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Glacier changes during the last forty years in the Tarim Interior River basin, northwest China

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Abstract

By comparing digitized glacier outlines from the Chinese Glacier Inventory (CGI) during the 1960s–1970s and Landsat Enhance Thematic Mapper (ETM^+) images from 1999 to 2001, we investigated changes for about 7665 alpine glaciers among 11665 glaciers in seven sub-basins of the Tarim Interior River basin (TIRB). The results showed that the total glacier area was reduced by 3.3% from the 1960s/1970s to 1999/2001 and area losses for 1–5 km^2 glaciers accounted for 48.3% of the total glacier area loss in the TIRB. However, the glacier area reductions varied from 0.7% to 7.9% among the seven sub-basins of the TIRB during the study period. The glacier area changing with altitude showed that the maximum contribution of area shrinkage occurred at 4900–5400 m. Data from 25 meteorological stations in the TIRB showed increases in both the annual mean air temperature and annual precipitation during 1960–2000. This indicates that the glacier shrinkage in the TIRB over the last 40 years was largely due to regional climate warming that enhanced glacier ablation and overcame the effects of increased precipitation on the glacier mass balance.

Keywords: Glacier change; Climate change; Remote sensing

1. Introduction

Changes in mountain glaciers are a natural indicator of climate change [1,2]. Glaciers and ice caps are also believed to have a significant effect on the sea level [3–5]. Moreover, glacier runoff is the major contributor to water resources that are used to support the sustainable development of the environment, industry and agriculture in arid regions of northwest China [6]. Glacier change also leads to glacial hazards such as glacial lake outburst flooding (GLOF) in some regions [7]. Climate warming since the late 19th century has been the main cause for the retreating of glaciers in recent decades [6,8–12]. Climatic scenario predictions indicate that climate warming will cause further glacier retreat in the future [13,14]. However, owing to the remote location and dispersed distribution of glaciers, there has been little glacier monitoring in northwest China or in the rest of the world, for that matter. Thus there is a very limited dataset derived from continual glacier observation [6], and application of other techniques is desirable. The use of remote sensing (RS), geographical information systems (GISs) and global positioning systems (collectively known as 3S technology) allows new research on glacier change [9,15,16]. Global Land Ice Measurements from Space (GLIMS) has established a good method for glacier research using 3S technology [15,17,18].

The Tarim Interior River basin (TIRB) is located in the south of the Xinjiang Autonomous Region, an arid region of northwest China, with a total area of about 1.02×10^6 km^2 (Fig. 1). The Chinese Glacier Inventory

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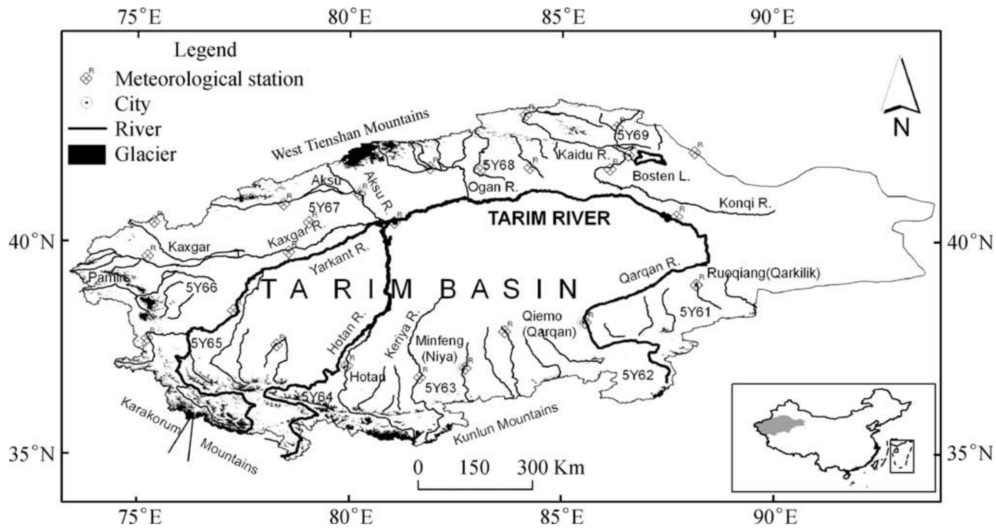

Fig. 1. River locations and glacier distribution in the TIRB (5Y** are the codes for watersheds as used in the China Glacier Inventory).

(CGI) shows that there are 11665 glaciers with a total area of 19877.7 km^2 in the TIRB, accounting for 33.5% of the total area covered by the CGI [19]. The terminus positions of most glaciers were higher than 3000 m a.s.l. and the snow lines were 3600–5700 m a.s.l. Glaciers, acting as a huge solid alpine reservoir that regulates annual runoffs, are a reliable water source for oases and for the sustainable development of the ecological environment, industry and agriculture in the TIRB [20]. These glaciers have experienced losses of mass prominently owing to an increase in temperature of 0.5 ± 0.2 °C over the past 50 years in northwest China [11,21–23]. In addition, the higher temperature causing the intensive ablation of glaciers will induce disasters occurring with largely increasing frequency that will potentially influence human welfare in downstream regions. Examples of such disasters are GLOF in the Yarkant River and Pamirs of China and glacier surging. Glacier changes in Tarim were reported by Liu et al. [22]. However, only 3081 glaciers were investigated for there were few RS data available at the time. In this work, we replenish data to investigate the glacier variation from the 1960s to the 2000s using the CGI and Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM$^+$) images for the TIRB, and consider reasons for climatic change in this region based on the results of glacier variation investigations and measurements taken at meteorological stations.

2. Methods and data

The glacier change was determined by comparing glacier area data for two different times in the TIRB. The earlier glacier area data were taken directly from the CGI in this region, which was mainly derived from topographical maps (1:100,000) based on aerial photos acquired for 1962–1977, and the latest glacier area data were obtained from 28 selected Landsat ETM$^+$ images that were almost cloud free and taken in 1999–2001 [19]. The glacier outlines from the CGI were vectored by commercial GIS software (ARCVIEW). Two digital elevation models (DEMs) (one 1:250,000 for the 1980s and the other derived using data from the Shuttle Radar Topography Mission with 90 m resolution) were used. To establish coregistration for all these images, 30–35 ground control points (GCPs) were selected from topographic map features that could be identified on each image. The residual root mean square error (RMSE) of verification points when comparing with topographic maps was commonly less than 56.7 m. Parts of the glaciers were masked using threshold ratio images from TM Band4/Band5 [18,24,25]. This method, however, was used only for a small number of glaciers. Most glaciers were mapped by manual delineation; in particular, the mapping of debris-covered glaciers required the combination of manual delineation with the DEM [26]. The data were presented in a Universal Transverse Mercator (UTM) coordinate system referenced to the World Geodetic System of 1984 (WGS84).

Error in the glacier extent was controlled by the image resolution and coregistration error [27–29]. According to the uncertainty formula derived from multi-temporal measurement of the position of a glacier tongue front using images [27,30], each position has an uncertainty (UN) that can be calculated by

$$UN = \sqrt{\sum_{1}^{n} \lambda^2} + \sqrt{\sum_{1}^{n} \varepsilon^2}$$

where λ is the original pixel resolution of each image and ε is the registration error of each image to the topographic map. Consequently, the mean uncertainty of all glacier tongues derived from 28 images can be calculated by

$$\overline{UN} = \sum_{i=1}^{28} UN_i/27$$

Thus the mean uncertainty for all glacier tongues was 48.2 m.

The uncertainty in the glacier area for an individual glacier was calculated by

$$a = A(2\overline{UN}/\lambda)$$

where a is the desired uncertainty in the area and $A = \lambda^2$. Thus the uncertainty in the area was 0.003 km^2.

Unfortunately, about 1446 glaciers had to be excluded from the study because they were covered by debris, snow or cloud in the images or because there were errors in the original topographic maps. In addition, 2555 glaciers having areas less than 0.2 km^2 and a combined area of 305.5 km^2 were also excluded owing to the limitations of the resolution of Landsat and the coregistration between CGI and Landsat ETM$^+$ images. The remaining 7665 glaciers with a combined area of 17465.8 km^2 and located in seven sub-basins in the TIRB were selected to investigate glacier area change. It should be noted that glaciers in West Tienshan were poorly represented in this study owing to snow coverage.

Meteorological data were available from 25 stations with at least 40-year records in the TIRB (Fig. 1). Among the stations, 20 were at an elevation of 1000–3600 m and were able to provide a climatic dataset for low mountains and mid-height mountains. The annual mean air temperature and precipitation at the 25 stations in the basin varied between −4.52 and 12.4 °C and 22.2 and 273.4 mm, respectively.

3. Results

Comparing glacier areas deduced from the CGI (1960s and 1970s) and those for 1999/2001, it was found that the glaciers generally shrank in the TIRB. The total area of the 7665 measured glaciers decreased by 574.09 km^2, about 3.3% of the area covered by the CGI. Three thousand five hundred and thirty three (46.1%) glaciers shrank by about 669.01 km^2, 1788 (23.3%) glaciers enlarged by about 94.91 km^2 and 2344 (30.6%) glaciers were stable. As for the relative changes of glaciers of different sizes (Fig. 2), percentages of area reduction of small glaciers were usually higher than those of large glaciers. The area losses of glaciers with areas 0.2–0.5, 0.5–1.0, 1.0–5.0, 5.0–10.0, 10.0–20.0 km^2, and larger than 20.0 km^2 were 6.0%, 6.0%, 5.8%, 4.2%, 1.5%, and 0.7%, respectively. This indicates that the small glaciers were more sensitive to climate change than large glaciers [30,31]. The relative changes in glacier areas also varied with glacier size (indicated by glacier area) in the seven regions of the TIRB, as seen in Fig. 3. The histogram shows that the relative changes in glacier area increased with decreasing glacier size. The glacier shrinkage was very strong for glaciers with areas of 1.0–5.0 km^2. Glaciers with areas of 1.0–5.0 km^2 accounted for only 27% of measured glacier area, but contributed about 48.3% of the loss of glacier area in the TIRB. However, glaciers larger than 10 km^2 in the Aksu River basin enlarged slightly by about 0.2% in glacier area.

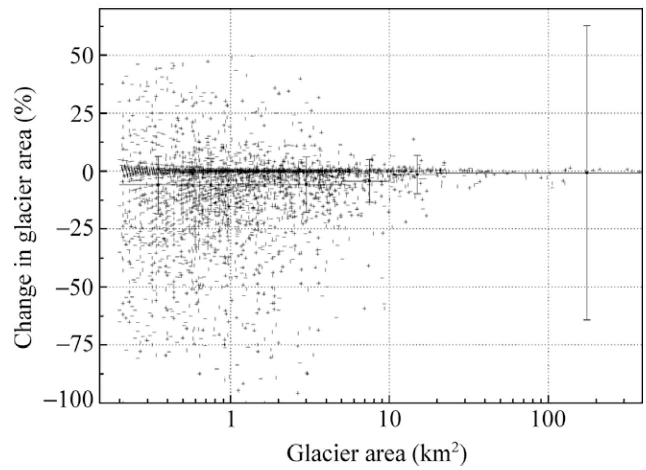

Fig. 2. Scatterplot showing relative changes in glacier area from the 1960s/1970s to 1999/2001. The plot is for 7665 glaciers in the seven sub-basins of the TIRB. Mean values of glacier area change are given together with one standard deviation for six distinct area classes (0.2–0.5, 0.5–1.0, 1.0–5.0, 5.0–10.0, 10.0–20.0, >20.0 km^2).

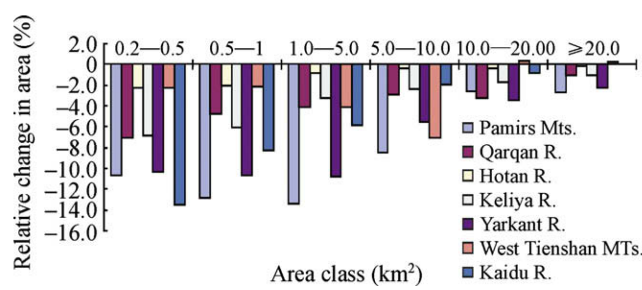

Fig. 3. Relative changes in glacier area for glaciers of different sizes for the seven sub-basins in the TIRB from the 1960s/1970s to 1999/2001 using data from the CGI and Landsat ETM$^+$.

The glacier change also showed obvious regional patterns among the seven sub-basins (Table 1). Prominent retreating of glaciers occurred in the Kaidu River basin and in the eastern Pamirs of China, with glacier areas decreasing by about 7.1% and 7.9%, respectively. The glaciers in the Yarkant River basin retreated by about 6.1% in glacier area. The glaciers in the Qarqan and Keliya sub-basins decreased by 3.1–3.4% in glacier area. There was slight shrinkage for glaciers in the Hotan River basin, with a decrease of 0.7% in total glacier area.

The glacier area changes in eight directions are plotted in Fig. 4. The maximum and minimum shrinkages of glacier area in the TIRB were in the south and east, about 5.5% and 1.7%, respectively; there was also prominent retreating of glacier areas in the northeast and southwest, about −4.6% and −4.5%, respectively. For the seven sub-basins, large glacier shrinkage was found south of the Keliya River, Hotan River, and Yarkant River, southeast of the Pamirs, northeast of West Tienshan and northwest of the Kaidu River. The results further show that the small glaciers shrunk more than the larger glaciers did.

According to the zonal altitude at intervals of 100 m for the 7661 glaciers, the area covered by glaciers was calculated using the ArcObject program in ArcGIS commercial

Table 1
Areas of investigated glaciers and area changes in the sub-basins in the TIRB for the 1960s/1970s and 1999/2001 periods.

River/Mountains	Period	CGI		Landsat 1999/2001	Glacier changes	
		Count	Area (km^2)	Area (km^2)	Change (km^2)	Relative (%)
Qarqan R.	1977–2001	399	779.14	752.55	−26.61	−3.4
Keliya R.	1970–1999	731	1348.39	1306.51	−41.88	−3.1
Hotan R.	1966/1970–2000	2487	5168.49	5131.75	−36.74	−0.7
Yarkant R.	1972/1977–2001	1421	3375.84	3170.57	−205.27	−6.1
Pamirs in China	1962/1965–2001	880	2263.42	2085.38	−178.04	−7.9
West Tienshan	1962/1965–2000	1249	4093.7	4039.2	−54.5	−1.3
Kaidu	1962/1965–2000	498	436.82	405.75	−31.07	−7.1
Summary		7665	17465.80	16891.71	−574.09	−3.3

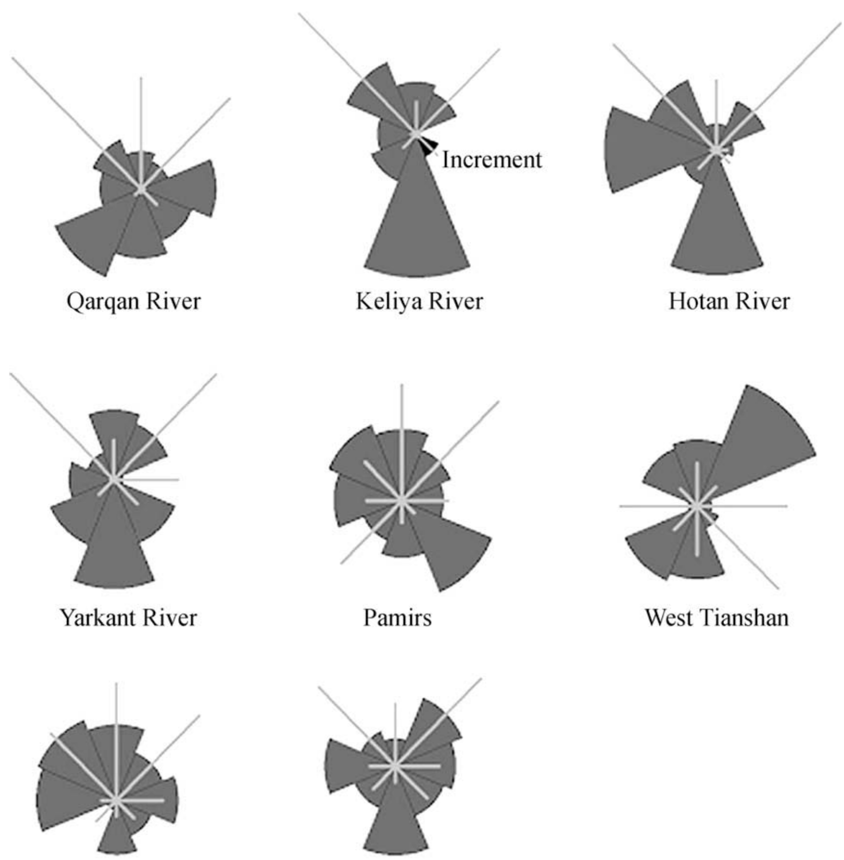

Fig. 4. Glacier area change in eight directions in the TIRB and the seven sub-basins of the TIRB (lines represent glacier areas and the wedges represent the relative changes in glacier areas).

software and is plotted in Fig. 5 for the CGI and 1999/2002 data. The altitude of the maximum area decrement was 4900–5400 m, which is not the altitude of maximum glacier coverage (6000 m). Furthermore, another peak of glacier area decrement was found at an altitude of 4100–4500 m. There was very little change in the area of glaciers at an altitude of 6100 m.

4. Climatic changes

The 25 meteorological stations at which temperature and precipitation data were recorded are far from the glaciers (see Fig. 1), so the absence of continuous and proximate meteorological observations in the TIRB prevents direct analysis of the climatic factors driving the glacial recession, and in some cases glacial advance, observed in the study areas. However, the data extend over the same four-decade period. Thus the climatic records from meteorological stations only represent the climatic nature of the TIRB.

The annual temperature increased during 1960–2000 at all stations except for one (36°52′E, 81°37′N) in the Keliya River basin (Fig. 6a). The linear trend of the annual mean temperature varied between −0.11 and 1.43 °C with a mean trend of 0.77 ± 0.16 °C (the mean value of all 25 stations with a confidence level of 95%). The trends of annual pre-

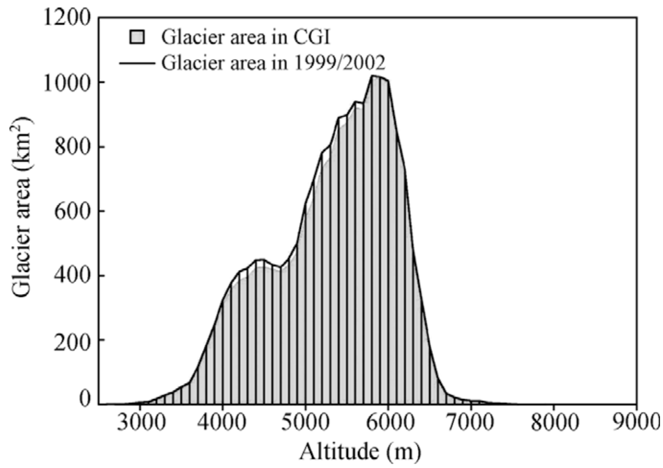

Fig. 5. Glacier area change with zonal altitude at intervals of 100 m from the 1960s/1970s to 1999/2001.

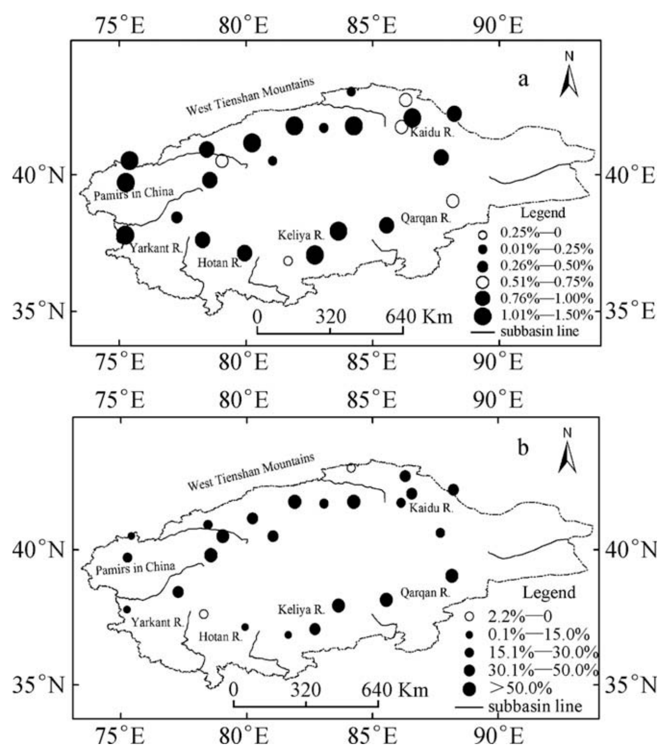

Fig. 6. Long-term total trends for mean temperature (°C/40a) (a) and mean precipitation (%/40a) (b) in the TIRB for 1960–2000.

cipitation for 1960–2000 were also calculated and are depicted in Fig. 6b. It is seen that precipitation increased at all stations except for two, one is in the Hotan River basin in the southern TIRB and the other in the Kaidu River basin in the northeast TIRB (Fig. 6b). The annual precipitation trends varied between −2.2% and 102.3% with a mean trend of 22.8 ± 7.9% in the study basin. Climate warming and increasing precipitation have been reported at most stations in northwestern China, and there was a notable regional change from being warm and dry to being warm and wet in 1987 owing to the westerly circumfluence [10,32]. However, the amplitudes of changes in temperature and precipitation varied in the sub-basins. The climate warming in the east and west TIRB was strong. Temperature significantly increased by about 1.2 °C in the Pamirs of the western TIRB and in the Qarqan sub-basin of the eastern TIRB in 1960–2000. Furthermore, the climate cooled by 0.11 °C in the Keliya River basin in the southern TIRB in 1960–2000 and the radiosonde altitude of 0 °C in the summer atmosphere dropped by about 100 m [33]. Consequently, it has become significantly warmer and wetter in the Qarqan River basin, Pamirs, West Tienshan Mountains, and Kaidu River basin; however, it has become warmer and drier in the Hotan River basin; and although one station indicated that it has become slightly cooler and significantly wetter, the other two stations indicated that it has become warmer and wetter in the Keliya River on the whole.

The recent glacial recession in the TIRB is consistent with the warming trend recorded by meteorological stations. Climate warming, however, did not always result in glacial recession owing to increased precipitation. This phenomenon also occurred for Urumqi Glacier No. 1 in the Tienshan Mountains to the east of the TIRB, where the summer temperature and annual precipitation increased by 0.8 °C and 87 mm (19%) and the cumulated mass balance decreased by 10032 mm [34]. Regarding the regional pattern of glacier change responding to climatic change, glacier recession in the Pamirs and the Kaidu River basin had the maximum response to the warming and increasingly wet climate; the second greatest response occurred in the Qarqan River and Keliya River basins and the West Tienshan Mountains. However, glaciers shrank only 0.7% in the Hotan River basin in response to the climate change. Furthermore, some glaciers were found to advance in this study. Unfortunately, we cannot tell if the glacier mass decreased because of the lack of mass-balance observations. In addition, increased accumulation could offset losses attributable to surface melting for some glaciers.

5. Conclusions

Glacier area decreased by 3.3% in the TIRB, northwest China, from the 1960s/1970s to 1999/2001. Area losses for small glaciers with areas of 1–5 km^2 accounted for 48.3% (277.3 km^2) of the total area loss in the TIRB. There were regional differences in the area changes for the sub-basins of the TIRB. A general warming of 0.77 ± 0.16 °C/40a and increase in precipitation of 22.8 ± 7.9% were observed at most meteorological stations in the TIRB over the last four decades. Increasing annual precipitation is favorable for glaciers. Therefore, we believe that the glacial recession in the TIRB was mainly controlled by the regional climate warming observed at meteorological stations, which enhanced glacier ablation. Although glaciers have generally retreated in the TIRB over the last 40 years, it is remarkable that a significant number of glaciers have advanced. Glacier area changes are affected not only by climate fluctuations, but also by factors such as glacier dynamics and glacier dimensions. Unfortunately, there is no glacier mass balance record and glacier dynamics information in the study region [35]. Thus we do not have the necessary data available for determining the reason for the advance of some glaciers.

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