2008-1-280

J. Mt. Sci. (2008) 5: 299–309
DOI 10.1007/s11629-008-0224-7

Glacier Extent and Volume Change (1966~2000) on the Su-lo Mountain in Northeastern Tibetan Plateau, China

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Abstract: The topographic maps of 1:50, 000 scales, aerial photographs taken in 1966, one Landsat image taken in 1999, and SRTM data from 2000 were used to quantify the losses in area and volume of the glaciers on the Su-lo Mountain, in the northeastern Tibetan Plateau, China in the past 30 years. The total glacier area decreased from 492.9 km^2 in 1966 to 458.2 km^2 in 1999. The volume loss of the studied glaciers reached 1.4 km^3 from 1966 to 2000. This agrees with documented changes in other mountain glaciers of the whole Tibetan Plateau.

Keywords: Glacier change; Su-lo Mountain; ETM + image; Tibetan Plateau; China

Introduction

Mountain glaciers are recognized as one of the top priority climate indicators by the Inter-governmental Panel on Climate Change (IPCC) as they are particularly sensitive to climate changes, and their recent rapid ablation across the world has been connected with global warming (Barry 2006). Ice loss to the sea currently accounts for virtually all of sea-level rise not attributable to ocean warming, but about 60 % of the ice loss is from small glaciers and ice caps rather than from the two ice sheets (Meier et al. 2007). In addition, melting of glaciers can result in river floods, glacial lake outburst, glacial debris-flow hazards and water resource shortages, which directly affect the sustainable development of society and ecosystems.

The Qilian Mountain (36~39° N, 94~104° E) (Figure 1) is located in the northeastern fringe of the Tibetan Plateau. There are 2895 glaciers with a total glacier area of 1972.5 km^2 (Wang et al. 1981), representing a large freshwater reservoir for the arid inland regions, and they feed many rivers including the Su-lo River, Dang River, and Haerteng River. The region has relatively high precipitation (>300 mm yr^{-1}) at high elevations (Ding and Kang 1995, Zhu and Wang 1996), for example, mean annual accumulation reaches 400 mm in the Dunde ice cap (Hou et al. 2002), but low precipitation (50 mm yr^{-1}) occurs downstream along the Su-lo River (Wang et al. 1981). Thus people are confined to several oasis cities with the Gobi Desert extending downstream of these cities. The glaciers on these mountains constitute a vital water source for the people living in and surrounding this region. Therefore, the melting of glaciers has important impact on the lowland desertification, water resources and the stability of the hydrological systems in this arid region.

Received: 6 September 2008
Accepted: 8 October 2008

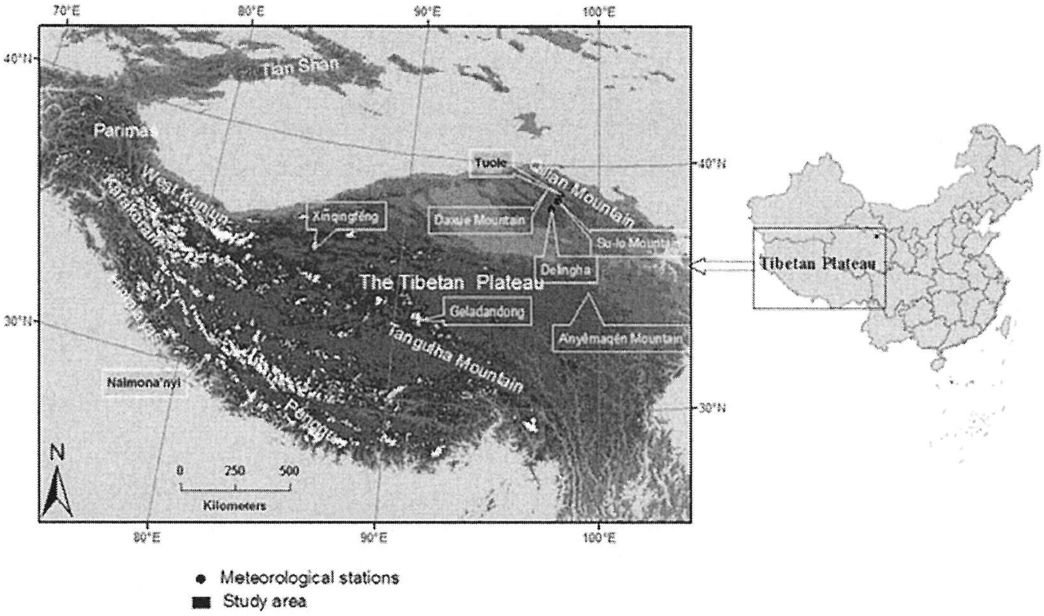

Figure 1 Location map of the Qilian Mountain and the study area (Su-lo Mountain)

The majority of the glaciers in the western Qilian Mountain have retreated rapidly since the end of the Little Ice Age (LIA) due to the duration of the negative glacier mass balance (Liu et al. 1999). Furthermore, glacier shrinkage rate was larger during 1956~1990 than from the LIA maximum to 1956 (Liu et al. 2002). It should be noted that the glacier shrinkage in the western Qilian Mountain between 1956 and 1990 was inferred, assuming that glacier area change in the region is the same as the same area class glacier change in Daxue Mountain (Figure 1), a sub-range of the western Qilian Mountain during the same periods (Liu et al. 2002). Moreover, the study of Liu et al. (2002) was limited in chronological scope to 1990, without importance for more recent data. Therefore, it is necessary to document glacier changes in other sub-ranges (e.g. Su-lo Mountain) to validate the result and update the current glacier inventory. In addition, Liu et al. (2002) have made rough estimates of ice volume change in the Su-lo Mountain on the basis of the experiential formula between glacier area and volume, but with wide uncertainty. Lack of observed glacier altitude change information also prevented a differentiation of the influences of climatic and topographic controls on glacier melt. The authors of this paper detected the glacier extent and volume changes over the last 30 years in the Su-lo Mountain, a sub-range in the western Qilian Mountain based on 1966 aerial photography, topographic maps, Landsat Thematic Mapper satellite images acquired in 1999, and digital elevation model (DEM) from 2000 Shuttle Radar Topography Mission (SRTM).

1 Study Area

The Su-lo Mountain with an elevation over 5500 m asl is located in the western Qilian Mountain, the northeastern Tibetan Plateau, China (Figure 1). The mountain range extends from northwest to southeast, and has an important function as water storage and water supply for the animal husbandry and arid surroundings with irrigated farmland nearby. The range includes three peaks above 5500 m, the highest of which is Tuanjie Peak (38°31' N, 97°46' E) at an altitude 5827 m asl. The regional climate is dominated by Siberian anticyclone in winter. Influenced by the Asian summer monsoon, the greatest precipitation falls during May~August (Liu et al. 2002). Annual precipitation in mountainous regions is about

300~400 mm (Zhu and Wang 1996), and even >750 mm at altitudes of > 5000 m asl (Wu and Liu 1980). The annual mean air temperature in mountainous areas above 5000 m asl is < -10°C. The borehole temperature at 10 m was about -8.6 °C, which was derived from 89m deep ice-core drilling at the summit (5356 m asl) of 5Y446F1 glaicer (Figure 2) in June 2007. The annual snow accumulation could reach 800 mm, derived from snowpits in the Gangnalou No.5 glacier (Figure 2) (Wu and Liu 1980). Most of the glacierized terrains in the Su-lo Mountain can fall into three regions: the west, the north and south Su-lo Mountain ice fields (Figure 2).

According to the Chinese Glacier Inventory (Wang et al. 1981), there are 494 glaciers with a total area of 557.53 km^2 in the Su-lo Mountain. Their equilibrium line altitude is situated around 4600~5010 m asl and the minimum of glacier terminus altitude is 4280 m asl. Among them, 359 glaciers are situated on the northern slopes covering a total area of 417.79 km^2, and 135 glaciers on the southern slopes covering a total area of 139.75 km^2. There are 8 glaciers larger than 10 km^2, but most of them are smaller than 1 km^2. They undergo simultaneous accumulation and ablation during the summer monsoon period, and are called "summer accumulation types" glaciers. Glacier mass balance is particularly sensitive to summer meteorological conditions.

2 Data and Methods

2.1 Data

The data used in this study include:

(1) Twelve topographic maps of 1:50,000 scale published in 1973 and 1975 (with about ± 5 m horizontal accuracy), which were compiled from snow-free aerial photographs taken in 1966.

(2) DEM1966 obtained by digitizing contour-lines (10m interval) from 1:50,000 topographic maps. Its vertical accuracy is ± 19 m on steep slopes (> 25°), and ± 11 m on the slopes less than 25° in high mountainous regions, respectively; SRTM data generated from the records of the C-band antenna (wave-length 5.6 cm) SRTM flown 11~22 February 2000. The linear vertical absolute

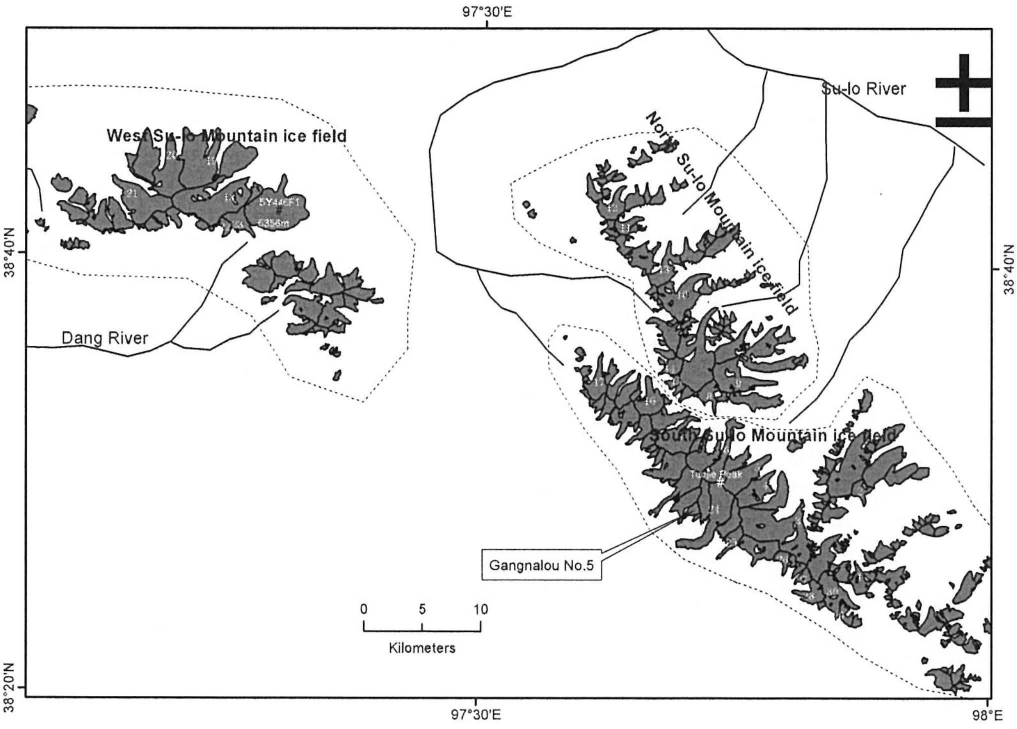

Figure 2 Glacier distribution in the Su-lo Mountain

height error shall be less than 16 m for 90% of the data (Rabus et al. 2003). The DEM have many holes in the north Su-lo Mountain ice field, but only few holes in the west and south Su-lo Mountain ice fields due to the specific method of terrain elevation data acquisition by means of interferometric radar remote sensing (Möller et al. 2007). Therefore, the volume change was not detected in the north Su-lo Mountain ice field due to many artifacts. The raw SRTM DEM was contoured with intervals of 10 m, and re-interpolated within ArcInfo TOPOGRID using the same tolerance parameters. These few holes were replaced by the interpolated values (maintaining the original DEM values where data were available in the raw image) (Jarvis et al. 2004).

(3) One 28.5 m resolution free-cloud image of this study area, obtained from 23 September 1999 [Landsat Enhanced TM Plus (ETM+)]. We used the DEM1966 for orthorectification of the Landsat image. The accuracy of orthorectification is within one image pixel. Co-registration for the orthoimage is based on the 1:50,000 scale topographic maps. The registration error to the topographic maps was 19 m (less than one pixel).

2.2 Extent change

The glacier outlines in 1966 were interpreted from aerial photographs by stereophotogrammetry and were transferred to 1:50,000 topographic maps, and then vectored by commercial GIS software (ArcGIS 9.2). The uncertainty of the glacier area is < 5% (Wang et al. 1981). To determine glacier outlines in the images from 1999, we first calculated TM4/TM5-ratio images using a threshold of 2.2 (Paul 2002). Although almost all glacier areas could be identified in the TM4/TM5-ratio image, pro-glacial lakes and parts of water bodies were misclassified as glaciers, which would make the detected glacier areas too large. According to Bolch and Kamp (2006), three land cover classes could be determined using the Normalized Difference Vegetation Index (NDVI): water bodies (NDVI < -0.4), non-vegetated areas (-0.4~0.01), and vegetated areas (NDVI > 0.01). Misclassified pixels of water bodies and lakes were eliminated using NDVI. Debris-covered glaciers were digitized manually using a slope map derived from the DEM and a color composite map (ETM+ band 5, 4, 3). The raw ice polygons were visually checked for classification errors such as persistent seasonal snow and moraines.

2.3 Volume change

For accurate comparison with DEM 1966, the SRTM data were transformed from the World Geodetic System of 1984 (WGS84) to the Krasovsky_1940 datum, which is used in the DEM 1966. The data were also interpolated to the same grid as the transformed DEM 1966. After the preparation of the DEMs, the final estimation of ice elevation and total volume changes was performed in ArcGIS comparing for each glacier surface, by cut-and-fill procedures, the differences of altitudinal values observed between the 1966 and 2000 DEMs.

2.4 Solar radiation

The total incoming solar radiation (sum of direct and diffuse radiation) under clear sky condition in the study area was estimated with the TopoView version 1.1 solar radiation model. A simple transmission model (e.g. Pearcy 1989, Rich 1989 & 1990) was implemented to compute direct solar radiation from the solar constant, accounting for latitude and atmospheric effects based on transitivity and air mass depth. Diffuse radiation was computed using a uniform overcast sky algorithm (Rich 1989 & 1990, Pearcy 1989). For each cell of the reference DEM, the potential solar radiation was estimated for the annual period, as both time spans are interesting in terms of glacial mass balance. In the process, the program considered the shadows casted by surrounding topography, the trajectory of the sun throughout the day (hourly), the earth–sun distance (monthly), atmospheric extinction and daily solar position.

3 Accuracy and Error Analysis

Discussion on the terminus and area changes should be considered in the context of the associated uncertainty. The measurement accuracy of the glacier front position depends on the spatial resolution of the dataset and errors in imagery registration (Hall et al. 1992 & 1995, Williams et al. 1997, Silverio et al. 2005, Ye et al. 2006b). The terminus change uncertainty U is estimated from (Hall et al. 2003, Silverio et al. 2005)

$$U=\sqrt{a^2+b^2}+\sigma \tag{1}$$

where a, b and σ are the image resolution of image a and b, and the error of image registration, respectively. The accuracy is ± 81.1 m for the case where the 1999 ETM + image is registered to the topographic maps. The spatial resolution of the dataset and errors in imagery registration also play an important role in the measurement of the glacier area. According to Hall et al. (2003) and Ye et al. (2006b), the measurement uncertainty of glacier area (U_{Area}) can be obtained by:

$$U_{Area}=2Ua+\sigma^2 \tag{2}$$

where U is the terminus uncertainty, a the image pixel resolution (28.5 m for the ETM+ data), and σ is the image registration error. Thus changes in the glacier areas among the digital images during 1966~1999 were measured using formula (2) with an accuracy of ±0.011 km^2.

The elevations of glacier-free outcrop areas were compared between the SRTM DEM and 1966 DEM, yielding a mean bias of -0.85 m and a standard deviation of 18 m.

4 Results

The Su-lo Mountain glacier area in 1966 was 492.9 km^2. It decreased to 458.2 km^2 in 1999. Ice-volume losses of the west and south Su-lo Mountain ice fields between 1966 and 2000 amounted to an estimated total of 1.4 km^3, with an annual loss rate of 0.041 km^3 yr^{-1} and mean ice thinning about 4 m during this period.

The noticeable differences in the observed shrinkage trends related to the orientation of the studied glaciers. This effect was quantified by grouping the values of area and ice depth into two sets: north-facing (including north, northeast and northwest aspects) ice masses and south-facing (including south, southeast and southwest aspects) ice masses. The north-facing glacial bodies in the Su-lo Mountain decreased in area by 5 %, but by 7.7% in the south-facing glaciers during 1966-1999. Ice depth of many glaciers increased in their accumulation zones, but decreased in their ablation zones of the north-facing glaciers in the west and south Su-lo mountain (Figure 3 and 4). There was no evident change in the mean ice depth of the north-facing glaciers, but the depth of the south-facing glaciers decreased by about 14 m from 1966 to 2000.

5 Discussion

Annual precipitation and summer temperature are the two main factors controlling the glacier development on the Tibetan Plateau. Summer temperature dictates ablation, while annual precipitation influences accumulation of glaciers. There is one meteorological station, very close to the Su-lo Mountain, namely, the Tuole Station (38°48' N, 98°25' E) with an elevation of 3367 m asl (Figure 1). Linear trend analysis of mean summer temperature and annual precipitation from the station shows that the average increasing rates of summer temperature and annual precipitation are 0.23°C decade^{-1} and 8.7 mm decade^{-1}, respectively. It can be concluded that the summer temperature of the Su-lo Mountain during 1966~1999 may have increased by approximately 0.8°C, and annual precipitation increased by about 29 mm, 10% of the long-term annual mean precipitation. There was a clear increasing trend in temperature while the annual precipitation varied significantly and showed a slight increasing trend during 1957~2003 (Figure 5). The moving t test of the mean summer air temperature showed an abrupt warming since mid-1990s (Figure 5). The annual precipitation had a relatively rapid decrease in the 1990s, especially during the latter half 1990s. The sharp increase in the summer air temperature causes an increase in summer melting by sensible heat and leads to a continuous shift of the equilibrium line toward high altitude (Hasnain 2002, Kadota et al. 1993, Fujita and Ageta 2000). In addition, a decrease in precipitation would cause a lowering of the surface albedo, and the snow/ice melt would be accelerated (Fujita and Ageta 2000).

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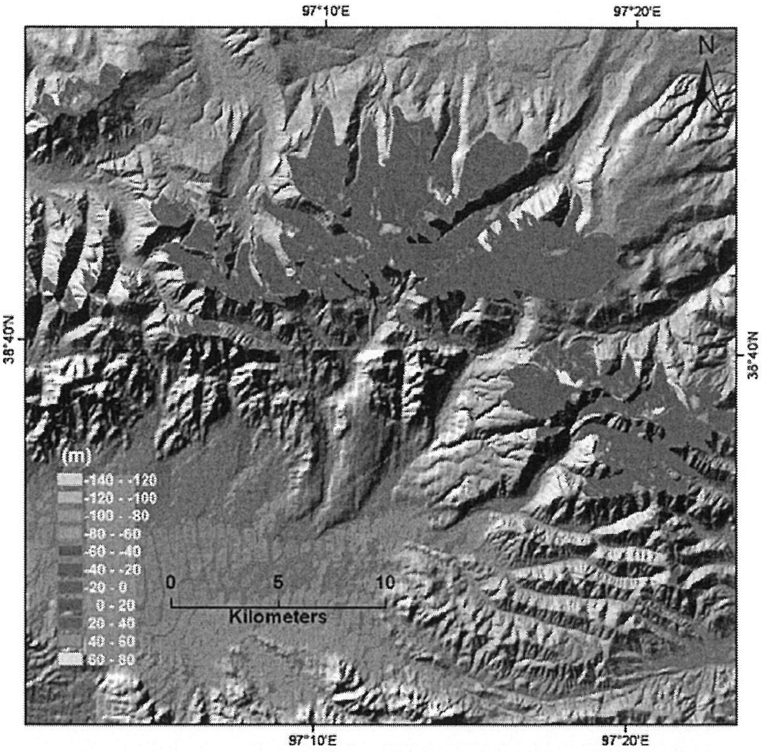

Figure 3 Glacier elevation changes in the western Su-lo Mountain ice field during 1966 ~2000

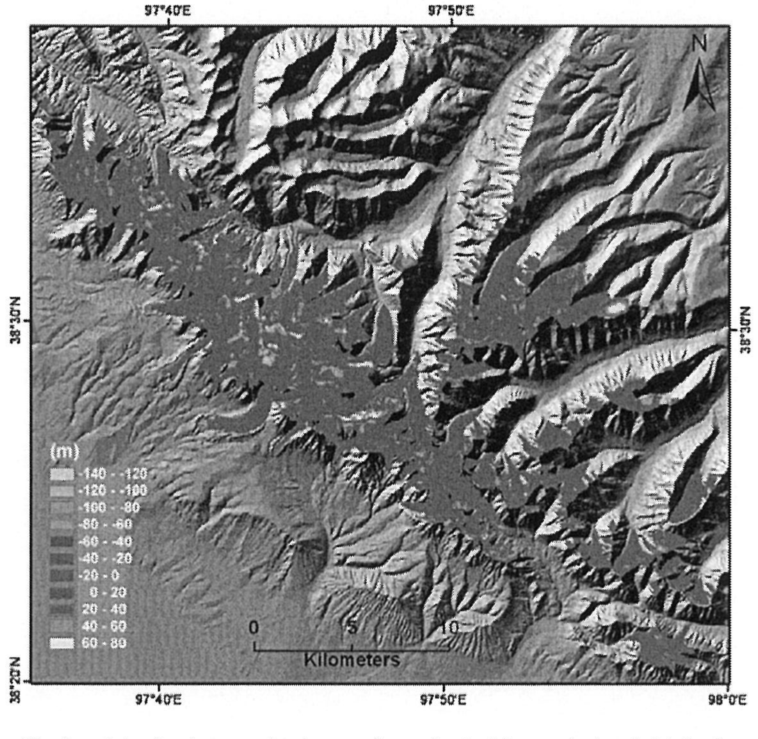

Figure 4 Glacier altitude changes in the southern Su-lo Mountain ice field during 1966~2000

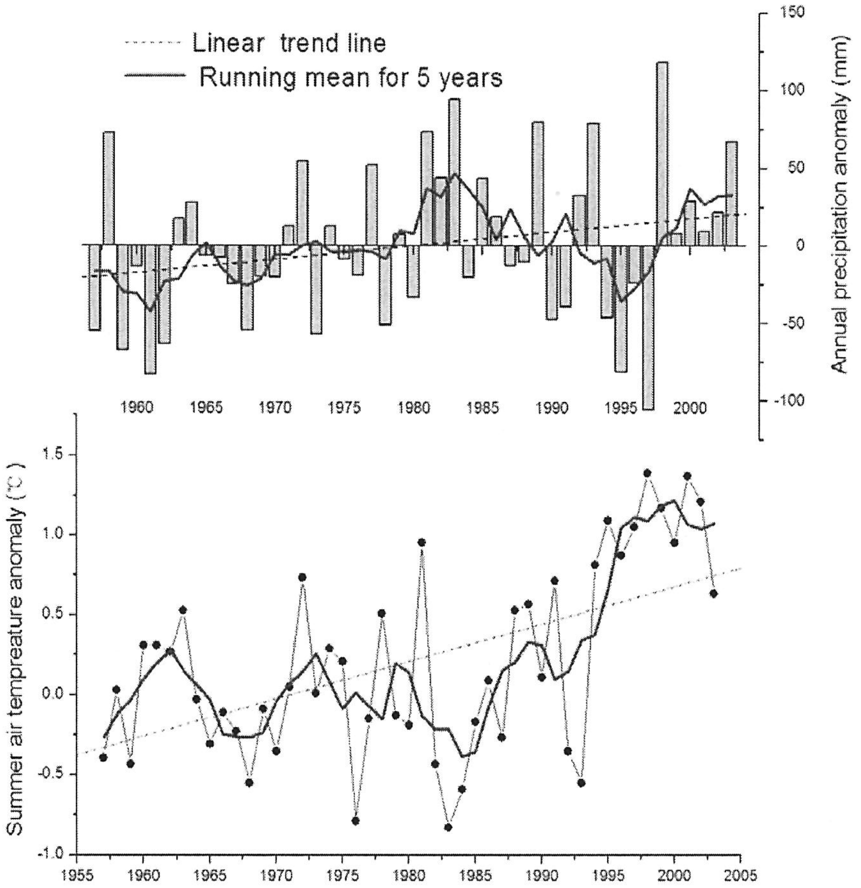

Figure 5 Changes in mean summer temperature (curves) and annual precipitation (bars) From the Tuole Station, as anomalies from the mean between 1961 and 1990

sensitivity based on an energy-balance model of 12 glaciers around the world shows that the area-weighted glacier mass balance will decrease by 0.40 meter per year for a uniform 1 K warming (Oerlemans and Fortuin 1992). Oerlemans et al. (1998) discussed the effect of the increased precipitation on the same glaciers by calculating the changes in annual balances when air temperature was increased by 1°C and precipitation simultaneously by 10%. Braithwaite and Zhang (2000) assessed the sensitivity of the mass balance of 5 Swiss glaciers to air temperature changes using a degree-day model. If annual precipitation also increased by 20% it would partly offset the effect of the 1°C higher temperatures but could not compensate for it. The glaciers in the Tibetan Plateau are more vulnerable than those of the other regions (Fujita and Ageta 2000). The glacier equilibrium line in the Tibetan Plateau can rise by 100~160 m with the 1°C increase in mean air temperature from June to August (Kang 1996). If the equilibrium line keeps the original altitude under the rise of summer air temperature by 1°C, a precipitation increase on needs to be above 70%, even 100% for the glaciers in the Qilian Mountain (Kang 1996). Under the rise of air temperature from 1966 to 1999 (about 0.8°C), the rise of the glacier equilibrium line in the Su-lo Mountain is almost impossible to be restrained by the increase in precipitation as described above. Therefore, the glaciers in this region should retreat as increases in annual precipitation do not compensate for ablation rate increases caused by the dramatic summer air temperature rise during the study period.

There is a significant negative relationship between percent area change and the deviation between the maximum elevation of the glacier and its median elevation ($p < 0.01$). This shows that the glaciers with median elevations closer (in altitude) to their maximum elevations are losing more area. A significant negative relationship between the percent area loss and the maximum elevation of the glacier (at the head) ($p < 0.01$) indicates that the glaciers located on lower summits are also losing more areas. We found a significant negative relationship ($R = -0.3$, $p < 0.01$) between the change in area vs the altitudinal range of a glacier, calculated as maximum minus minimum elevation. This suggests that the glaciers with a smaller altitudinal range are losing more of their area. Glacial initial size plays an important role in the subsequent shrinkage process, as it is found by Ye et al. (2003) and Chueca et al. (2007). The smaller the glaciers in this study area, the larger their percentage changes in area (Figure 6). This finding highlights the significant sensitivity of the smaller glaciers to changes in the main climatic factors, which always exhibit a strong vertical gradient, and thus control the accumulation and ablation processes. Correlation analysis shows that the potential incoming solar radiation seems to control the loss of volume per surface unit in the glaciers of the Su-lo Mountain ($R = 0.6$, $P < 0.05$). The higher the solar radiation inputs, the greater the loss of volume per surface unit is. There is also a significant positive relationship ($P < 0.05$) between ice depth loss and slope. On very steep slopes ice thickness is reduced because of a faster ice flux (Hubbard 1997). Thus, in periods of glacial shrinkage when the head of a glacier enters steeper areas, the deglaciation processes become more rapid, while sudden detachment events might even be observed (Benn and Lehmkuhl 2000).

6 Glacier Changes over the Tibetan Plateau

Records of glacier changes over the Tibetan Plateau have been obtained by aerial photographic measurements and high-resolution remote sensing monitoring. Table 1 shows clearly the regional differences of glacier recession over the Tibetan Plateau in the last few decades. Glacier coverage in the A'nyêmaqên Mountain from the headwaters of the Yellow River decreased by 17% from 1966 to 2000 (Yang et al. 2003) that in the Pumqu River basin of the central Himalaya by 9% from 1970s to 2001 (Jin et al. 2005) in the Naimona'nyi region of the western Himalaya by 8.4% (Ye et al. 2006a) in the Karakoram by 4.1% from 1966 to 1999 (Shangguan et al. 2006) in the Xingqingfeng by 1.4% from 1973 to 2000 (Liu et al. 2004) and in the western Kunlun Mountain by only 0.4 % from 1970 to 2001 (Shangguan et al. 2007). In general, the glacier recessions in the Su-lo Mountain in the last few decades were larger than those of the extremely continental-type glaciers in the central and northwestern Tibetan Plateau, but smaller than those in the western and central Himalayas and A'nyêmaqên Mountain. However, they agree with the average 7% decrease for the glaciers across China since the 1960s (Yao et al. 2004). Air temperature increased more significantly during October-March than during April-September, particularly on the northeastern Tibetan Plateau where it increased by about 1°C, compared to 0.4~0.5°C in the central Tibetan Plateau during October ~ March next year (Zhao et al. 2004). Annual accumulation increased in the central and northern Tibetan Plateau since the 1950s, but decreased sharply in the Himalayas (Hou et al. 2002). In addition, if summer air temperature was increased by 1°C, annual precipitation would increase by about 40 % in the northwestern and central Tibetan Plateau, by 70~100 % in the Qilian Mountain to keep the glacier equilibrium line unchanged (Kang 1996). Based on the ice-core $\delta^{18}O$ record and radiosonde observations, the northwestern and central parts of the Tibetan Plateau possibly experienced a cooling trend during 1961~2002, which may explain partly for the relatively stable condition of the glaciers in this areas (Shi et al. 2006, Ding et al. 2006). Prominent warming and reduction of precipitation, especially since the late 1980s, resulted likely in a dramatic glacier mass loss in the A'nyêmaqên Mountain in the last 40 years (Ding et al. 2006). According to Hou et al. (2002, 2007) and Ren et al. (2006), the summer temperature increased rapidly and annual accumulation from ice-core record in the central Himalaya declined dramatically since the 1960s, which might lead to the rapid glacier recession in this region.

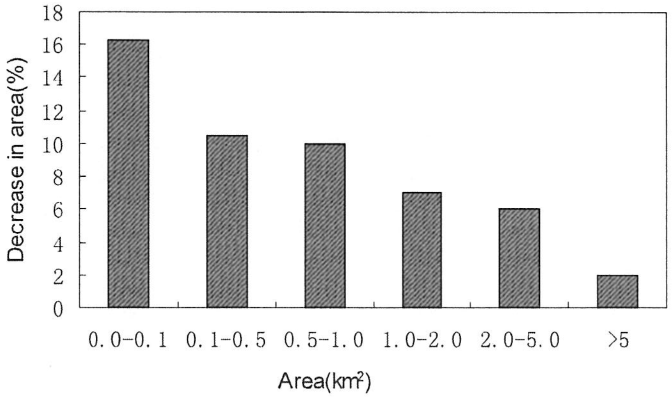

Figure 6 Decrease in area of each class of glaciers (categorized by area) in the Su-lo Mountain during 1966~1999

Table 1 Comparison of glacier changes over the Tibetan Plateau (TP)

Region	Time-span	Glacier type	Area change (%)	Resource
East Pamiras (northwestern TP)	1962/66~1999	Extreme continental	-7.9	Shangguan et al. 2006
Xinqingfeng (northwestern TP)	1973~2000	Extreme continental	-1.7	Liu et al. 2004
Geladandong (central TP)	1969~2002	Extreme continental	-4.8	Ye et al. 2006
Karakoram (northwestern TP)	1969~1999	Sub-continental	-4.1	Shangguan et al. 2006
Pumqu (central Himalayas)	1970~2001	Sub-continental	-9.0	Jin et al. 2004
Naimona'nyi (western Himalayas)	1976~2003	Sub-continental	-8.8	Ye et al. 2006
Daxue mountain (northeastern TP)	1956~1990	Extreme continental	-4.8	Liu et al. 2002
Su-lo Mountain (northeastern TP)	1966~1999	Extreme continental	-7.0	This study
A'nyêmaqên Mountain (northeastern TP)	1966~2000	Sub-continental	-17.0	Yang et al. 2006
West Kunlun (northwestern TP)	1970~2001	Extreme continental	-0.4	Shangguan et al. 2007

7 Conclusions

The total glacier area in the Su-lo Mountain decreased by about 7% during 1966~1999. The majority of glaciers in this region are thinning, and the global volume loss is about 1.4 km^3 from 1966 to 2000. The summer temperature increased dramatically in the last 30 years, which is possibly a direct driver of glacier recession over the same period in this region. In addition, the local variables such as the orientation of each glacier, its altitude, slope and initial size seem to exert a considerable influence on the spatial differences in the magnitude of the losses.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (40576001 and 40825017), the Chinese Academy of Sciences (KZCX3SW344 and 100 Talents Project), the Korean Research Council of Public Science and Technology (PP07010), and the National Key Technology R&D Program (2006BAB18B01).

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