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ORIGINAL ARTICLE

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Study on the change of Keqikaer Glacier during the last 30 years, Mt. Tuomuer, Western China

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Abstract Using radio echo sounder, ice thickness of Keqikaer Glacier tongue was measured in 1981 and 2004. Data obtained by comparing topographical maps, aerial and satellite photographs at different times, illustrates changes of the thickness and advance/retreat of Keqikaer Glacier. Keqikaer Glacier has been in intensive retreat since the 1990s and become thinner since the 1980s. Measured thickness of the ice tongue indicates reducing with a speed of 0.5–1.5 m a^{-1} since 1981. The shrinkage of the glacier terminus is less than 2% of the total length during the last 30 years; however, the retreat of terminus position and the thinning of the ice thickness provides significant information that these glaciers on the south slope of Mt. Tuomuer are in an intensively decreasing phase in recent time.

Keywords Radio-echo sounding · Map comparison · Ice tongue · Keqikaer Glacier · China

Introduction

Keqikaer Glacier is on the south slope of Mt. Tuomuer, Chinese west Tienshan, approximately 60 km north to Akzo city, Xingjing Uigur Autonomous Region, China (41°40′–41°40′N, 80°04′–80°12′E). It is a large dendritic mountain valley glacier that extends from 6,342 to 3,020 m a.s.l with a length of 25 km and an area of 83.6 km^2 (Fig. 1). One of the most common characteristics of Keqikaer Glacier and the other large valley glaciers in Mt. Tuomuer area is the presence of debris covering a large portion of the ablation zone (Su et al. 1985; Wang and Su 1984; Xie et al. 2004). The thickness of debris increases from zero at 3,900 m a.s.l. to over 2 m near the terminus of Keqikaer Glacier. Supraglacial debris cover reverses the ablation gradient and reduces the equilibrium accumulation area ratio, and leads to the glacial terminus spread to low altitude area (Su et al. 1985). In contrast to clean glaciers, the response of debris-covered glaciers to climatic variation is commonly delayed, subdued and given topographic expression by thickening and thinning rather than by terminus advance and retreat, because reduced ablation beneath the debris cover allows extended ablation zone to evolve (Kirkbride and Warren 1999). In this paper, a standard radio echo sounder (RES, B-1) was used to determine ice thickness at several points on Keqikaer Glacier, including three transverse profiles (TP) in July 2004. Comparing the result measured in June 1981 by the same RES (Zhu 1982), change of the ice thickness has been analyzed. Aerial photos and topographical maps were used to analyze the changes of the Terminus. Based on these data, it may be possible to analyze the change (in ice thickness, terminus position) of the ice tongue of Keqikaer Glacier during the last 30 years.

Thinning of Keqikaer Glacier

Measurements made in 1981

The radar method is the most widely used means for determining the ice thickness of glaciers (Sun et al. 2003). During 1980–1982, to provide database for the

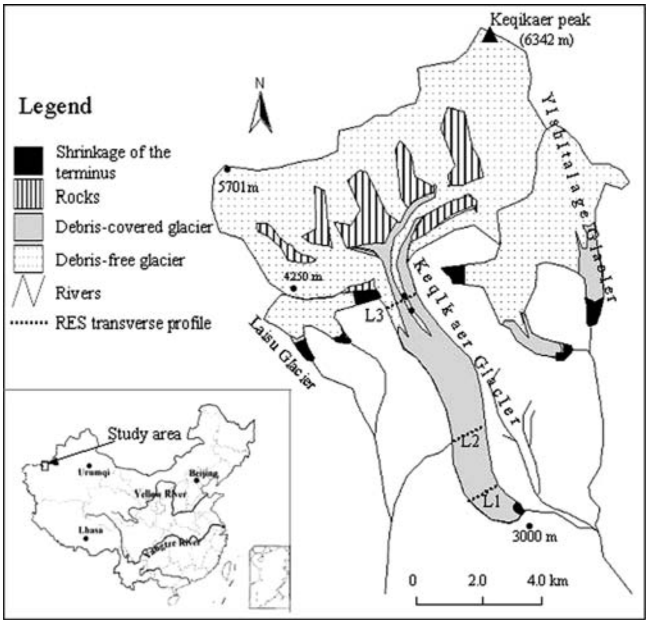

Fig. 1 Map of Keqikaer Glacier and some other glaciers at the source region of Atuoyilake River basin

work of Tienshan glacier inventory, persons from the Institute of Glaciology and Geocryology, Chinese Academy of Science (IGGCAS) have made ice thickness measurements of more than 20 glaciers in Chinese Tienshan by using B-1 RES (Zhang et al. 1985). The B-1 RES was made by IGGCAS in 1980 (Zhu 1982), and was ameliorated in 1983 and 2002. The equipment consists of transmitter, receiver and digital oscillograph. It is a high-resolution radar operating at a frequency of 300 MHZ, which is capable of sounding approximately 500 m in temperate ice with an accuracy of about 10 m. Thickness of Keqikaer Glacier including two TP and some points below 3,800 m a.s.l. was measured in June 1981 for the first time (Zhu 1982). The result indicated that the thickness exceeds 89 m of the L1 TP at 3,170 m a.s.l. and 105 m of L2 TP at 3,300 m a.s.l. Average thickness was 74 and 95 m at the L1 and L2 TP, separately. Four points were measured on the 3,750 m a.s.l. and the average thickness arrived at 205 m in this area. Few small lakes and shallow riverways on the surface of the ice tongue at that time (Zhu 1982; Wang and Su 1984).

Research revealed that three main obstacles hamper the use of RES on temperate debris-covered glaciers (Zhu 1982; Gades et al. 1999). Firstly, the supraglacial debris weakens the amount of energy transmitted into and out of the underlying ice. Secondly, englacial rock and water inclusions cause much of the transmitted energy to be depleted to scattering. Thirdly, the rugged surfaces of many glaciers reflect some energy, which complicates the interpretation of the bed reflection. Therefore, several spots were selected to determine the adjacent ice thickness during the survey, because over short distances, the bed reflection is spatially consistent and appears in each record, but interfering reflections (from rock or water inclusions) generally appear at different depths in each record.

Measurements made in 2004 and the results

To analyze the change of the thickness since 1981, the second measurement was made in July 2004 by using B-1 RES. In this measurement, L1 TP and L2 TP were detected again, and added the third TP at 3,750 m a.s.l. In addition, the topographic pattern of ice surface was measured by using the Differential Global Position System (DGPS). These DGPS surveys have a horizontal accuracy of ± 1.0 m and a vertical accuracy of ± 0.3 m. The radar data obtained in 2004 revealed that the ice tongue of Keqikaer Glacier has become thinner since 1981. The average ice thickness is only 63 m at L1 TA and 78 m at L2 TA, reduced 11 and 17 m in the last 20 years, respectively, decreasing at a rate of about 0.2–1.0 and 0.5–1.0 m a^{-1} during the last 20 years. In addition, the ice surface undulates and many large longitudinal valleys with depths of 25–30 m have been formed on the ice tongue since 1981. For example, there is a large longitudinal valley near the east lateral margin of glacier across the 3,170 m contour line with a depth of 40–50 m, and a width of about 100 m. This valley contributes most of the lost ice volume in L1 TP. The L3 TP is near the 3,750 m contour line; this profile was only detected in July 2004. The decreasing speed of the thickness in this area was estimated at about 1.0–1.5 m a^{-1} during the last 20 years by analyzing the fresh moraine on both sides of the glacier and these data obtained in 1981. Based on these data obtained in 1981 and 2004, ice thickness changes and ice lost at three TA were plotted in Fig. 2. As no topographic data of the ice surface is available for 1981, the authors regard the ice tongue has a plain surface in spite of undulate appearce in that time. The ice surface in 2004 was measured by DGPS.

Change of the glacial terminus position

Huang Diqing made the earliest accuracy record of Keqikaer Glacier terminus position in 1942 (Su et al. 1985). He plotted the terminus position in his manuscript by a sketch map. A contour map of Keqikaer Glacier and surrounding region at a scale of 1:50,000 was produced in 1974, the earliest topographic record of this glacier. The horizontal accuracy of the glacier topography on this map was estimated by the authors to be about ± 20 m. Personnel from the Chinese Academy

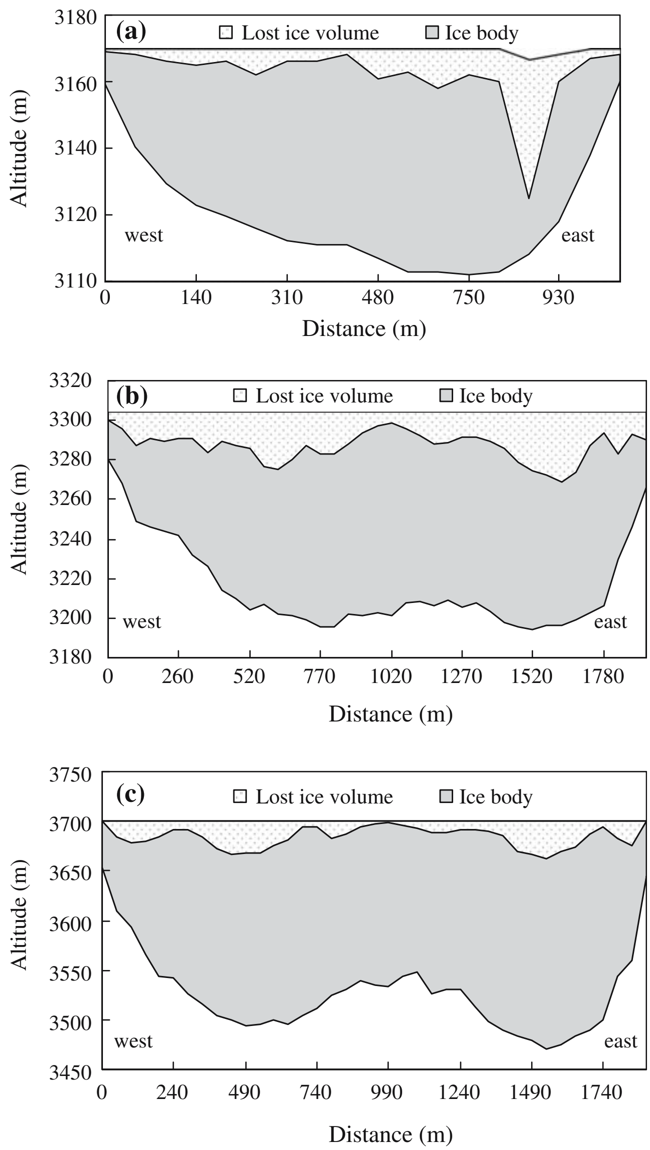

Fig. 2 Radar results of transverse profiles on Keqikaer Glacier showing the thickness of the glacier and the lost ice volume since 1981 (the x-coordinate is the distance from the west lateral margin of the glacier) **a** L1 transverse profile (3,170 m a.s.l.) **b** L2 transverse profile (3,300 m a.s.l.) **c** L3 transverse profile (3,750 m a.s.l.)

of Science resurveyed the terminus position several times between 1973 and 1984 (Wang and Su 1984). Some photos of Keqikaer Glacier have been made by those scientist since 1970. Aerial photography taken in 1989 has been used, and data from Landsat Thematic Mapper (TM, acquired on October 1999) has also been used. As this glacier is only 60 km to Akzo city, and as there is a coal mine near the terminus, many people have reached this glacier and provided some records about the position of glacial terminus. Since June 2003, terminus position has been seasonally determined using DGPS.

Keqikaer Glacier was described during the scientific survey in 1978 as follows: “Keqikaer Glacier has a length of 25.0 km, and there is no fresh moraine ahead of the glacial terminus, the glacial terminus is on the old gramineous moraine, which shows Keqikaer Glacier advanced and expanded since little ice age (LIA), and has advanced 850 m between 1942 and 1976 analyzed by the survey and the aerial photograph (Su et al. 1985).” Retreat of Keqikaer Glacier occurred since the 1980s, however, the glacial terminus didn’t retreat during 1976 and 1981, contrarily had slight advance in this period. The accuracy record of the glacial retreat was found during 1981 and 1984 with an annual rate of less than 5.0 m a^{-1} (Wang and Su 1984). After that, this retreat was interruptedly accompanied by periods of stability or slight advance until the early 1990s. There is no clear shrinkage that took place until 1989 by comparing the contour map with the aerial photography. Keqikaer Glacier has been in intensive retreat since 1990, the annual rate reached 15–20 m a^{-1}. The terminus retreated about 180 m from 1989 to 1999 by comparing the aerial photography and the TM image. The glacial terminus has retreated 80 m from July 1st, 2003 to September 11th, 2005 by the measurements of the fixed markers during the scientific survey. From Fig. 3 it can be seen that the main retreat appears near the outlet of glacier melt water, but on the left of the outlet, retreat does not appear. Following these data introduced above and some maps drawn previously, the glacier advance and retreat since 1942 is given in Table 1.

Discussion and conclusion

Relevancy of our results to current glacier ablation

Ablation of the terminus is not the strongest on Keqikaer Glacier, because thick debris covers the low area of the tongue. Research indicated that the protec-

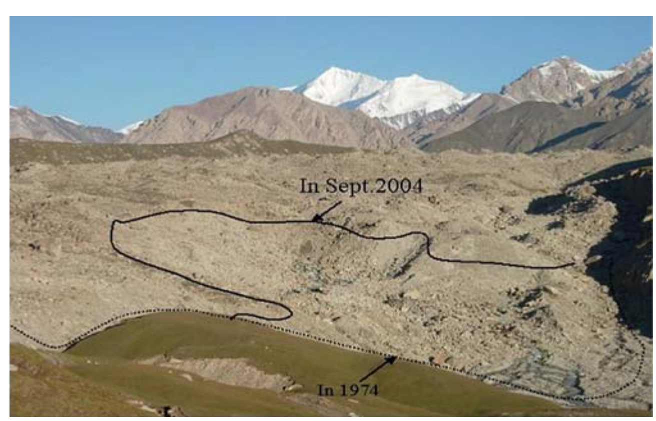

Fig. 3 Photograph of Keqikaer Glacier shows the terminus position in 1974 and September 2004

Table 1 Terminus changes of Keqikaer Glacier since 1942

Duration	Terminus advance (+) or retreat (−)	Advance or Retreat Rate (m a^{-1})	Source
1942–1976	+850	+25	Su et al. (1985)
1976–1981	Stationary	0	Wang and Su (1984)
1981–1985	−20	−4	Zhu (1982) and Wang (1987)
1985–1989	Stationary or slight advance	0 or +2	Aerial photography
1989–1999	−180	−18	TM image
1999–2002	−80	−20	TM image measured
2003–2005	−80	−30	Measured

tion displayed on its weakening effect for glacier ablation when surface debris reaches a certain thickness (Wang and Su 1984). The strongest ablation occurs from 3,750 m a.s.l. to 3,850 m a.s.l. in this area. Debris layer has been reduced from 10 to 0 cm (Fig. 4). The weakening effect of different thickness of debris by drilling ablation stakes was measured. Results of the observation is such: when surface debris thickness is less than 3 cm, the glacier ablation appears at a peak value state; while it was more than 3 cm, the glacier ablation is weakened, i.e. 3 cm is a critical value. As the debris layer is thicker than 100 cm, the ablation of the glacier is influenced a little by the day's temperature but responds to the month or a period of 10 days' average temperature and the ice ablation was reduced by 95%. That is, the ablation is very low between 3,100 and 3,450 m a.s.l. In this region, surface debris is thicker than 100 cm in most area. Figure 5 shows the intensity of surface ablation of glaciers under debris of different thickness compared to the net glacier. However, as for Keqikaer Glacier, because of the erosion by the melt water and uneven melting, supraglacial lakes and glacial thermal karsts of all shapes, such as melt holes, funnels and

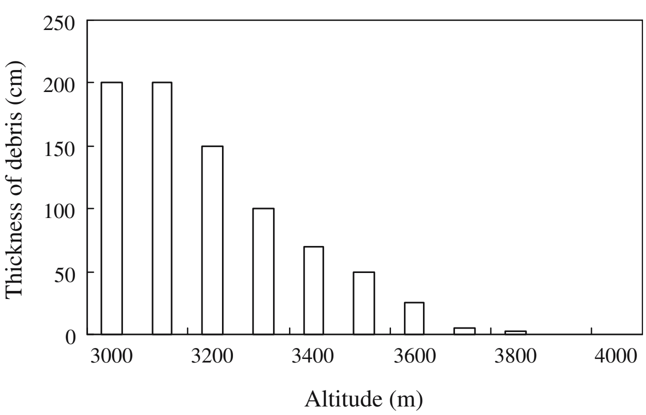

Fig. 4 Thickness of the debris on different elevation on Keqikaer Glacier

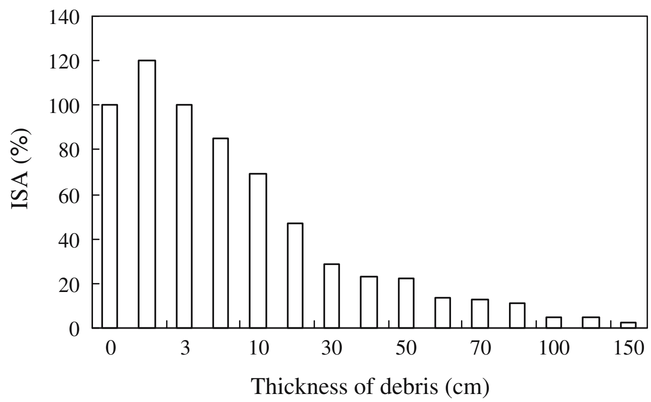

Fig. 5 Intensity of surface ablation (ISA) of glaciers under debris of different thickness comparing with the net glacier

under ditches are formed within the glacier. The englacial and underwater ablation, in fact, is due mainly to the conduction of heat by the surface melt water, which accelerates glacial ablation. The surface melt water in the lakes and surface rivers on the tongue has a positive temperature, usually varying between 0.1 and 4.0°C in the rapid ablation period. Collapses of the melt holes, funnels and under ditches, draining of the lakes always form a different size cavity or pitted plain, which leads to the important decreasing process of the ice thickness in the debris-covered area. Therefore, the ice tongue becomes more thinning in spite of the thick debris covers on the ice surface at the low altitude region. Figure 6 shows that a large supraglacial lake, which is at 3,280 m a.s.l., had broken in July 2005 and the drained lake became a large pit on the glacier. Water volume drained from this lake reached 4.75×10^5 m^3, equal to 1 day's average runoff volume from Keqikaer Glacier in early June.

From the data provided above, it can easily be seen that the average decrement of the ice thickness has exceed 10% on the three profiles since 1981, but shrinkage of the glacier terminus is less than 2% of the total length since the 1980s. By means of this simple estimation, the total decrement of the volume in the ablation area of Keqikaer Glacier has reached 0.33 km^3 since 1981, which provides about 0.16×10^8 m^3 melt water additionally to Atuoyilake River every year and accounts for 11% of the annual runoff volume. Loss of the thickness provided 95% of the total volume but the shrinkage of the terminus provided only 5%. It followed that thinning of the ice tongue is more important than the retreat of the terminus for Keqikaer Glacier.

Keqikaer Glacier is a relative steady glacier in this area

It is well known that mountain glaciers are widely recognized as excellent indicators of climate change over

Fig. 6 Photographs of the supraglacial Lake, which locates at 3,280 m a.s.l on Keqikaer glacier, in **a** July 2004; **b** September 2005

the recent centuries (Haeberli 1995; IPCC 2001). Most of the glaciers in the world show a decreasing trend over the twentieth century, and substantial and statistically significant change started in 1988, which can be considered as a shift in glacier regime at the global scale with no delay to a new mode of global climate (Dyurgerov 2003). Change of Keqikaer Glacier is synchronous to this trend. However, retreat of Keqikaer Glacier is obviously smaller than that of some other glaciers in Mt. Tuomuer area. For example, Qiongtailan Glacier, which also is at the south slope of Mt. Tuomuer, has retreated 1.3 km since LIA and has been retreating since 1942 with a speed of 17 m a^{-1} (Su et al. 1985; Liu and Xie 1998). Yishitalage Glacier, which is the second large glacier in Atoyilake River basin, has retreated 0.9 km since 1976 with a retreat rate of 30 m per year; and so on. Research indicated that smaller glaciers are more sensitive to climate warming than large ones, and their relative changes are greater than that of larger glaciers (Ye et al. 2001). Those small glaciers in this area have shrunk much since the 1980s, the Laisu Glacier, left of Keqikaer Glacier (Fig. 1), has retreated 0.6 km since 1976 and the area has decreased by 10%. Some small circus glaciers had disappeared during the last 30 years. Therefore, it can be determined that Keqikaer Glacier is a relative steady glacier in this area. The significant information given by the retreat of terminus and thinning of ice thickness is that these glaciers at the south slope of Mt. Tuomuer are in intensive decreasing phase in recent time, and this signal is more remarkable than the retreat itself.

Summary

Results of this paper indicated that Keqikaer Glacier has been in intensive retreat since 1990, and in spite of the thick debris covers on the ice surface at the low altitude region, the ice tongue still becomes more thinning during the last 30 years. Thickness of the ice tongue has been reducing at a speed of 0.5–1.5 m a^{-1} since 1981. Supraglacial lakes and diversiform glacial thermal karsts of all shapes have contributed much to the loss of the ice volume in the debris-covered area. The shrinkage of the glacier terminus is less than 2% of the total length, which is less than some other large glaciers in this area. Keqikaer Glacier is a relatively steady glacier in this area. The significant information given by the retreat of the terminus and the thinning of the ice thickness is that these glaciers on the south slope of Mt. Tuomuer are in intensive decreasing phase in recent time.

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