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Current State of Glacier Changes, Glacial Lakes, and Outburst Floods in the Ile Ala-Tau and Kungöy Ala-Too Ranges, Northern Tien Shan Mountains

天山山脈北部地域，イリ・アラタウとクンゴイ・アラトー山脈における氷河変動，氷河湖，氷河湖決壊洪水の現状

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Key words：glacier shrinkage, glacial lake, glacial lake outburst food（GLOF）, past GLOF, the northern Tien Shan, ALOS, Corona
キーワード：氷河縮小，氷河湖，氷河湖決壊洪水，過去の氷河湖決壊洪水，天山山脈北部，ALOS，Corona

要旨

天山山脈北部地域のイリ・アラタウとクンゴイ・アラトー山脈を対象に，Corona（KH-4B），Hexagon（KH-9），ALOS（PRISM，AVNIR-2）の衛星データを用いて，最近の氷河の面積変化，氷河湖の分布とその特徴を明らかにした。この山岳地域には760以上（約570 km^2）の小規模な山岳氷河が分布しており，これらの氷河は1971～2007年の36年間で15%の面積を消滅した。この急速な氷河縮小にともない，現在の氷河前面には約320の小規模な氷河湖（0.0001～0.2 km^2）が発達している。この地域でみられる氷河湖のタイプは，氷河前面に広がるデブリ帯に形成されたサーモカルスト湖や融氷水湖，あるいは氷河と接するモレーンダム湖である。現在観察できる氷河湖のほとんどは1980年代以降に出現しており，氷河縮小が大きい場所で氷河湖の出現率が高い傾向にある。イリ・アラタウ山脈北面において1970年代に大規模な氷河湖決壊洪水（GLOF）を発生させた氷河湖の面積は0.01～0.05km^2であった。この面積はヒマラヤに比べるとかなり小規模であるが，数名の犠牲者と家屋や道路などの建設物に被害がでている。現在，この面積の氷河湖の数は決壊が集中した1970年代と同数に達しており，決壊する危険性の高い氷河湖が存在しはじめている。

Ⅰ. Introduction

In extensively glacierized areas such as the Andes and Himalayas, glacier hazards such as glacial lake outburst floods（GLOFs）and glacier-ice avalanches have caused serious downstream damage. For example, a combined ice-rock avalanche and debris flow in 1962 and 1970 caused ～19,000 causalties in the Huascaran region of Peru（e.g., Carey, 2008）. In the Nepal Himalaya, a GLOF from the Dig Tsho glacier lake destroyed a hydroelectric power station and 14 bridges in 1985（Ives, 1986）. Himalayan glacial lakes, which have been growing from the 1950s to 1970s（Ageta et al., 2000; ICIMOD, 2007）, present a threat to local human populations. In the Tien Shan Mountains of Central Asia, several GLOFs occurred from the 1950s to 1970s（e.g., Kubrushko and Staviskiy, 1978; Kubrushko and Shatrabin, 1982）. According to several reports, these glacial lakes from which the GLOFs occurred were quite small-scale in area, compared to the Himalayas. However, the GLOFs in the Tien Shan had caused both casualties and infrastructure damage downstream（Baimoldaev and Vinohodov, 2007）.

In the Tien Shan, the more recent behavior of glaciers indicates an overall shrinkage in area（Aizen et al., 2006; Narama et al., 2006; Bolch, 2007; Niederer et al., 2007）. As a result of this glacier melting,

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present lakes may develop rapidly at glacier fronts. However, the current status of glacial lakes is poorly known for this region. This paper reports on the present condition of glaciers and glacial lakes, and the past incidence of GLOFs in the Ile Ala-Tau (Zailiyskiy Alatau) and Kungöy Ala-Too ranges of the northern Tien Shan.

Ⅱ. Study area

The study area is the Ile Ala-Tau and Kungöy Ala-Too ranges in the northern Tien Shan, where more than 760 glaciers occupy a large surface area (~570 km^2; Fig. 1). Most of the glaciers here are large-scale (>1 km^2), relative to those in other regions such as the Talas and Kyrgyz Ala-Too ranges. In this region, maximum precipitation occurs in June to August. The mountain ranges are about 4,000 m a.s.l. with a west-east trend. The geomorphological characteristics combine to form complicated local climate. Annual precipitation for 1981-1990 is highest in the central part of both ranges (e.g., Tuyuksu (Central Tuyuksuiskiy) Glacier: 901 mm; 3,450 m a.s.l.; Fig. 1). On the north flank of the Ile Ala-Tau range, moisture supplied from the Kazakh plain increased eastward (e.g., Kaskelen: 585 mm, 1,137 m a.s.l.; Talgar: 747 mm, 1,015 m a.s.l.; Issyk: 677 mm, 1,095 m a.s.l.). The eastern part of the southern flank of the Kungöy Ala-Too range is affected by vapor from Ysyk-Köl lake (e.g., Cholpon-Ata: 307 mm, 1,645 m a.s.l.; Kyrchyn: 625 mm, 2,100 m a.s.l.; and San-Tash: 850 mm, 2,236 m a.s.l.). Annual precipitation at Shabdan (455 mm, 1,520 m a.s.l.), located in Chong-Kemin valley, is comparatively low.

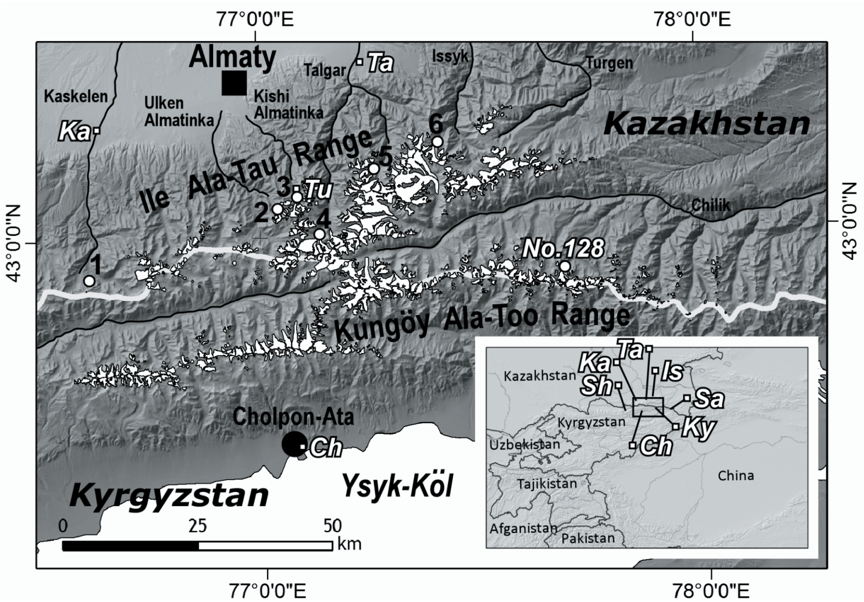

Fig. 1. Study area in the Ile Ala-Tau and Kungöy Ala-Too ranges in the northern Tien Shan. White circles and number (1-6) indicate locations of GLOFs in the 1970s in Table 1. Locations 3 and 1 show the glacial lakes in Figs. 7 and 8. №128 glacier shows the location of glacier in Fig. 5. Locations of meteorological stations; Ka: Kaskelen, Tu: Tuyuksu, Ta: Talgar, Ch: Cholpon-Ata, Sh: Shabdan, Is: Issyk, Ky: Kyrchyn, Sa: San-Tash.

Ⅲ. Satellite image processing and GLOF data

The area and distribution of present glaciers and glacial lakes were clarified using Panchromatic

Remote-Sensing Instrument for Stereo Mapping (PRISM) and Advanced Visible and Near-Infrared Radiometer type 2 (AVNIR-2) satellite data from the Advanced Land Observing Satellite (ALOS) for 16 August 2006 and 17 September 2007. The PRISM sensor includes nadir, forward, and backward sensors and generates a stereoscopic data set 35×35 ㎞ (triplet mode) and 70×35 ㎞ (nadir only) in width with a spatial resolution of 2.5 m (JAXA, 2009). The AVNIR-2 image has four bands collected by a visible to near-infrared radiometer with spatial resolution of 10 m. Distribution of glaciers and glacial lakes in the 1970s was extracted using Corona KH-4B images (spatial resolution 1.8 m) for 17 and 23 September 1971. Glacial lake area after GLOFs in the 1970s was extracted using Hexagon KH-9 (spatial resolution 6-9 m) for 7 September 1980. Recent changes in glacial lake area (glacier No. 128) in the Kara-Say river drainage on the northern flank of the Kungöy Ala-Too range was investigated using Hexagon KH-9, Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and ALOS (PRISM/ AVNIR-2) satellite data for 7 September 1980, 29 October 1991, 8 August 1999, 3 October 2002, 21 June 2005, 17 September 2007, and 01 September 2008.

Orthoprojection of the satellite data was generated using ground control points (GCPs) from 1:50,000 topographic maps (reference data) and Shuttle Radar Topography Mission (SRTM) 3 data using PCI Geomatica version 10.1 software. Orthorectification resulted in a root mean square error (RMSE) of less than 30 m for satellite data. Glaciers (>0.01 km^2) and glacial lakes (>0.0001 km^2) outlines were extracted in detail manually using ArcGIS 9.2. Pro-glacial lakes with areas >0.0001 km^2 in debris-covered dead-ice zones were enumerated.

Past GLOFs on the northern flank of the Ile Ala-Tau range were identified using GLOF reports (Tokmagambetov et al., 1982; Mochalov and Stepanov, 1986; Baimoldaev and Vinohodov, 2007; Yegorov, 2007). The locations and lake-area changes of GLOF events in the 1970s were rechecked using Corona KH-4B (1971) and Hexagon KH-9 (1980) satellite data.

Ⅳ. Results

1. Recent glacier shrinkage in the Ile Ala-Tau and Kungöy Ala-Too ranges

More than 760 glaciers (∼570 km^2) are present in the Ile Ala-Tau and Kungöy Ala-Too ranges. Small-scale glaciers (<1 km^2) represent only 27% of the total glacier area of all classes in the study area (Fig. 2). Glacier polygon data from Corona KH-4B data taken in 1971 and ALOS PRISM data taken during 2006 and 2007 indicate that glacier coverage has decreased by ∼15% over a span of 36 years (1971-2007). The glacier reduction differed greatly among the eight locations in the Ile Ala-Tau and Kungöy Ala-Too ranges (Fig. 3). Glacier shrinkage was particularly significant at sites 1, 6, 7, and 8 (19-20%) and comparatively low

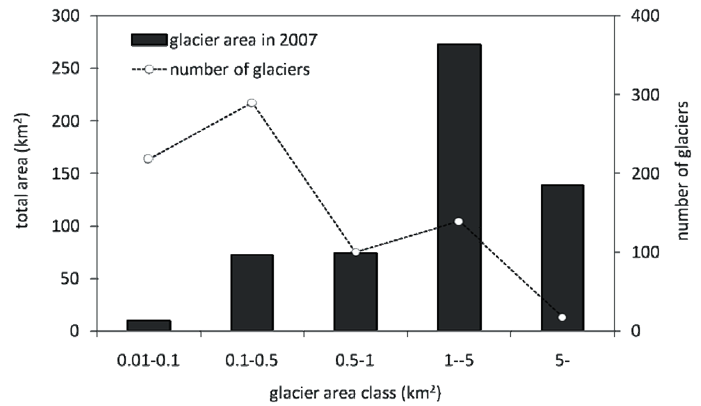

Fig. 2. Glacier area and number, by the glacier size class in ∼2007 in the Ile Ala-Tau and Kungöy Ala-Too ranges.

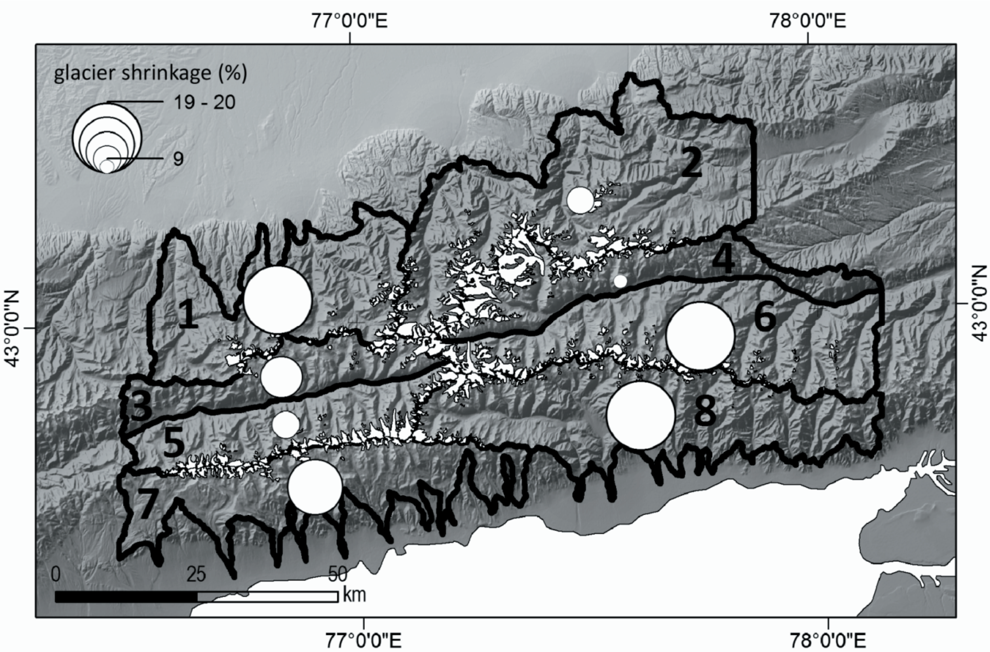

Fig. 3. Glacier shrinkage from 1971 to ~2007 at eight locations in the Ile Ala-Tau and Kungöy Ala-Too ranges.

at site 4 (9%). As a reason of the small glacier shrinkage at site 4, in addition to a number of micro-climatic and glaciological factors involved (Kuhn, 1995), site 4 has many large-scale glaciers which relative changes are small for geometric reasons. Fifteen percent (1971-2007) of the total glacier shrinkage is large compared to glacier loss of 8% (1971-2002) in the Teskey Ala-Too range (Narama et al., 2006) and 9% (1977-2003) in the Ak-Shiyrak range (Aizen et al., 2006). Regional glacier coverage for the Ile Ala-Tau and Kungöy Ala-Too ranges diminished (16-38%) from 1955 to 2000 (Bolch, 2007). The rate of glacier loss for 1975-1990 was faster than that for 1955-1975 (Severskiy et al., 2006). Ongoing glacier reduction is a trend that has persisted since 1955.

2. Distribution of glacial lakes in 1970 and 2007

Glacial lakes documented in this region are either "moraine-dammed lakes" or "supra-dead-ice lakes". Moraine-dammed lakes are glacial lakes which dammed meltwater by small-scale terminal moraine, and contacted to present glacier ice. Supra-dead-ice lakes include thermokarst lakes and glacier meltwater pooling lakes, which developed on the debris-covered dead-ice zone at the glacier front, and separated from glaciers completely. Both lake types have a significant potential to cause GLOFs, because terminal moraines and debris-covered zones, including their dead-ice cores, are susceptible to melting under atmospheric warming. In addition, the lakes themselves promote further glacier melting and quickly grow large as a result of thermal convection (Ben et al., 2000; Sakai et al., 2000; Kääb and Haeberli, 2001). Glacier-dammed lakes such as Merzbacher Lake in the Sary-Jaz region (Mayer et al., 2008) were not found in the study area.

The status of glacial lakes (>0.0001 km^2) in the Ile Ala-Tau and Kungöy Ala-Too ranges was assessed for ~270 lakes in 1971 and ~320 lakes in ~2007. Figure 4 shows the distribution of glacial lakes (>0.005 km^2) in ~2007 at eight locations. Sites 1, 2, and 6 have a remarkable number of glacial

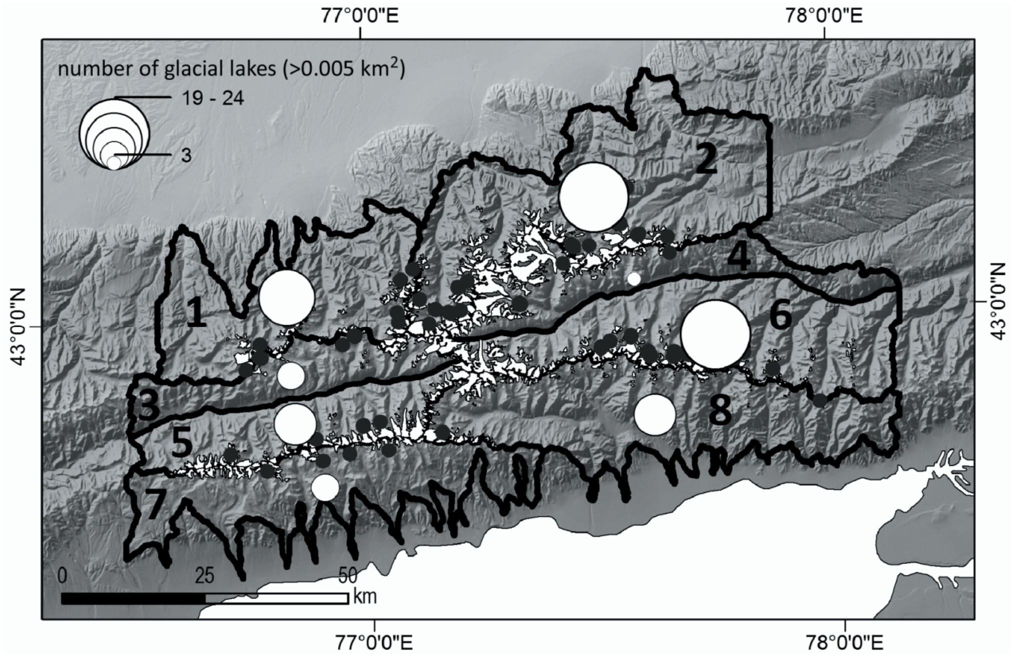

Fig. 4 . The number of glacial lakes (>0.005 ㎢) in ~2007 for eight study locations, small circle: distribution of glacial lakes (>0.01 ㎢).

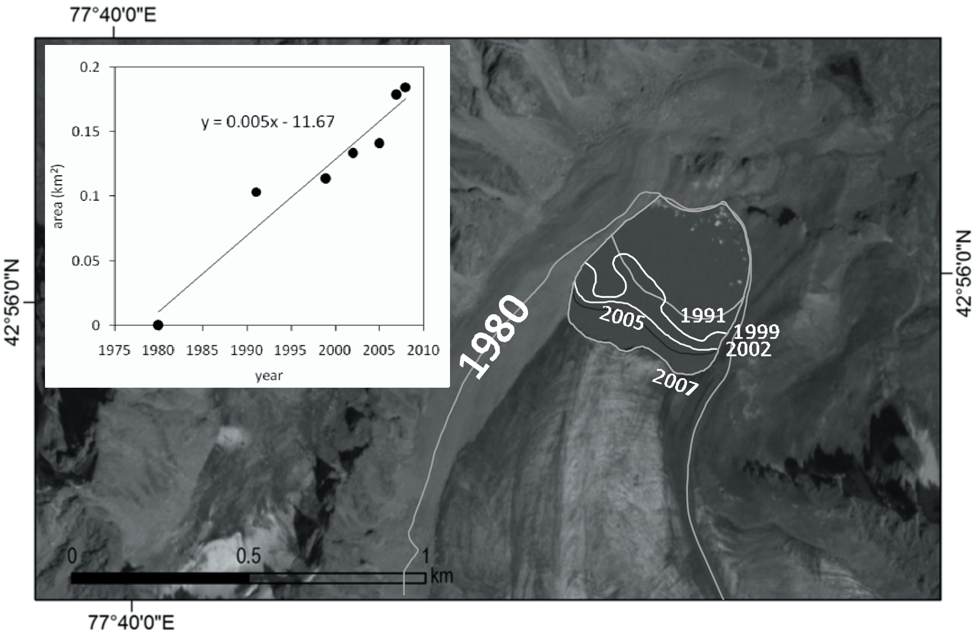

Fig. 5 . Area change since 1980 of a lake associated with No.128 glacier of the Kara-Say river. Recent changes of this glacial lake were investigated using the following images: Hexagon KH-9, Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and ALOS (PRISM/ AVNIR-2) data.

lakes. In contrast, locations on the southern flank of the ranges have few lakes. The number of glacial lakes and the extent of glacier shrinkage (Fig. 3) do not co-vary. The glacial lake (>0.1 km^2) that exhibited the greatest expansion is located upstream of the Kara-Say river on the northern flank of the Kungöy Ala-Too range (Figs. 1 and 5). This glacial lake, which was not present in Corona (KH-4B) and Hexagon (KH-9) images taken in 1971 and 1980 has expanded in the same speed (0.0059 km^2/year) since 1980 (Fig. 5). This expansion speed is quite small, compared to 0.015-0.03 km^2/year of the Himalayan lakes (Ageta et al., 2000; Komori et al., 2004).

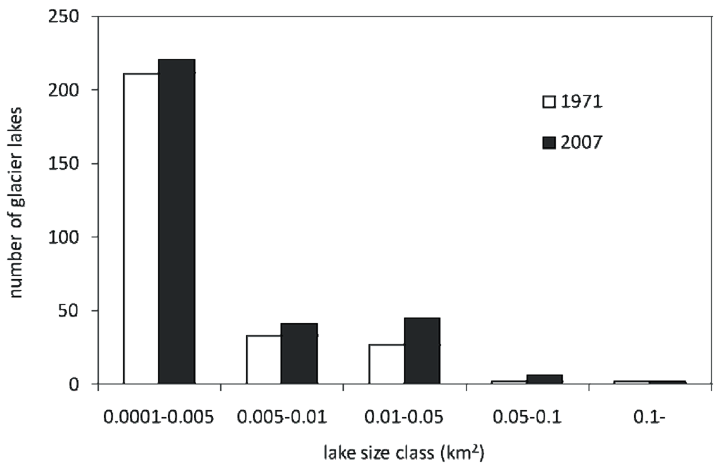

Fig. 6. The number of glacial lakes in each area according to size class in 1971 and 2007.

Glacial lakes were divided into five size classes (0.0001-0.005 km^2, 0.005-0.01 km^2, 0.01-0.05 km^2, 0.05-0.1 km^2, >0.1 km^2) based on Corona photographs (KH4-B) taken in 1971 and ALOS data (PRISM) for 2006-2007 (Fig. 6). The number of glacial lakes in each size class was approximately the same in 1971 and 2007. The small-scale lakes (0.0001-0.005 km^2) represented >70% of the lakes in both 1971 and 2007. These results highlight the dominance of the small-scale lakes in this region. In contrast, the number of the large glacial lakes (>0.1 km^2) is two in the present. In this region, 83% of the present-day glacial lakes have appeared since the 1980s.

3. Past GLOFs in the 1970s-1980s

Records from the northern flank of the Ile Ala-Tau range show that catastrophic GLOFs occurred at four glacial lakes in the 1970s-1980s (Table 1). Some lakes exhibited repeated large GLOFs over

Table1. Past GLOFs of the 1970s-1980s in the northern flank of the Ile Ala-Tau range. 'date': year-month-day. Data source: GLOF data: Tokmagambetov et al., 1982, Mochalov and Stepanov (1986), Yegorov (2007); area in 1971 and 1980: this study; runoff and volume: Mochalov and Stepanov (1986), Baimoldaev and Vinohodov (2007).

location (fig. 1)	valley	river	glacier No.	date	area (km^2) in 1971	area (km^2) in 1980	runoff (m^3/s)	volume (m^3)	GLOF degree
4	Talgar	Leviy Talgar	151	1970-07-14					large
4	Talgar	Leviy Talgar	151	1971-07-12					large
3	Kishi Almatinka	Kishi Almatinka	Tuyuksu (127)	1973-07-15	0.0417	0.0126	350,000	224,000	catastrophic
5	Talgar	Srednii Talgar	182	1974-07-22					large
5	Talgar	Srednii Talgar	182	1974-08-02					large
2	Ulken Almatinka	Kumbelisu	Sovetov (117)	1975-08-19					catastrophic
6	Issyk	Zharsai	Zharsai (205)	1977-07-03					large
2	Ulken Almatinka	Kumbelisu	Sovetov (117)	1977-08-03	0.0410	0.0212	30,000	74,000	catastrophic
1	Kaskelen	Kaskelen	35	1980-07-23	0.0428	0.0088	30,000	220,000	catastrophic

a brief time span. Most GLOFs in the 1970s occurred in July and August when rapid glacier melting and high precipitation occur. As reports of GLOFs, the main factors controlling GLOFs in this region were melting and collapse of dead-ice cores within terminal moraines, or headward erosion of moraines by meltwater (Kubrushko and Staviskiy, 1978; Baimoldaev and Vinohodov, 2007). These lake sizes of catastrophic GLOFs concentrated 0.01-0.05 km^2 in size. The size changes of four glacial lakes that experienced catastrophic GLOFs in the 1970s were investigated using Corona KH-4B (1971) and KH-9 (1980) satellite photographs.

(1) The Tuyuksu glacier lake flood on 15 July 1973

The Tuyuksu glacier lakes experienced a GLOF on 15 July 1973 (Fig. 1 - locations 3 and 7; Table 1), which resulted in 10 casualties and serious structural damage (Baimoldaev and Vinohodov, 2007). As reported in the previous studies (Medeuov and Nurlanov, 1996; Baimoldaev and Vinohodov, 2007), the collapse of lake No.2 resulted in a GLOF that drained ~224,000 m^3 of water from two lakes combined (lakes No.2 and No.3), and the flood continued to discharge for two hours. The GLOF reached the Mynzhylki dam after four minutes of the collapse and the Medeu dam after 21 minutes (Baimoldaev and Vinohodov, 2007). The second flood occurred on 16 July 1973, 400,000~536,000 m^3 of water and sediments flowed into water reservoir for 24 hours. The lake volume was changed from 20,000 m^3 in 1951, 32,000 m^3 in 1956 to 260,000 m^3 in 1973, indicating the glacial lake had developed rapidly in the 1960s. In addition, at the Tuyuksu glacier meteorological station (3,450 m), high precipitation in June (234.1 ㎜; average 164.4 ㎜ for 1972-2007) and high temperature in July caused a rapid rise in lake levels.

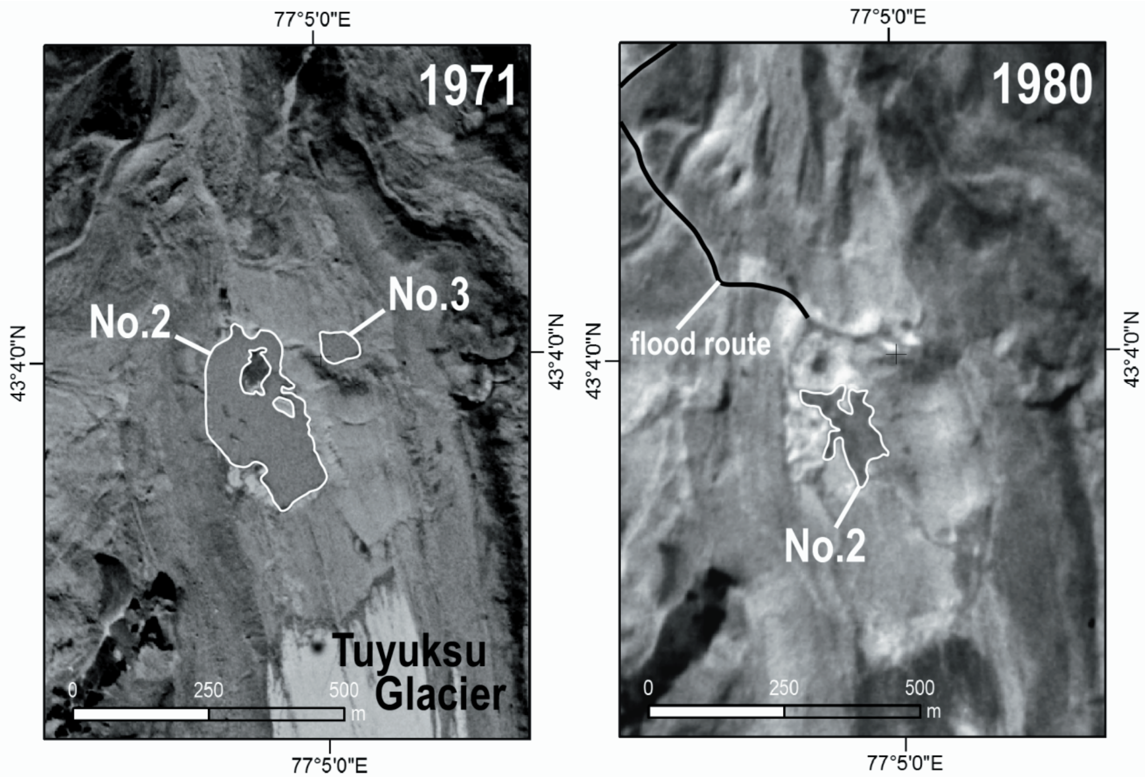

Fig. 7. Satellite images of Tuyuksu glacier lake for 1971 (KH-4B) and 1980 (KH-9). A GLOF occurred on 15 July 1973.

Analysis of satellite data shows that the total area occupied by lakes No.2 and No.3 on 23 September 1971 was 0.0417 km^2 (Fig. 7; Table1). This area had been reduced to 0.0126 km^2 on 7 September 1980, as a result of the loss of 0.0291 km^2 during the collapse of lake No.2-3. According to DEM created from ASTER images on 5 and 30 September 2001, water depth of the Tuyuksu glacier lake No.2 was 10-15 m. These lakes were shallow lakes, which dammed meltwater by the moraine (Photo 1).

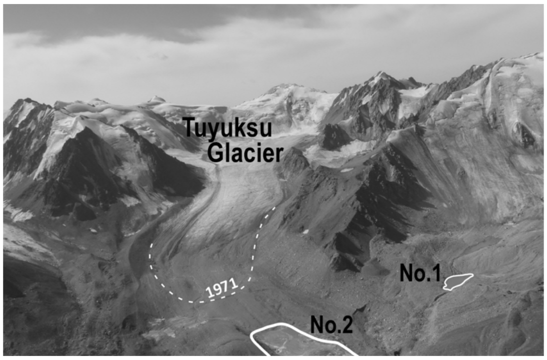

Photo 1. Frontal area of Tuyuksu glacier (Photo: V.N. Vinokhodov, 22 Aug 2006).

(2) GLOF of the Kaskelen river on 23 July 1980

The glacial lake at No.35 glacier front in the Kaskelen river (Fig. 1 - locations 1 and 8 ; Table 1) experienced a GLOF on 23 July 1980, in which ~220,000 m^3 was discharged (Mochalov and Stepanov, 1986). The total lake area was 0.0428 km^2 in the Corona photograph of 23 September 1971, but had decreased to 0.0088 km^2 by 7 September 1980. The outflow of the glacial lake crossed a debris-covered dead-ice zone. No.35 glacier is a hanging glacier on a steep bedrock slope (Photos 2 and 3). The collapsed lake had developed on the debris-covered dead-ice zone and had separated from the glacier completely. This situation demonstrates that GLOFs from moraine-dammed lakes and from thermokarst lakes can produce similar scales of damage.

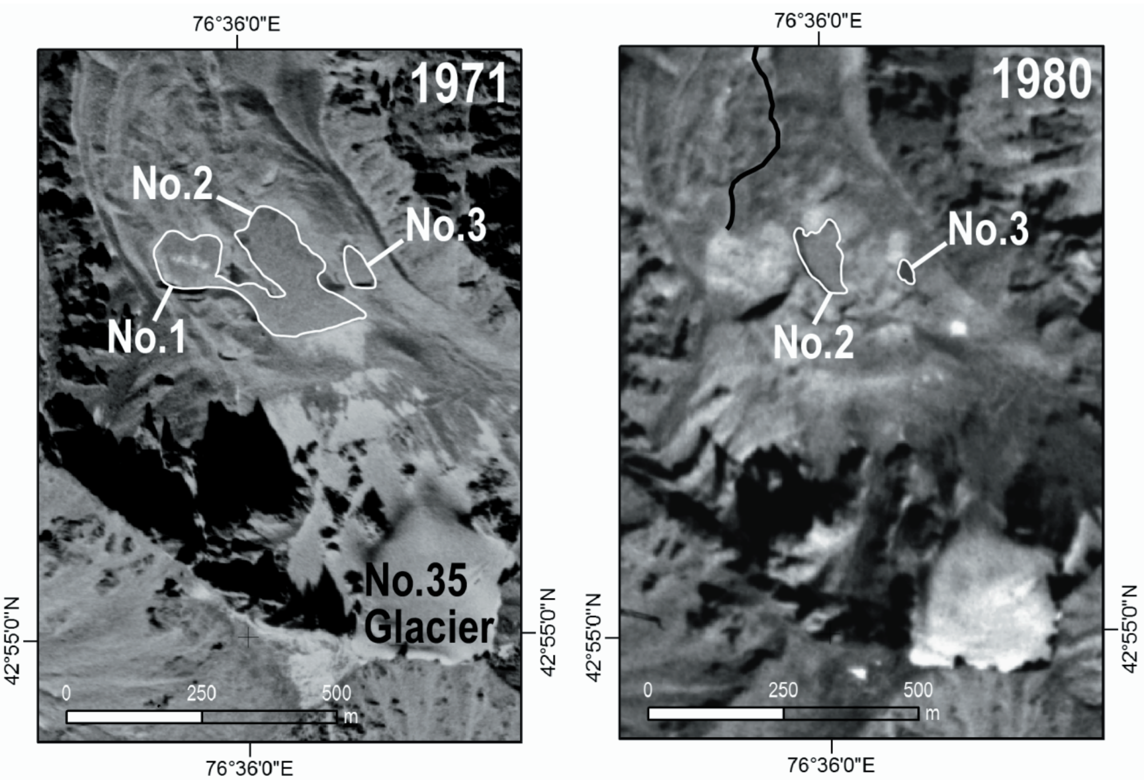

Fig. 8. Satellite images of the glacial lake associated with No.35 glacier for 1971 (KH-4B) and 1980 (KH-9). A GLOF occurred on 23 July 1980.

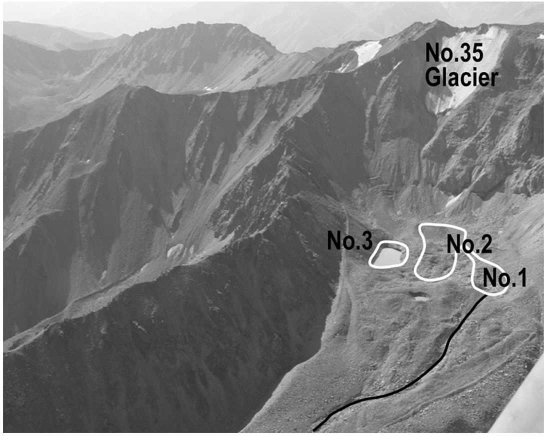

Photo 2. Frontal area of glacier #35 (Photo: V.N. Vinokhodov, 22 Aug 2006).

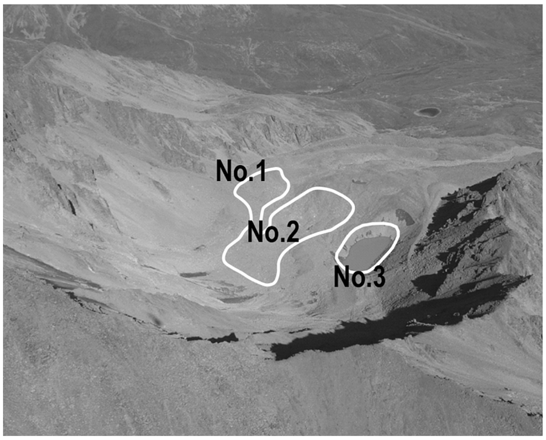

Photo 3. Frontal area of glacier #35 (Photo: V.N. Vinokhodov, 22 Aug 2006).

V. Discussion: Characteristics of glacial lakes

The number of glacial lakes at the eight study locations in ~2007 is not coincided with glacier shrinkage (Figs. 3 and 4). However, the relationship between glacier size reduction and appearance ratio (the number of glacial lakes / the number of glaciers; Fig. 9) indicates that the development of glacial lakes related with glacier shrinkage. Especially, sites 1, 2, and 6 at which the development of the glacial lakes is remarkable are high crowd zone of glacial lakes in this region. Glacial lakes responsible for catastrophic GLOFs in the 1970s were predominantly in the 0.01–0.05 km^2 size range (Table 1). At present, the number of glacial lakes in this size range has reached the number found in the 1970s, indicating a high risk of GLOFs today (Fig. 6). Sites 2 and 6, which have many lakes in the >0.01 km^2 size, are most likely to be a highly dangerous zone of GLOFs in this region (Fig. 4).

Water volume of GLOFs in the 1970s is small compared to typical Himalayan GLOFs, because the moraines that dam up meltwater in this region are small, having formed during glacier retreat since the 1900s. As a result of these recent formations, many moraines contain dead-ice cores and are very unstable under conditions of atmosphere warming. In contrast, glacial lake moraines elsewhere in the Himalaya are huge, having formed during the Little Ice Age and late Holocene (Iwata et al., 2002). Many glacial lakes are shallow (10–15 m) in this

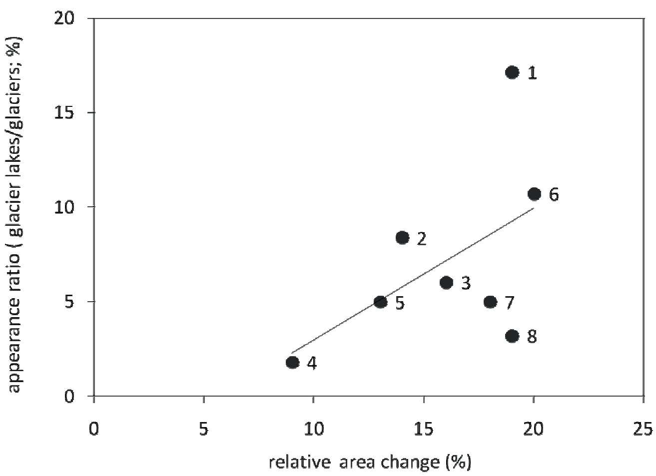

Fig. 9. Relationship between the glacier shrinkage and the appearance ratio in glacial lake for eight location sites.

region (Kubrushko and Staviskiy, 1978); clearly, size of a moraine-dammed lake and lake depth are a function of moraine scale related to glacier expansion. The study area has moraine-dammed lake type and supra-dead-ice lake type (such as thermokarst lakes or meltwater pooling lakes) on debris-covered dead-ice zones. Melting and collapse of dead-ice cores inside terminal moraines and debris-covered zones have increased the occurrence of GLOFs. In addition, the lower limit of the alpine permafrost on the northern flank of the Ile Ala-Tau range has risen in recent decades (Marchenko et al., 2007). The GLOF of supra-dead-ice lakes in the Kaskelen river in 1980 discharged large water volume (Fig. 8), showing that moraine-dammed lakes and supra-dead-ice lakes can be equally destructive. These GLOF events of the 1970s caused casualties and infrastructure (house, road, bridge, and water reservoir) damages downstream in this region (Baimoldaev and Vinohodov, 2007), indicating that the GLOF damages of small-scale glacial lakes are not necessarily small in this region.

Although artificial lakes and barriers to prevent debris flows have been constructed to lessen the potential effects of GLOFs along the northern flank of the Ile Ala-Tau range (Baimoldaev and Vinohodov, 2007), tourists and transhumance herders are numerous in the regions downstream of glacial lakes in this area. Measures to predict and prevent GLOFs are required.

Ⅵ. Conclusions

In the Ile Ala-Tau-Too and Kungöy Ala-Too ranges, approximately 320 small and shallow glacial lakes (0.0001-0.2 km^2) are now present as a result of glacier shrinkage since the 1970s-1980s. Such lakes are especially abundant on the northern flank of the Ile Ala-Tau range and the northern flank of the eastern Kungöy Ala-Too range. Most glacial lakes are moraine-dammed lakes and supra-dead-ice lakes (including thermokarst lakes and meltwater pooling lakes) on debris-covered dead-ice zones at glacier fronts. These lakes are unstable, associated melting of dead-ice core inside terminal moraine and debris-covered zone. Catastrophic GLOFs associated with lakes 0.01-0.05 km^2 in size occurred in the 1970s, when the number of glacial lakes in the region was approximately the same as that found today. In view of this, some glacial lakes in the area may pose a GLOF risk.

Acknowledgments

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