Glacier changes in the west Kunlun Shan from 1970 to 2001 derived from Landsat TM/ETM+ and Chinese glacier inventory data

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ABSTRACT. Recent studies have indicated that widespread wastage of glaciers in western China has occurred since the late 1970s. By using digitized glacier outlines derived from the 1970 inventory and Landsat satellite data from 1990/91 to 2001, we obtained area changes of about 278 glaciers with a total area of 2711.57 km^2 in the heavily glaciated west Kunlun Shan (WKS) in the northern Tibetan Plateau (TP). Results indicate that the prevailing characteristic of glacier variation is ice wastage, and glacier area decreased by 10 km^2 (0.4% of the total 1970 area) between 1970 and 2001. Both the south and north slopes of the WKS presented shrinkage during 1970–2001, but whereas on the north slope a slight enlargement of ice extent during 1970–90 was followed by a reduction of 0.2% during 1990–2001, on the south slope the glacier area decreased by 1.2% during 1970–91, with a small increment of 0.6% during 1991–2001. Comparisons with other glaciated mountainous regions in western China show that glaciers in the research area have experienced less retreat. Based on records from the Guliya ice core, we believe that an increase in air temperature was the main forcing factor for glacier shrinkage during 1970–2001.

1. INTRODUCTION

Glaciers in middle–low latitudes of Asia have retreated continually for the duration of the negative glacier mass balance since the 1990s (Yao and others, 2004), and climate scenario simulation has indicated that they will shrink more under warmer conditions in the future (Oerlemans and others, 1998; Shi and Liu, 2000). Small glaciers and ice caps are believed to have a significant effect on sea level (Dyurgerov and Meier, 1997; Zuo and Oerlemans, 1997; Van de Wal and others, 2001). Moreover, the glacier runoff derived from changes of glacier mass is an important source of fresh water to support the sustained development of the ecological environment, industry and agriculture in the arid regions of northwest China (Yao and others, 2004). Strong glacier ablation has also caused the runoff of some rivers to increase (Shi, 2001). The glacier changes not only influence river runoff and sea-level rise but also record the characteristics responding to climatic fluctuation. Therefore, monitoring glacier changes is one of the components of the Global Climate Observing System (GCOS) (Haeberli and others, 2000).

The west Kunlun Shan (WKS) are located in the northern Tibetan Plateau (TP) (centered at 35°40′ N, 81° E), where several large glaciers have developed. These ranges are situated in transitional climatic conditions between the humid and arid parts of the TP monsoon and the west wind. Thus, the WKS is one of the sensitive areas for west wind and monsoon circulation. In addition, glacier changes in the WKS influence human welfare as meltwater supplies the arid Tarim basin. The remote location and large size of the glaciers makes them difficult to investigate by fieldwork. Remote-sensing (RS), Geographical Information System (GIS) and global positioning system (GPS) (3S) technology has provided a new and valid means of research into the cryosphere (Li and others, 1998; Zhang and others, 2001; Paul and others, 2004). Moreover, Global Land Ice Measurements from Space (GLIMS) carried out glacier research with 3S (Kääb and others, 2002; Paul, 2002; Paul and others, 2004; Kargel and others, 2005). Accordingly, this study used Chinese glacier inventory (CGI), Landsat Thematic Mapper (TM; path 145, row 35, 15 November 1990, and path 145, row 36, 7 October 1991) and Enhanced TM Plus (ETM+; 6 February 2001, 20 October 2001) images to obtain glacier distribution maps in the WKS supported by RS and GIS technology. We investigated the glacier changes over 32 years in this region and discussed the reasons for glacier changes combined with ice-core records.

2. STUDY AREA

The WKS (35°20′–36° N, 80–82° E) (Fig. 1) is located in the northern TP. The topographic features of its two slopes are very different. The terrain on the north slope drops steeply towards the Tarim basin, whereas the south slope, where a planation surface has remained at about 6400 m, is a low slope towards the TP (Li and others, 1986; Yang and An, 1992). Consequently, we investigated the glacier change on the north and south slopes separately. According to the CGI (Yang and An, 1992), there are 278 polar-type glaciers with a total area of 2711.57 km^2 in the WKS. These are made up of 105 glaciers with a total area of 1108.92 km^2 on the south slope, and 173 glaciers with a total area of 1602.66 km^2 on the north slope. Figure 2 shows the share of the total number and area of WKS glaciers on each slope comprised by different area-size classes. The majority of glaciers are <5km^2 in area and these cover about 6% of the total area on the south slope and 9% on the north slope. On the north (south) slope, 5% (2%) of glaciers are >20 km^2 in area, and

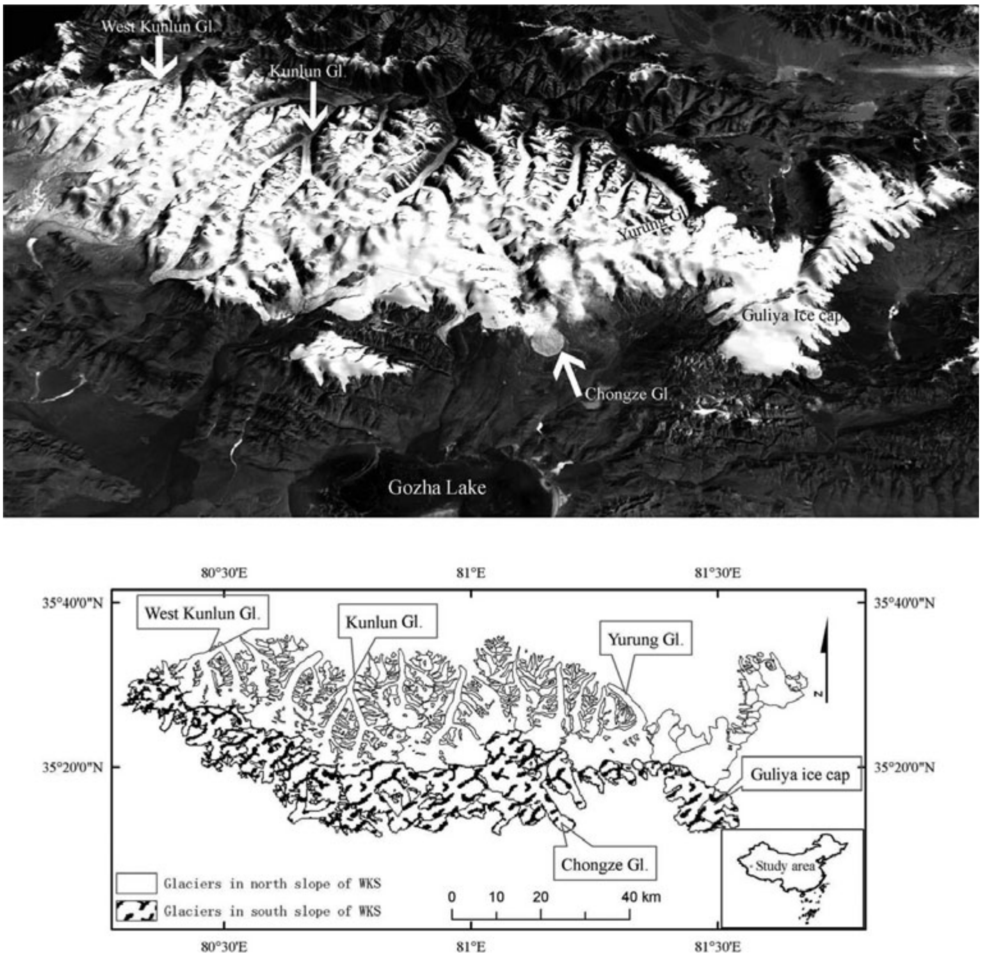

Fig. 1. Distribution map of existing glaciers in the WKS, from the CGI.

these cover about 85% (83%) of the total area. Of these glaciers, 16 are >50 km^2 in area. Some noted glaciers (e.g. west Kunlun, Kunlun and Yulong glaciers and Guliya ice cap) (see Fig. 1) are considered to be representative of large alpine glaciers in the Kunlun Shan. Based on the fieldwork record, Guliya ice cap is the coldest site on the TP, with a lowest temperature of –24.1°C and a monthly mean temperature of –17.8°C in May and –19.0°C at 10 m depth of ice temperature (Yao and others, 1995).

3. DATA SOURCES AND METHODS

Among the data used in this study were the CGI for Kunlun Shan (Yang and An, 1992) which was derived from aerial photographs and topographic maps (1 : 100 000) from 1970 onwards. The glacier outlines of the CGI were interpreted from aerial photographs by stereophotogrammetry and were transferred to 1 : 100 000 topographic maps, and then vectored by commercial GIS software (ArcView). Two Landsat TM images (path 145, row 35, 15 November 1990, and path 145, row 36, 7 October 1991) and two ETM+ images (path 145, row 35, 2 June 2001, and path 145, row 36, 20 October 2001) with cloud-free and low snow cover were used. This study used ETM+ bands 5, 4, 3, 2 and band 8 (panchromatic data). A digital elevation model (1 : 100 000) of this region was derived from topographic maps.

To establish co-registration of these images, 30–35 ground-control points (GCPs) were selected from topographic map features that could be identified on each image. However, it is difficult to distinguish the marked ground objects in the two images for the temporal difference of the two images, which led to difficulty in selecting the GCPs. Thus, the residual root-mean-square error (rmse) of verification points compared with topographic maps is <45.2 m. The ratio image from bands 5 and 4 (Zhang and others, 2001; Paul, 2002) (TM4/TM5 $\geq$ 2.1) was used to classify glaciers from Landsat TM/ETM+ mainly based on glacier ice with very low reflectance in the middle infrared. Those glacier distribution maps derived from the CGI and Landsat images were vectorized, and then the glacier changes in 1970, 1990/91 and 2001 were obtained with GIS-based processing.

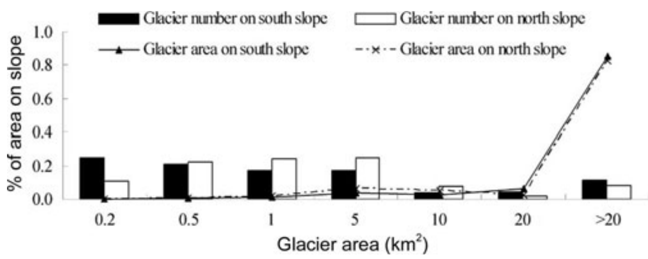

Fig. 2. Frequency of glacier number (bars) and area (lines) according to seven area classes on the south (black bars; solid line with triangles) and north (white bars; dot-dashed line with crosses) slopes of the WKS.

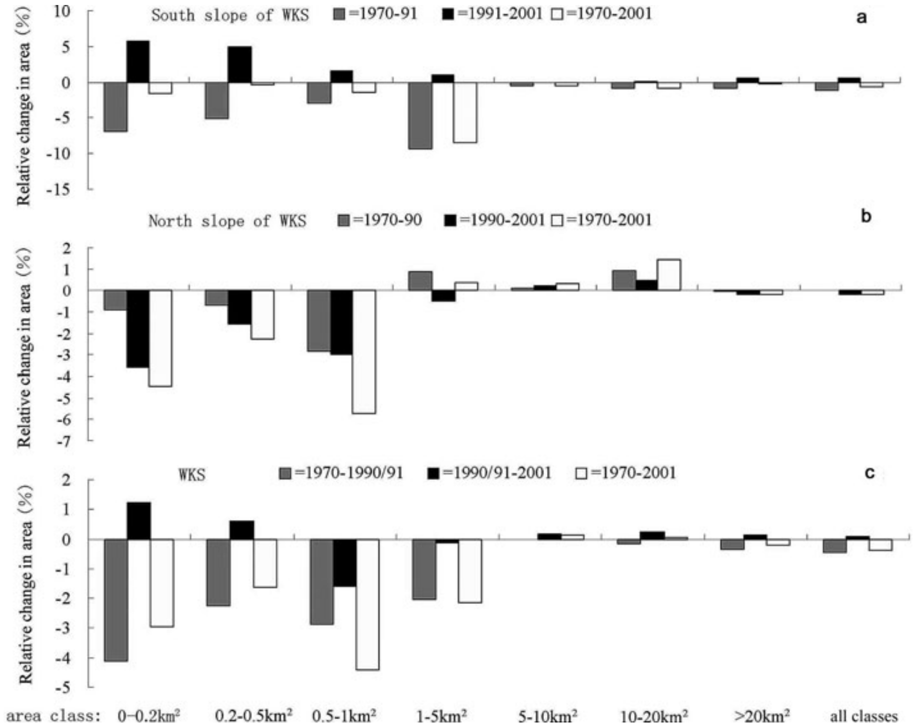

Fig. 3. Relative changes in glacier area (%) for the south (a) and north (b) slopes of the WKS and the whole mountain range (c), separated into area classes and the periods 1970–1990/91, 1990/91–2001 and 1970–2001. Note that the *y*-axis scales differ. Data from the CGI (1970), Landsat TM (1990/91) and Landsat ETM+ (2001).

4. RESULTS

4.1. Glacier changes

Glacier area changes in the WKS were obtained in order to compare the glacier extents derived from aerial photographs in 1970 and from Landsat TM/ETM+ in 1990/91 and 2001. The relative changes in seven classes by glacier area, the three time intervals and the separation into two regions are plotted in Figure 3. Glacier area on the south slope decreased by 12.90 km^2 (1.2% of the total 1970 area) from 1970 to 1991 and increased by 6.10 km^2 (0.6% of the total 1991 area) from 1991 to 2001, and thus decreased by 6.8 km^2 (0.6% of the total 1970 area) for the whole period 1970–2001 (Fig. 3a). Glacier area on the north slope increased by 0.28 km^2 from 1970 to 1990 and decreased by 3.51 km^2 (0.2% of the total 1990 area) from 1990 to 2001, and thus decreased by 3.23 km^2 (0.2% of the total 1970 area) during 1970–2001 (Fig. 3b). Figure 3c summarizes the glacier area changes for the periods 1970–90/1991–2001 for individual glacier area classes. Glacier area in the WKS decreased by 12.60 km^2 during 1970–1990/91 and increased by 2.60 km^2 during 1990/91–2001. For the whole period 1970–2001 the total area loss is 10.00 km^2, or 0.4% with respect to the 1970 area.

Altogether, glaciers in the 0.5–1 km^2 class experienced an area loss of about 4.1% between 1970 and 1990/91 (with respect to the 1970 area), and about 1.6% between 1990/91 and 2001 (with respect to the 1990/91 area). Thus, the total area loss is 4.4% for the whole period 1970–2001. Glacier-area changes in the class <0.5 km^2 are smaller than those in the class 0.5–1 km^2 during 1970–2001 because the increment of glacier area in the class <0.5 km^2 in 1990/91 offsets part of the decrease in 1970–1990/91. However, all the glaciers in the classes 1–5 and >20 km^2 together contributed 30% and 49% of total area loss during 1970–2001.

Recently, records of glacier changes in west China have been obtained by fieldwork investigation, ground and aerial photographic measurements and high-resolution RS monitoring. Table 1 shows the changes in the extremely continental-type glaciers in west China. Glacier changes in the WKS in the last few decades have been the smallest in west China, smaller than those in, for example, Xinqingfeng ice

Table 1. Statistics of the extremely continental-type glacier change in west China

Location	Time-span	Glacier count	Area change		Source
			km^2	%	
Geladandong	1969–2000	753	–14.91	–1.7	Lu and others (2002)
Xingqingfeng glacier	1973–2000	88	–6.79	–1.6	Liu and others (2004)
East Pamirs	1962/66–1999	297	–66.02	–7.9	Shangguan and others (2006)
WKS	1970–2001	278	–10.0	–0.4	This paper

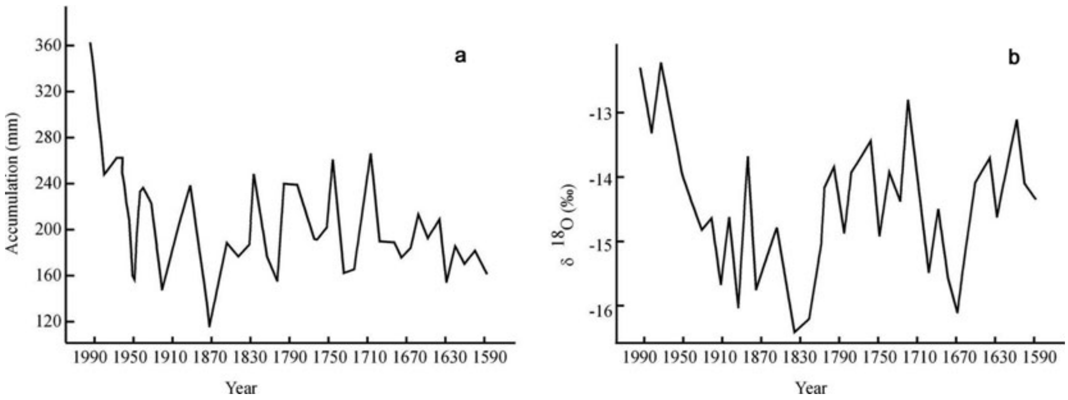

Fig. 4. Trend of glacial accumulation (a) and $\delta^{18}O$ (b) decadal variation since the Little Ice Age recorded in the Guliya ice core (Yao and others, 1995). Glacier accumulation and $\delta^{18}O$ are positively correlated with air temperature and precipitation in the study region.

cap in the north central Kunlun Shan (Liu and others, 2004) and Geladandong in the Yangtze River source region (Yang and others, 2003).

5. DISCUSSION AND CONCLUSIONS

Glaciers are one of the most distinctive natural indicators for studying changes from space related to climate. Analysis of repeated space images has been applied to 278 glaciers in the WKS. Because there was no meteorological station in the alpine zone of WKS, the Guliya ice-core records were selected to reflect the temperature and precipitation (Fig. 4). The $\delta^{18}O$ record from the Guliya ice core (Yao and others, 1996) indicated that it was warm after the 1950s, but temperatures cooled in the 1970s (Fig. 4b). Su and others (2003) found that the temperature has risen about 0.1–0.3°C$\,$(decade)$^{-1}$ on the north slope of the WKS since the early 1960s; and for one region, the higher the altitude was, the more the temperature rose. The net accumulation from the ice core is the direct record for precipitation in the glacier region (Yao and others, 1995). The accumulation from Guliya ice cap showed that precipitation greatly increased after the 1950s (Fig. 4a). The atmospheric warming and precipitation increase recorded by meteorological stations in northwestern China has also been reported after 1957 (Shi and others, 2003). The above-mentioned data indicated high temperature and precipitation after the 1950s in the alpine area of the WKS. Annual increases in precipitation represent favourable climatic conditions for glaciers, and increased accumulation in the WKS could offset losses attributable to surface melting. Therefore, we believe that glacier wastage in the WKS can probably be correlated with regional warming.

The work presented here shows that the glaciated part of the WKS has decreased by about 0.4% during 1970–2001, the smallest decrease in the extremely continental-type glacier area of west China. However, glacier changes differed between the north and south slopes of the WKS. Some parts of glaciers in the WKS advanced. Unfortunately, we cannot tell whether the glacier mass is loss or not because of the lack of mass-balance observations, but we believe that the terrains of the two slopes have great influence on glacier kinematics; furthermore, increased accumulation could offset losses attributable to surface melting. Also glaciers of different size respond at different speeds to climate change (Ding, 1995), and some glaciers may not have begun to respond yet.

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