −0.72),而与降水的关系相对较差。20 世纪 80 年代末以来,1 号冰川退缩速度明显增大,尤以 2000—2002 年为甚,西支冰川退缩速度为连续的高值(退缩速度分别为 6.92 m/a、6.95 m/a 和 6.25 m/a);东支冰川的退缩速度与高度大于 4 200 m 的高度带区间的平均物质平衡值有较好的相关关系(相关系数为 0.65),表明了 1 号冰川进退的动力主要源于冰川积累区的物质平衡大小。

关 键 词:乌鲁木齐河源;1 号冰川;物质平衡;气温;降水
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0 引 言

冰川物质平衡是水热等气候因素对冰川综合作用的结果,是冰川反映气候变化的最敏感的指标之一,其动态变化是引起冰川规模和径流变化的物质基础。天山乌鲁木齐河源 1 号冰川(简称 1 号冰川,下同)位于中国天山中段,天格尔Ⅱ峰(4 476 m)北坡乌鲁木齐河源,属大陆型双支冰斗—山谷冰川(分东、西 2 支),是中国唯一长期监测(自 1959 年至今)物质平衡的冰川。1993 年 1 号冰川东、西 2 支完全分为 2 个独立的冰川[1]。

针对 20 世纪 80 年代中叶以来中国西部许多地区出现的气候转型问题[2],加之 1 号冰川与高亚洲冰川有着重要的相关联系,对气候变化反映具有的明显性[3,4];本文试图通过分析研究中国观测系列最长且有西部代表性的 1 号冰川物质平衡特征,进一步研究其在气候变化中的反馈作用

1 资 料

本文统计了 1 号冰川 1980 年以来实测的表面单点物质平衡,分析其变化特征。由于物质平衡观测点布设一直处在更新和合理化的过程中,不同年份各测点位置均有变动,但总体位置及高度区间变化不大。从 2001 年始,分别在东、西支冰川表面,从冰舌开始自下而上布设 13~15 个横剖面,冰川消融区各横剖面等距离布设 3 根测杆,积累区资料以雪坑观测结果获得。测点平均密度为 29 根/km^2[5]。在按整体计算 1 号冰川物质平衡的同时,自 1988 年开始还分别计算了东、西 2 支冰川单独的物质平衡,并对冬季物质平衡过程进行了计算分析。气象资料主要选用乌鲁木齐河源大西沟气象站(海拔 3 539 m)的资料。

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科奇喀尔冰川夏季表碛区热量平衡参数的估算分析

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摘 要：利用能量平衡原理、热传导理论和通量传输理论建立了一个热量平衡参数的估算模型，对西天山的科奇喀尔冰川夏季消融区中部表碛区的热量平衡参数进行估算与分析．结果表明：净辐射是表碛面热量收支的主要热源，吸收的热量主要以潜热和感热的形式向大气输送水汽和热量，剩余部分用于表碛增温耗热．与消融区上部的冰面和表碛面相比，在消融区中部表碛面热量收入中感热输送减小，同时向上的地热输送增加．热平衡支出项中，感热交换、蒸发耗热和地热通量的比例分别为39.1%、39.9%和21%，其中感热通量与蒸发耗热的比例比消融区上部有所提高，蒸发耗热的增加比较显著．在总的热量支出中，平均只有7.8%的热量可以用于表碛下部的增温和向深层传导．

关键词：表碛；热量平衡；湍流热通量
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西天山大陆型和亚大陆型冰川的重要特征之一是冰川消融区有大面积的表碛覆盖．冰川表面的冰碛物一方面减小了地表反照率，增加了太阳辐射的吸收；另一方面由于其阻热作用，抑制了下部冰层的消融，因此表碛的存在必然影响到冰川的发育、冰川形态的演化以及冰川对于气候变暖的响应[1~4]．同时，冰川表面有无表碛以及表碛厚度的差异都会对其能量平衡格局产生重要的影响[5]．寇有观等[6]对天山托木尔峰西琼台兰冰川消融区上部表碛面热量平衡特征的研究表明，辐射平衡为主要的热源，占热平衡收入的73%，其次为感热交换，占23%；同时，在热量的支出项中冰层的消融耗热占到41%，为主要的支出项，感热和蒸发耗热次之．在珠穆朗玛峰中绒布冰川[7]、喀喇昆仑山巴托拉冰川[8]、以及尼泊尔Khumbu冰川[9]等地进行的冰川表碛区热量平衡的研究也都得到了类似的结果，其共同点之一就是热量平衡中冰层消融耗热为主要的热汇，与此相对应的是，研究区的表碛厚度都较小(2~20 cm)．研究表明，当表碛厚度超过某一临界厚度时(2~3 cm)冰川消融将急剧减小[10~13]，因此在消融区表碛厚度较大的地方热量平衡的组成将会产生较大的差异，这种能量收支状况的差异也必然会对冰川的发育产生影响．

本文旨在利用能量平衡原理、热传导理论和通量传输理论建立热量平衡参数的估算模型，对西天山的科奇喀尔冰川夏季消融区中部表碛区的热量平衡参数进行模拟与分析，以对表碛堆积较厚地区的热量平衡及水汽的收支状况进行深入的了解．

1 资料与方法

1.1 区域与观测概况

科其喀尔冰川(图1)位于新疆温宿县以北的托木尔峰山汇南部，地理位置41°48′N，80°10′E，属亚大陆型冰川．冰川上限为海拔6 342 m的科奇喀尔峰，下限海拔3 060 m，平衡线海拔为4 300 m；冰川总长26.0 km，面积约83.56 km^2，冰储量达到15.79 km^3；冰川消融区面积约为30.6 km^2，其中表碛区面积约占消融区总面积的63.7%[14]．表碛主要由灰白色、杂色花岗岩岩块及碎屑组成．消融区上部表碛厚度较小，向着冰川末端方向厚度逐渐增大．末端表碛平均厚度约为1.5 m，局部超过2 m.

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表碛下冰面消融的模拟与估算

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摘 要:根据热传导理论和能量平衡原理建立了一个简单的数学模型,对表碛下冰面的融化热进行了估算. 模型将表碛分为三层:第一层冰碛以剧烈的温度变化和夜间负温梯度的存在为特征;第二层为中间过渡层,温差和温度变化都较小;第三层为靠近下伏冰体的薄层冰碛,以温度低和变化稳定为特征. 模型仅以地表温度时间序列、表碛厚度和导热系数、土壤热容量等参数为计算输入,即可对表碛不同层位的土壤温度及其下部冰体融化所需热量进行模拟估算. 在科其喀尔冰川表碛区选取了3个具有不同表碛厚度的试验点(Spot 1,0.8 m;Spot 2,1.5 m;Spot 3,2.1 m)进行了模型测试. 模型试验表明,模型对于不同厚度表碛下冰面融化热的模拟是较好的,然而对于不同层位地温序列的模拟仍有一定的偏差,造成这些偏差的原因主要是来自于模型假设和土壤温度垂向上的时间相位差. 模拟结果同时也显示了不同表碛厚度下冰面消融的差异,冰面消融热平均分别为:Spot 1:26.87 W·m^{-2}, Spot 2:9.81 W·m^{-2}, Spot 3:6.92 W·m^{-2}.

关键词:表碛;冰面融化;地表温度;科其喀尔冰川
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1 前言

自20世纪60年代以来,基于不同尺度的(流域尺度和大尺度)水文模型被陆续建立起来[1,2],并用于水文过程研究和水资源的评价. 然而,很少有模型将冰川区的产汇流过程作为其模型架构的一部分进行模拟与分析,其原因主要在两个方面:一方面是由于冰川区冰雪融水的产汇流过程与非冰川区的产汇流过程在产流原理和汇流特点上的较大差别;另一方面是由于冰川区特殊的结构与组成所造成的冰雪水文过程的复杂性与不确定性[3]. 正是这些原因阻碍了一般意义上的降水-径流模型在冰川作用区的应用,因此,对整个冰川区冰雪水文过程的模型研究需要首先对其中涉及的一些关键的物理过程提出可行的解决方案.

对于有表碛覆盖的大陆型和亚大陆型冰川来说,表碛覆盖面积常常占到整个冰川消融区面积的60%以上,表碛区的冰川融化及其汇流会对冰川区出口断面的流量过程产生重大的影响. 因此,对于表碛下冰面消融的观测和估算模拟一直以来都为人们所关注. Østream[4]就表碛覆盖对冰面融化强度的影响进行了研究,认为当表碛厚度小于某一临界值时(约30 mm),表碛的存在会加速冰面的融化;而当表碛厚度超过临界值后,随着厚度的增加,冰面消融强度会急剧减小. 其后的观测研究也得出了同样的结论[5~8]. 而对于消融量的估算,Kraus[9]首先从能量平衡的观点出发,同时考虑了风速、气温和湿度等气象要素的变化对冰面消融的影响建立了一个理论模型进行计算;Nakawo *et al.*[10,11]针对薄层表碛利用辐射平衡方程进行冰面消融的估算,估算结果与实测消融量有着较好的一致性,但该模型忽略了表碛本身的储热变量,即假设表碛吸收的辐射能全部用于冰的融化. 这样的简化处理在表碛厚度小于30 cm时不会造成较大的计算误差,而随着表碛厚度的增大,地表吸收的热量在向下传递的过程中会有相当一部分被表碛层吸收,到达并用于冰面融化的热量因此会不断减少,此时应用简化方法进行消融量的计算必然会使估算值大大高于实际的

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20世纪初以来青藏高原东南部岗日嘎布山的冰川变化

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摘 要: 采用地形图、航空摄影相片、中巴资源卫星和Landsat TM数字影像, 对青藏高原东南部岗日嘎布山区20世纪初以来的冰川变化进行了研究, 分析了该地区冰川对20世纪后期全球变暖的响应. 结果表明: 20世纪初期至1980年, 研究区的冰川基本处于退缩状态, 期间冰川面积减少了13.8%, 储量减少了9.8%, 储量减少量相当于249.2×10^8 m^{3}水当量, 因冰川萎缩导致其对河川径流的调节作用减弱了一半左右. 1980年以来, 本区气候表现出升温和降水增加, 在此气候变化背景下, 冰川总体呈面积减小的退缩状态, 但有一定数量的冰川处于前进之中, 这可能与不同规模冰川对气候变化的响应特点和响应时间有关.

关键词: 青藏高原东北部; 冰川变化; 水资源影响
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1 前言

根据Warrick(1996)的研究, 过去1个世纪中全球海平面平均上升了(18±5)cm, 尽管海平面上升的原因还不是十分清楚, 但比较一致的观点认为海洋热膨胀和陆地冰体物质变化是最主要的影响因素. Zuo *et al*.[1]计算得出1865—1990年全球冰川由于增温增加的融化量相当于同期海平面上升了5.7 cm(其中山地冰川和小冰帽贡献了2.7 cm); Van *et al*.[2]利用ECHAM4 T106输出的未来气候情景对未来70 a冰川变化对海平面上升影响的研究表明, 冰川进一步萎缩将导致海平面上升57 mm, 其中中亚地区的冰川贡献最大, 占海平面上升量的31%, 其次为阿拉斯加和加拿大北部地区的冰川. Dyurgerov *et al*.[3]和Meier *et al*.[4]对全球物质平衡观测系列的分析结果也证实冰川对海平面上升有显著的贡献, 如1945/1946至1998年间观测冰川的物质平衡揭示出山地冰川和小冰帽冰量减少总量(90 km^3·a^{-1})相当于同期海平面年上升量的15%~20%(贡献速率(0.25±0.11) m·a^{-1}), 其中中亚地区、阿拉斯加地区等冰川变化的贡献也是最高的.

近期的研究结果使对冰川变化对海平面影响的重要性得到了进一步的支持. Arendt *et al*.[5]利用机载雷达测高计对1950年代中期至1990年代中期期间阿拉斯加67条冰川体积变化的研究表明, 这些冰川厚度减薄速率达到0.52 m·a^{-1}, 按此速率外推到整个阿拉斯加地区的冰川, 则该地区每年冰储量减少(52±15)km^3(水当量), 相当于海平面年均上升(0.14±0.04)m·a^{-1}. 对其中28条冰川于2000—2001年进行重复测量发现冰川厚度减薄速率已增加到1.8 m·a^{-1}, 外推整个阿拉斯加地区, 则相当于海平面年均上升(0.27±0.10)m·a^{-1}, 表明阿拉斯加地区1990年代中后期冰川退缩加剧十

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喀喇昆仑山克勒青河谷近年来发现有跃动冰川

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摘 要：根据冰川编目、Landsat MSS/TM/ETM+影像和相关的历史考察制图，利用GIS进行了不同时期的冰川分布图的制作，对比分析了不同时期冰川范围. 重点监测了喀喇昆仑山北坡克勒青河的5Y654D48、5Y654D97的不同时段内的冰川运动状况. 结果发现：5Y654D48冰川和5Y654D97冰川分别在1990—2000年与1977—1990年间运动速度达272 $m \cdot a^{-1}$，213.1 $m \cdot a^{-1}$，比其它时段运动速度大7～20倍，具备跃动冰川的运动特征. 分析认为，5Y654D48冰川在1990—2000年、5Y654D97在1977—1990年间曾分别发生过冰川跃动.

关键词：跃动冰川；克勒青河；Landsat；GLIMS

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1 引言

跃动冰川是指冰舌在几天或至多2～3 a内以超出正常冰川速度10倍以上的快速前进的一种特殊冰川，而这种前进可能会带来灾难性后果. 跃动冰川在世界许多冰川作用区均有相关的考察和资料，例如阿拉斯加的黑高速冰川(Black Rapids Glacier)、花冰川(Variegated Glacier)[1]等. 喀喇昆仑西段巴基斯坦境内的洪扎河流域和什约克河上游有11条跃动冰川[2].

中国发育有大量的山地冰川，在全球冰川研究中占据重要的地位[3]. 但由于跃动冰川一般发育在边远地区，因而对跃动冰川的监测非常困难，在中国境内仅在西藏东南部的南迦巴瓦峰西坡发现则隆弄冰川是跃动冰川[4]. 杨建平等[5]根据遥感资料，认为唐古拉山5K451F12、阿尼玛卿山哈龙1号冰川及2号冰川是跃动冰川. 其它地区可能存在跃动冰川，如昆仑山的莫诺马哈山峰、喀喇昆仑有几条冰川可能为跃动冰川[6]，但都没有相关监测、研究资料. 喀喇昆仑山地形崎岖，海拔高，发育有大量的山地冰川，1985—1987年中国科学院兰州冰川冻土研究所和新疆水利部门曾联合对叶尔羌河上游克勒青河源区的冰川(如木斯塔冰川5Y654D42、音苏盖提冰川5Y654D53等)考察[7]，但其周围未发现跃动冰川.

目前，GLIMS(Global Land Ice Measurements from Space Project，全球陆地冰监测计划)推广应用遥感(RS)与地理信息系统(GIS)手段来监测冰川变化以及冰川灾害. 上官冬辉等[8]应用遥感数据与《中国冰川目录》资料对喀喇昆仑山区北坡克勒青河流域的23条典型冰川(14条大冰川和9条小于1 km^2的冰川)进行过监测，并发现5Y654D48、5y654D97于1976—2000年分别前进了2 050 m、1 998 m，但由于资料限制，未能对其进行分析. 本研究在上次工作的基础上，参考了1937年资料[9]，比较了Landsat的4期影像资料，再次对位于喀喇昆仑山北坡克勒青河的5Y654D48、5y654D97两条冰川进行遥感调查.

2 数据源

研究对象位于喀喇昆仑山北坡克勒青河流域(35°58.50′N 、76°18.00′E；36°11.21′N 、76°

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利用 ASTER 影像对慕士塔格-公格尔山冰川解译与目录编制

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摘 要:以帕米尔东缘的慕士塔格-公格尔山为试验区, 利用2001年ASTER遥感数据, 综合空间锐化增强处理、比值图像取阈值和目视判读等提取冰川边界; 利用ASTER的同轨立体像对提取DEM, 区分表碛覆盖的冰川范围; 自动、半自动和人工量算冰川的有关参数, 进行冰川解译和新的冰川目录编制. 与中国冰川编目数据对比分析, 1962/1966—2001年间研究区冰川面积退缩了67.89 km^2, 占总面积的(6.2±1.0)%. 结果表明, 运用高分辨率的ASTER遥感资料可快速、直观地实现基于GIS的冰川编目, 方便地观测冰川的动态变化, 从而节约冰川编目和观测冰川变化的时间和经费, 在实践上具有很大的优势.

关键词:慕士塔格-公格尔山; 冰川变化; GLIMS; 遥感; ASTER
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1 引言

冰川目录是记载山地冰川在某个时间下的状态特征, 是监测冰川规模、研究区域或全球气候变化、恢复古气候和预测未来变化的基础或背景资料. 2002年完成的中国冰川目录主要反映的是1950—1980年间航空制图时期的冰川状态[1], 其后的数十年, 尤其是近10 a来全球气候变暖的大背景下, 冰川如何变化需要监测. 因此有必要以第一次冰川目录为基础, 利用先进技术手段进行冰川变化的系统监测.

借助遥感手段研究冰川的性质和特征、监测冰川的动态变化是20世纪70年代以来冰川学研究的重要手段之一[2~9], 传统的冰川编目是以野外考察、地形图和航空像片为数据源, 以巨大的时间、人力和财力耗费、覆盖率低和重复性差为代价[10]. 鉴于此, 国际冰川学界不断寻求利用卫星遥感技术进行冰川目录的数据更新和冰川变化监测的研究[4~6, 11~14]. 由美国USGS(U. S. Geological Survey)及NASA发起、多个冰川大国共同参与的GLIMS(Global Land Ice Measurements from Space project, 全球陆地冰监测计划)计划就是在这种背景下诞生的[15], 该计划应用高分辨率的ASTER(Advanced Space-borne Thermal Emission and Reflection Radiometer, 先进的星载热发射与反射辐射计)、Landsat TM/ETM+影像数据作为新一代冰川编目的主要数据源, 充分应用航空相片数据、SPOT等高分辨率的遥感影像[16], 旨在对全球的陆地冰川现状及变化进行动态监测. 目前在部分地区已有成功的应用, 如瑞士2000年冰川目录(SGI2000, Swiss Glacier Inventory 2000)[13]和KGIS(King George Island)[4]冰川目录等.

本文以慕士塔格-公格尔山为研究区, 选取ASTER高分辨率卫星影像数据作为数据源, 探讨基于

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托木尔峰南麓径流变化的气候因素分析

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摘 要：以冰雪融水补给为主的托木尔峰南麓河流，温度的上升和降水的增大均对径流的增加有积极的作用．互功率谱分析表明：本区冰雪融水补给为主的径流周期波动主要受温度周期波动的影响，温度对径流量变化的影响显著大于降水对径流的影响，对径流主要的周期变化起控制作用，径流量的不同尺度周期波动变化对温度的响应存在滞后性．降水是径流周期变化的次要控制因子，对径流的影响具两面性和不确定性．

关键词：径流量；波动变化；互谱分析；托木尔峰南麓
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引言

1980年代中期以来，我国西北地区出现了气候由暖干向暖湿转变的趋势．在温度大幅上升的基础上，降水和冰雪融水持续增加，水文与生态环境发生了显著的改变[1]．西天山托木尔峰南部地区是气候变湿最显著的地区之一．伴随气候由暖干向暖湿的转变，托木尔峰南麓以冰雪融水补给为主的河流径流量自1980年代中期以来增加十分显著．作为冰雪融水补给为主的托木尔峰南麓河流，温度的上升促进了冰雪消融，增加了冰雪融水对河流的补给量，降水量的增大则明显增大了流域内非冰川区的产流能力，因此，温度的上升和降水的增大均对径流的增加有积极的作用．径流量变化与温度和降水量变化周期波动间的响应规律如何，是值得深入研究的课题．本文通过时间序列的互谱分析，对托木尔峰南麓径流变化的气候因素进行了分析．

2 研究区水文特征及研究方法

2.1 径流基本特征及近年来变化趋势

托木尔峰高山区是天山山脉最大的冰川作用中心，每年山区平均产流约63.4×10^{8}m^3，其中56％为冰雪融水[2]，是我国新疆阿克苏地区和伊犁地区重要的水资源，也是塔里木盆地北侧塔里木河主要支流的源头．发源于托木尔峰南部冰川区的较大河流有木扎尔特河、喀拉玉尔滚河、台兰河、阿特奥依拉克河、库玛拉克河等，库玛拉克河和发源于托木尔峰西部高山区的托什干河在阿克苏地区汇合后成为阿克苏河．除了喀拉玉尔滚河和阿特奥依拉克河外，上述其它河流均有水文观测站并有多年径流观测资料，各河流基本径流参数见表1.

从表1可以看出，发源于托木尔峰冰川区的河流冰雪融水补给比重均＞50％，最高达到了80％以上(木扎尔特河阿克布隆站)．流域内冰川覆盖度越大，则径流模数越大，随着河流流域面积的增大，径流模数逐渐递减．由于丰富的冰雪融水补给，本区河流径流量具有高度的季节集中性和多年径流变化的稳定性，径流量主要集中在夏半年5～9月份，多年径流变差系数＜0.20[3]．近40 a来，本区径流、气温和降水变化具有较好的同步性(图1)．据已有研究表明[4]，天山山区呈现出明显的升温趋势，平均气温在4个10 a内升高了0.6 ℃，夏、秋、冬三季呈现出明显的升温趋势，其中夏、冬两季平

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天山南坡科其卡尔巴契冰川度日因子变化特征研究

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摘 要：度日模型是估算冰川消融的一种简单而有效的方法. 根据科其卡尔巴契冰川2003年的观测资料，分析了该冰川度日因子的空间变化规律及其影响因素. 研究表明：各高度上的度日因子，介于2.0～9.7 mm·℃$^{-1}$·d^{-1}之间变化，平均值为5.7 mm·℃$^{-1}$·d^{-1}，与青藏高原各冰川及其它地区冰川相比较小；随着海拔的增高，度日因子随之递增；随平均气温的升高而随之递减. 由于冰面状况复杂，度日因子变化幅度较大，裸冰区的度日因子明显大于表碛覆盖区. 人为测量误差、反照率、地形等对度日因子的影响也不容忽视.

关键词：科其卡尔巴契冰川；冰川消融；度日因子；正积温

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1 前言

冰川物质平衡是联结冰川波动和气候变化的关键因子，因此，冰川物质平衡的估算和恢复备受各国冰川学家关注[1~5]. 冰川消融和积累是冰川物质平衡的重要组成部分，是冰川全球水循环的关键过程. 冰川消融特征更能反映气候变化的特点，对于冰川消融来说，冰面能量的收支状况决定了冰面消融状况，而气温是衡量能量状况的理想指标，在一定的时段内，正积温对冰面消融的影响不容忽视[6~8]. 度日模型正是基于冰面消融和正积温之间的线性关系建立的[1,3,6~13]，度日因子是该模型的关键参数，它把冰川消融与正积温紧密的联系在一起，是冰川表面及其近冰面层能量转化过程的简化描述.

Finsterwalder和Schunk(1887)首次在阿尔卑斯山冰川变化研究中引入了度日的概念. Braithwaite *et al.*[6~8]将度日应用于格陵兰冰盖消融过程的分析，表明冰川冰的度日因子要大于雪的度日因子，冰川冰和雪的度日因子之间的差别取决于其所处的气候条件. Johannesson *et al.*[9]运用度日因子模型对冰岛、挪威和格陵兰3个地区的不同冰川进行消融速率的估算；刘时银等[3,4]将度日因子模型应用于抗物热冰川和乌鲁木齐河源1号冰川的物质平衡研究中，并对乌鲁木齐河源1号冰川平衡线高度对气候变化的敏感性进行了估算. Braithwaite *et al.*[1]运用修正的度日模型评估了瑞士5条冰川物质平衡对于气候变化的敏感性[1]；Singh *et al.*[11]讨论了喜马拉雅山Dokriani冰川上雪和冰川冰度日因子的年际变化；Kayastha *et al.*[12]分析尼泊尔喜马拉雅山、青藏高原等典型冰川消融度日因子的空间变化特征. 此外，Shin *et al.*[13]应用度日因子研究了表碛厚度变化对于夏季冰川消融的影响.

目前，西天山南坡的阿克苏河是向塔里木河输水量最大的一条源流河，该河也是一条冰川覆盖率较高的河流，冰川融水对河川径流的补给作用非常显著. 近50 a来，发源于西天山南坡的阿克苏河、台兰河、木扎提河等河流的径流量均表现出增加的

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新疆阿克苏地区近40 a气候、水文变化特征分析*

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摘 要：近20 a来，阿克苏平原绿洲区气候明显变暖增湿，戈壁区略有变干的迹象。同期，由于气温升高，冰川消融加快，山区降水增多，源流出山口径流量略有增加；根据塔里木河干流阿拉尔水文站监测结果，近40 a来，年径流量呈持续稳定减少趋势。20世纪90年代，径流量平均距平为－4.85，径流量减少达10.58%。这主要是人类干预和源流区粗放农业发展，耗水量不断增加，导致汇入塔里木河干流水量不断减少，从而引起中下游生态急剧恶化。

关键词：气候变化；径流量；人类干预；阿克苏；新疆
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气候变化对径流过程的影响是全球变化研究的重要部分，在径流对气候变化的响应过程中，雪冰径流对气候变化最为敏感[1]。雪冰水资源是我国西部干旱区重要的水资源之一，约占水资源总量的40%左右。近年来，我国西北降水量增长趋势明显，阿克苏地区降水趋势与之一致，但与蒸发量增长平衡后，其差值的变化存在一定的不确定性。

1 研究区的基本概况

阿克苏地区位于新疆天山南麓、塔里木盆地北缘，总面积1.33×10^5 km²，东接巴音郭楞蒙古自治州，南隔塔克拉玛干沙漠与和田地区相望，西南连接喀什和克孜勒苏柯尔克孜自治州，西北同吉尔吉斯斯坦和哈萨克斯坦共和国接壤，北以天山为分水岭同伊犁哈萨克自治州交界。区内总人口2.20×10^6人。区内主要河流是阿克苏河，其上游为发源于帕米尔高原的托什干河和发源于西天山托木尔峰地区的昆马力克河。全区现共有22个水文站点，拥有连续资料的站点14个，超过20 a连续资料有10个站点，有降水蒸发资料站点13个。

根据气象观测和1977－1978年的科学考察，山区降水主要来自大西洋和北冰洋的暖湿气流补给，6～8月的降水量占全年的50%左右，而5～9月占70%左右，因此，冰川的补给主要发生在夏季[2]。沈永平[3]等对阿克苏河支流台兰河冰川物质平衡的研究表明，累计冰川物质平衡－12.6 m；台兰河流域雪冰融水占台兰站控制流量的65.3%，雪冰融水的变化对流域水资源量的影响非常明显。40 a来，由于气温升高引起的冰川净消融相当于每年补给河流1.24×10^8 m³，占河流年径流量的15%。王顺德等[4]对塔里木河的研究表明，塔里木河中上游耗水量不断增大。由于人类活动，原有植被受到严重破坏，导致下游生态不断恶化[5]。

2 资料来源

阿克苏地区的主要河流是阿克苏河和渭干河及塔里木河干流。本文选取的流域气象水文站点有9个(表1)。

3 区域近40 a气候变化趋势

全球气候在过去100 a中变暖了0.3～0.4 ℃，近40 a中变暖了0.2～0.3 ℃[6]；中国区域气候研究表明，1951－1990年平均气温升高了0.3 ℃[7]。新疆近40 a来气温也同样呈上升趋势，北疆变暖幅度大于南疆，而且变暖主要在冬季。降水呈明显的增湿趋势，主要集中在夏秋两季的5～9月。南疆降水偏多幅度大于北疆，各季降水均有增加趋势[8～10]。阿克苏地区是一个地理位置比较特殊的绿洲生态系统，北面是天山托木尔峰，南面是塔克拉玛干沙漠，区域内的降水、气温和蒸发等变化都具有不同特征。

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高寒草地春季积雪融水和雨水混合补给径流模拟

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摘 要：介绍SCS降雨径流方程的基本原理，基于该方程的使用范围存在一定的局限性，在原方程框架的基础上，对集水区的补给水量计算和土壤持水量估算进行修正，以适应高寒地区积雪融水和雨水混合补给以及有冻土层存在的径流模拟。利用修正的径流方程对新疆托木尔峰地区阿托依纳克草场集水区的日径流量进行模拟计算，结果通过Nash and Sutcliffe目标函数的检验，流域日径流量模拟取得较好的结果，CR=97.68%。表明利用积雪的能量平衡和修正的SCS径流方程来模拟高寒草地积雪融水和雨水混合补给径流是可以实现的。

关 键 词：混合补给 能量平衡 SCS径流方程 阿托依纳克
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过去对于小流域水文径流研究，许多专家学者大多是在平原[1,2]或黄土高原[3~5]下垫面比较单一的流域，通过小面积野外定点观测试验，对不同土质、地面坡度进行了试验研究，也取得了许多成果。SCS[6]径流方程在这方面应用最为广泛。但由于试验范围的限制，所取得的成果代表性不够强。高寒草地区水量补给来源主要是积雪融水和降雨的混合补给，同时高寒地带春季草地下垫面潜层季节性冻土的存在形成近似地下隔水层，与原方程中主要补给来源是雨水，以及下垫面是单一的黄土或其他土质等不相吻合。这就要求对SCS进行一定的修正，以适应高寒地区特殊的水量补给源及下垫面季节性冻土存在的特性。

研究方法

1.1 SCS径流方程的基本原理

Mockus(1972)通过分析流域降水累积曲线、降水的保持力和径流量与流域降水和保持力的关系，建立了各要素间的比例关系：集水区的实际入渗量(F)与实际径流量(Q)之比等于集水区该场降雨前的最大可能入渗量(或潜在入渗量S)与最大可能径流量(或潜在径流量Q_m)之比[7]。SCS径流模型是基于这个假定的基础上建立的，能反映不同土壤类型、不同土地利用方式及前期土壤含水量对降雨径流的影响，具有简单易行，所需参数较少，对观测数据的要求不很严格土壤质地有关[9]，没有考虑地表的粗糙率，地下季节性冻土特殊隔水层等因素对径流的影响。本文对原径流方程进行修正，提出了能够适应高寒地区模拟积雪融水和雨水混合补给的SCS日径流量计算方程。

1.2 SCS径流方程的建立

原SCS径流方程中水量补给主要是降雨补给。在高寒草地地区，通过野外实际考察分析，春季流域径流补给主要是积雪消融补给，其次是降雨补给。其中积雪消融补给量占总补给量80%以上。必修对流域的补给水量进行重新分析计算，以适应SCS径流方程。

1.2.1 流域水量补给计算 在高寒草地小流域春季降水主要以降雪形式为主，其次是降雨。因此在计算流域水量补给时，径流方程中的水量补给应修正为积雪融水补给和春季降雨补给两个部分。即

$$R = Q_{snow} + P,$$

式中：Q_{snow}为日积雪消融的水当量（$mm \cdot d^{-1} \cdot m^{-2}$）；$P$为日降雨量（$mm \cdot d^{-1} \cdot m^{-2}$）

由于积雪消融补给不同于降雨补给，影响流域积雪融水径流的峰量的主要因素是太阳短波辐射和大气感热通量等。从野外获取的流量过程线形状来看，融雪径流缓涨缓落，且每天都有一个峰值的出现。流域径流量在每天9～11时后开始出现增长趋势，峰值一般在17～20 h出现，峰值出现后，流域径流量出现直线下降，直至为零（图1）。

积雪融水当量的计算。度—日因子法计算积雪融水量，比较简单，但存在积雪消融时，积雪密度的变化，严重影响了小流域积雪融水量计算的精度。本文通过积雪的能量平衡计算积雪融水径流深（$mm \cdot d^{-1} \cdot m^{-2}$），且对原平衡方程进行了简化，参数

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西天山南坡科其喀尔冰川区夏季水体的化学特征

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摘 要: 2003年7~9月在西天山南坡科其喀尔冰川区采集水样的实测资料表明, 本区各类水体都呈碱性, pH值和电导率与水的硬度有很好的正相关关系. 另外, pH值、电导率及Ca^{2+}以外的各项离子在空间上均呈"之"字形变化规律, 总体随海拔升高各值呈现降低趋势. 冰川区各种水体以Ca^{2+}为主, 其中阴离子以SO_4^{2-}浓度最大. 各类离子都与矿化度有较好的相关关系, 随矿化度升高而增大.

关键词: 科其卡尔冰川; 化学特征; 矿化度; pH值; 离子
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有关天山托木尔峰地区的水化学研究主要集中在台兰河流域西琼台兰冰川[1], 对科其喀尔冰川水化学的研究尚无人进行. 在2003年中科院寒旱所刘时银研究员组织了科其喀尔冰川考察队. 在考察期间, 对科其喀尔冰川沿不同海拔高度采集了冰面湖水、冰面河水及大气降水, 共计44个有效样品. 结合前人在临近流域西琼台兰冰川所做的一些工作[1, 2], 就科其喀尔冰川的水化学特征做初步的分析和讨论.

1 研究区概况及样品的采集与处理

1.1 研究区概况

科其喀尔冰川位于西天山托木尔峰山汇南部, 新疆阿克苏地区温宿县境内, 属于亚大陆型冰川. 冰川上限为科其喀尔峰, 海拔6342 m, 下限冰舌末端海拔高度为3020 m, 冰川作用正差达3000 m; 冰川总长25.1 km, 面积82.8 km^2, 冰舌伸出山谷约2.0 km, 冰舌区表碛覆盖较厚[1]. 科其喀尔冰川融水径流是阿特奥依纳克河源头. 阿特奥依纳克河由科其喀尔等三条冰川融水径流形成, 全长约40多公里, 由北向南流至温宿县城北部消失.

托木尔峰地区的降水主要靠来自大西洋和北冰洋的潮湿气流补给[3], 降水量主要集中在夏季和冬季, 春秋两季降水量相对较少, 其中5~9 月份占70%左右, 冷季降水量约占30%; 降水量随海拔高度呈明显递增趋势, 据推算托木尔峰地区南坡冰川区的降水梯度为30 mm/100 m[1]. 科其喀尔冰川区雪线以上冰川物质积累区气候严寒, 降水丰沛, 多年平均降水估计可达1000 mm以上. 受区域地形地貌的影响, 科其喀尔冰川区夏季降水主要以冰雹等固态降水为主.

1.2 采样点布设及样品处理

2003年7月7日至9月10日, 在科其喀尔冰川末端200 m处设立气象站点, 包括水样的采集. 8月9日、18日和9月12, 13日从冰川末端到海拔4200 m高山自动气象站处, 每海拔约100 m进行取样. 研究由于给水面积增大而造成的冰川径流水文地球化学过程的差异和进一步弄清冰川径流化学成分的来源, 于8月9日和9月12, 13日在冰川的不同海拔高度上的冰湖内采集了水样, 样点沿冰川主流线按由低到高的海拔高度布设(图1).

水样采集后, 当场装进用去离子水清洗过的水样瓶中带回住地, 立即存放于冰箱中制冷, 进行低温保存. 样品运回中科院寒旱所冰芯与环境实验室, 进行分析的前2天将样品取出, 室温下自然融化后进行pH值和电导率测定, 分别用MAT252同位素气体质谱仪, 原子吸收光谱仪, Dinex-100离子色谱仪, 电导率和pH计进行了K^+, Na^+, Ca^{2+}, Mg^{2+}, NO^{3-}, SO_4^{2-}, 电导率和pH值等项目的分析测定. 阳离子的测定误差一般低于0.1%, 阴离子低于0.3%, $\delta^{18}O$的测量误差低于0.5%.

2 结果与讨论

2.1 pH值与电导率

科其喀尔冰川区各类水体的pH值都比较稳定, 变化于7.46~8.07之间, 平均为7.67, 属于偏碱性

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基于RS和IMCORR的绒布冰川表面运动分析

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摘　要: 以绒布冰川为例, 利用ASTER影像, 借助IMCORR软件计算冰川表面运动速度, 结果表明, 绒布冰川2000-10-14~2001-04-24总位移为14.5 m, 平均运动速度为36 m/a, 并且在纵断面上, 冰舌末端的运动速度小于整体运动速度, 符合绒布冰川末端因由大量冰碛物存在而导致消融速度减慢的规律; 在横断面上中央则大于两侧, 这与1960年观测的结果相类似. 说明本文利用IMCORR软件计算冰川表面的运动速度是可行的.

关键词: ASTER图像; 冰川运动; IMCORR软件; 绒布冰川
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冰川物质平衡受冰川消融、冰川积累以及冰川运动控制, 冰川消融和积累过程主要受到气候的影响, 而冰川运动在消融和积累过程中都起着极其重要的作用. 因此, 研究冰川运动可以反射出气候的变化[1], 还可以反演各种灾害, 如: 雪崩、冰川泥石流和冰湖洪水等冰雪灾害[2]. 冰川的运动在空间上可分为: 垂直方向运动和水平方向运动(也称冰川表面运动), 对于冰川表面运动的评估, 一般采用GPS测量法[3], 该方法测量精度高, 但是耗资大, 并具有空间局限性, 对于快速运动冰川, 用该方法测量还比较危险; 图像对比法[2, 4]等, 该方法耗资小, 并且节约劳动力, 受空间约束很小, 但是结果受到图像本身质量限制, 如: 分辨率等, 同时也受到地表性质变化、云量以及不同反射率的影响.

GPS测量法在国内外运用广泛, 曾运用到格陵兰冰盖[6]、南极冰盖[7]、天山奎屯河哈希勒根51号冰川[8]等冰川区. 图像对比法, 在国外运用较为广泛, 主要应用软件有IMCORR[9~12], CIAS[5, 13], 主要还是集中在海洋性冰川的研究, 国内还是空白. 本文采用图像对比法, 尝试在利用ASTER图片基础上运用IMCORR软件来计算大陆型山谷冰川表面运动速度, 这还属首例.

1　绒布冰川概况

绒布冰川是珠穆朗玛峰(以下简称珠峰)地区最大的冰川, 位于东经86°20′~87°15′及北纬27°40′~28°20′之间, 发育于珠峰北坡, 扎卡曲河源区, 属于典型的树枝状的山谷冰川, 长22.2 km, 宽1.4 km, 面积达86.89 km², 冰舌区平均宽度1.4 km, 冰川末端海拔5 154 m, 顶端海拔7 260 m, 作用正差2 106 m, 平均坡度10%, 雪线在海拔5 800 m左右. 年平均气温−4° ~9°C, 年降水量约600 mm, 主要集中在夏季, 太阳辐射强烈, 昼夜温差大, 蒸散发强[14].

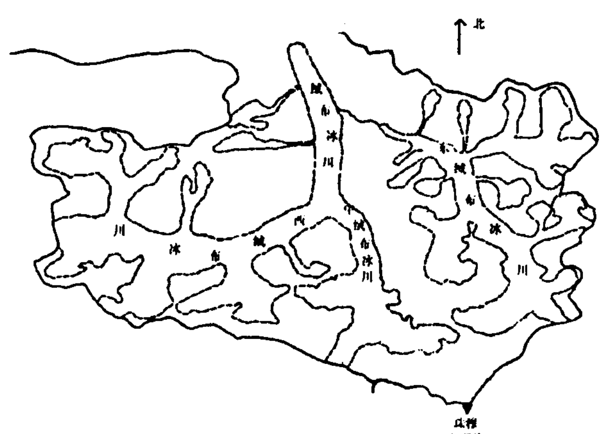

图 1　绒布冰川的位置
Fig. 1　The position of Rongpu glacier

2　ASTER 图像

ASTER是极地轨道环境卫星Terra上搭载的5种传感器之一, 它提供了可见光—近红

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中国西部冰川度日因子的空间变化特征

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摘要： 在冰川与积雪消融研究中，度日模型应用较为广泛，该模型是基于冰雪消融与气温，尤其是正积温之间的线性关系建立的。度日因子是该模型的重要参数，反映了单位正积温产生的冰雪消融量，其空间变化特征对于不同模型模拟冰雪消融过程的精度有较大影响。本文根据中国西部不同地区数十条冰川的短期考察和观测资料，分析了西部冰川度日因子的空间变化特征，结果表明：由于青藏高原及其周围地区独特的气候和热量条件，西部冰川度日因子具有明显的区域特征。在同一冰川上，度日因子的空间变化较为明显。从冰川类型来看，与极大陆型及亚大陆型冰川相比，海洋型冰川的度日因子较大。总体看来，西部冰川的度日因子由西北向东南逐渐增大，这与中国西部冰川的气候环境变化趋势是一致的，即在干冷的气候条件下，度日因子较小；而在暖湿的气候条件下度日因子较大。

关键词： 冰川；消融；度日因子；中国西部

1　引言

中国西部高山带广泛分布的现代冰川，其融水径流是干旱内陆河流域十分宝贵的淡水资源，其在不同时间尺度上的变化对该地区河川径流的影响非常显著[1-3]，是绿洲经济的命脉。据近期完成的中国冰川编目结果和基于新冰川编目资料进行的冰川融水对河流补给作用的计算表明，冰川融水补给在中国西部省区河流径流中所占比例分别为：新疆 25.4%、西藏 8.6%、青海 3.8%、甘肃 3.6%[4]，由此不难看出冰川融水在中国西部干旱区水资源形成与变化中的作用和地位是十分明显的。因此，冰川融水的模拟是评价与预测中国西部干旱区水资源变化的重要组成部分之一[3, 5]。

目前，在计算冰川融水的众多方法中，基于冰川消融与气温之间线性关系的度日模型是最为简单、应用最为广泛的方法[6, 7]。度日模型虽然相对简单，但在流域尺度上可以给出类似于能量平衡模型的输出结果[8, 9]。在度日模型中，度日因子是其的重要参数，其是冰川表面能量传递与转化这一复杂过程的简化描述，也就是说度日因子本身也依赖于冰川表面的能量收支状况[10-12]。Finsterwalder and Schunk (1887)[13]首次在阿尔卑斯山冰川变化研究中引入了“度日因子”的概念。随后，这一概念被广泛应用于挪威、冰岛、格陵兰、阿尔卑斯山、喜马拉雅山等地区的冰川与积雪变化的研究中[6, 12, 14-26]。

研究表明[22, 27-35]，对于大多数融水径流模型来说，如 HBV-model[27]、SRM-model[28]、UBC-model[29]、SHE-model[30]、HYMET-model[31]，这些模型的模拟精度在一定程度上取决于度日模型对冰川与积雪消融过程的模拟。然而，度日因子的空间和时间变化特征对模型模拟冰川与积雪消融过程的精度又有较大影响。因此，在使用度日模型模拟冰川与积

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度日模型在冰川与积雪研究中的应用进展

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摘 要：度日模型是基于冰川与积雪消融和气温，尤其是冰雪表面的正积温之间的线性关系建立的．度日模型已广泛应用于北欧、阿尔卑斯山、格陵兰冰盖、青藏高原等地区的冰雪消融、冰川物质平衡及对气候敏感性响应、冰川动力模型以及冰雪融水径流模拟等的研究中．度日模型尽管是对冰雪表面消融能量平衡这一复杂过程的简化描述，但在流域尺度上，通常可以获取类似于能量平衡模型的输出结果．度日模型也有其不足之处，仍需进一步的改进与完善．

关键词：冰川与积雪；消融；正积温；度日模型

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1 引言

冰川与积雪是干旱区宝贵的淡水资源，不仅是区域社会经济发展稳定的基础，也是生态与环境必要的、有机的组成部分[1]，其在不同时间尺度上的波动势必导致以冰雪融水补给为主河流水量的丰枯变化[2]．近期完成的中国冰川编目结果和基于新冰川编目资料进行的冰川融水对河流补给作用的计算表明[3]，冰川融水补给在中国西部省区河流径流中所占比例分别为：新疆25.4%、西藏8.6%、青海3.8%、甘肃3.6%．不难看出，冰川与积雪融水在干旱区水资源形成与变化中的作用和地位是十分显著的．因此，冰川与积雪消融研究已成为国内外学者关注的热点问题之一[4-9]．

近10 a来，冰川与积雪消融研究的方法从基于能量平衡的模型到基于单一或多个气候因子的统计方法都有了较大发展[9-13]．虽然冰川与积雪消融过程取决于其表面的能量收支状况，但对于能量平衡模型来说，该方法涉及的模型参数较多，计算过程较为复杂，受观测基础限制，应用受到一定的限制，尤其在偏远的高海拔山区．因此，基于单一气候因子的度日模型在冰川与积雪研究中应用较为广泛．度日模型是基于冰雪消融与气温之间的线性关系建立的，这一概念是Finsterwalder *et al*.[14]在阿尔卑斯山冰川变化研究中首次引入了的，随后，广泛应用于北欧、格陵兰、阿尔卑斯山、青藏高原等地区的冰雪消融研究中[15-28]．

对于度日模型来说，其优点在于：1)气温是模型输入的主要数据要素，相对于其它观测要素，气温是较为容易获取的；2)气温的空间插值相对较为容易；3)模型计算相对简单．基于以上特点，度日模型已广泛应用于冰川物质平衡、冰川对气候敏感性响应、冰雪融水径流模拟及冰川动力模型等的研究中[7-9,19-28]．这一模型虽然不能描述冰川与积雪消融的物理过程，但可以获取类似于能量平衡模型的输出结果[28]．然而，该模型也有两个不足之处：1) 虽然模型在较长时间段内能够取得较为理想的模拟结果，但其精度随着时间分辨率的提高而逐渐降低；2) 受地形及冰川与积雪表面条件的影响，模型对冰雪表面消融状况的空间变化特征无法精确描述．因此，度日模型还需进一步的改进与完善．本研究旨在介绍度日模型在国内外冰川与积雪研究中的应用进展，为中国西部冰川与积雪消融研究提供一定的理论方法．

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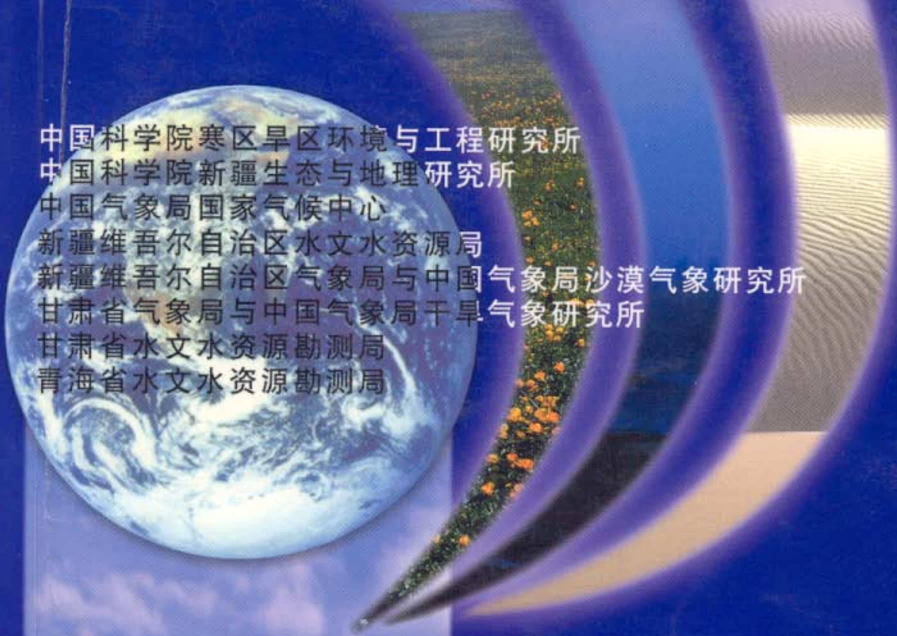

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