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LETTER

Distribution and interannual variability of supraglacial lakes on debris-covered glaciers in the Khan Tengri-Tumor Mountains, Central Asia

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Abstract

Supraglacial lakes are widely formed on debris-covered glaciers in the Khan Tengri-Tumor Mountains (KTTM), Tianshan, Central Asia. Study of their distribution characters based on regional-wide remote sensing investigations is still lacking, but it can promote our understanding about the influence of supraglacial lakes on the surface melting, hydrology and dynamics of debris-covered glaciers in this region. This study presents results of the supraglacial lake inventory in the KTTM region, based on multi-year Landsat images. We focus on the glacio-geomorphological characters of the supraglacial lakes and their late summer conditions, since all suitable Landsat images were acquired between August and September during 1990–2011. With a minimum threshold extent of 3600 m^2 for conservative mapping results, we totally mapped 775 supraglacial lakes and 38 marginal glacial lakes on eight huge debris-covered glaciers. Supraglacial lakes are concentrated on the Tumor Glacier and the South Inylchek Glacier, two biggest glaciers in this region. Although most supraglacial lakes are short-lived, a number of lakes can be repeatedly identified between different Landsat images. Detailed investigation of these 'perennial' lakes on the Tumor Glacier indicates that their filling frequency and area contributions have increased since 2005. Analysis of the area-elevation distributions for all mapped supraglacial lakes shows that they predominantly occur close to the altitude of 3250 m a.s.l., as high as the lowest reach of clean ice where surface debris begins to appear, and can further develop upglacier to a limit of about 3950 m a.s.l.. Total and mean area of supraglacial lakes in the KTTM region during the late summer seasons show great variability between years. Correlation analysis between the annual lake area and the observed nearby meteorological conditions suggests that warmer springs seem related to the draining of some supraglacial lakes during the following seasons, due to the evolution of glacial drainage from unconnected to connected systems by enhanced ablation during the springs.

1. Introduction

Supraglacial lakes are commonly found in the lower ablation region of some debris-covered valley glaciers, where glacier ice stagnates (Reynolds 2000, Benn *et al* 2012). Many studies have highlighted the temporal evolution of glacial lakes in the central Himalaya and indicated that most of the current big moraine-dammed or ice-dammed lakes are the consequences of coalescence and growth of supraglacial lakes (Sakai *et al* 2000, Komori 2008, Fujita *et al* 2009, Benn *et al* 2012, Thompson *et al* 2012). These glacial lakes pose a potential for glacial lake outburst floods (GLOFs) and destruction of property and loss of human life in the area downstream (Reynolds 2000, Richardson and Reynolds 2000, Bajracharya *et al* 2007, Jain *et al* 2012). Their existence also enhances ice ablation rates by ice margin calving processes around lakes (Sakai *et al* 1998, Sakai *et al* 2000, Benn *et al* 2012). Therefore, investigating the conditions of the supraglacial lakes formation and distribution will be a significant contribution to tracing their dynamics and the prediction of their future development (Bolch *et al* 2008).

Although direct observations of supraglacial ponds and lakes (Benn *et al* 2000) are still limited, remote sensing has been used to detect, measure and monitor their spatial and temporal changes in recent years (Wessels *et al* 2002, Box and Ski 2007, Gardelle *et al* 2011, Salerno *et al* 2012). However, supraglacial lakes on mountain glaciers are generally small and unstable, making tracing their variation difficult based on the middle-resolution satellites, e.g. Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper Plus (ETM+). In cold or wet seasons, mapping will also be influenced by snow cover, lake ice or cloud. However, it is possible to carry out an inventory of their status in one or two seasons, if there is a regular time window between years when the contamination of the satellite images by snow or cloud is at a minimum.

Few studies have systematically investigated supraglacial lakes considering their total area in a mountain region or on a specific glacier (Gardelle *et al* 2011, Salerno *et al* 2012). In the central Tianshan region, the physical conditions of some debris-covered glaciers enable the formation of different types of glacial lakes (Wang *et al* 2011, Wang *et al* 2013). Previous researches in the region have focused on the moraine dammed Petrov Lake (Jansky *et al* 2009, Jansky *et al* 2010) and the ice dammed Lake Merzbacher, which is famous for its regular outbursts at least once every summer that has led to remarkable floods in the downstream valley (Mayer *et al* 2008, Ng and Liu 2009, Glazirin 2010). However, the supraglacial lakes in this region were seldom reported based on scientific investigations, although they are widely distributed in the glacier ablation zone (Han *et al* 2010). To understand their distributions and temporal variations, we present our results of a regional inventory of supraglacial lakes on eight large debris-covered glaciers in the Khan Tengri-Tumor Mountains (KTTM), Central Asia. We focus on the spatial distribution and late summer conditions of these lakes during 1990 to 2011 and a further discussion emphasizes the formation conditions and consequent dynamics of these lakes.

2. Study area

The KTTM region is located in the center of Tianshan Mountains, crossing the Kyrgyzstan–China border (figure 1). There are more than 40 peaks exceeding 6000 m above sea level (a.s.l.) in the KTTM region, forming the largest glacierized complex in the Tianshan Mountains (Shi 2008). The Tumor (Pobeda) Peak (7439 m a.s.l.) and the Khan Tengri Peak (6995 m a.s.l.) are the highest peaks in the KTTM region. Climate here is characterized by warm summers with high precipitation rates, while winters are usually cold and dry, making the glaciers summer accumulation type (Aizen *et al* 1997). A striking glaciological feature in the KTTM region is the existence of many huge dendritic-form valley glaciers with thick debris covers (see photos of the Koxkar Glacier in the supplementary material, available at stacks.iop.org/ERL/10/014014/mmedia). These glaciers are often termed Tumor-type glaciers by Chinese glaciologists (Wang *et al* 1980). A glacier inventory shows that there are 1375 glaciers (509 in China) with a total area of 4093 km^2 in the KTTM region (Shi 2008). Meltwater from these glaciers forms the major source of rivers in the internal drainage basins in Central Asia, e.g., the Tarim basin and Balkhash basin, in which estimated glacial runoff accounts for 45–50% of the total surface discharge (Aizen *et al* 1997).

There are seven glaciers with areas larger than 100 km^2 in the KTTM region. An impressive characteristic of these glaciers is the extensive supraglacial debris mantle in their ablation zone (Han *et al* 2006, Hagg *et al* 2008). Rock falls together with avalanches are probably the main source of the supraglacial debris, which is transported downwards by ice flow and finally forms the medial or lateral moraine belts on the surface of the ablation area of the glaciers (Aizen *et al* 1997). Changes of the glacier surface elevation were not remarkable in this region during the past decades (Pieczonka *et al* 2013). Due to the ablation difference caused by the uneven thickness of debris mantle (Sakai and Fujita 2010), supraglacial lakes commonly form in the ablation area of these glaciers (Wang *et al* 2011, Wang *et al* 2013). In this study, we investigate supraglacial lakes on these seven debris-covered glaciers and, in addition, on another extensive debris-covered glacier (the Koxkar Glacier) in the KTTM region (figure 1). From 10 to 29 August 2010, a field investigation was carried out at the Koxkar Glacier, where a series of ablation measurements for different glacier surfaces (debris, ice cliffs and bare ice, etc) were performed and several supraglacial lakes were visited (Juen *et al* 2014).

3. Data and methods

We used the Landsat TM/ETM+ ortho-rectified images from 1990 to 2011 to map the supraglacial lakes. From the selected Landsat images (table S1 in the supplementary material), supraglacial lakes are easily identified on the eight glaciers in the KTTM region. The boundaries of these glaciers were manually adapted from the GLIMS dataset (Armstrong *et al* 2012), based on one sharp Landsat TM image

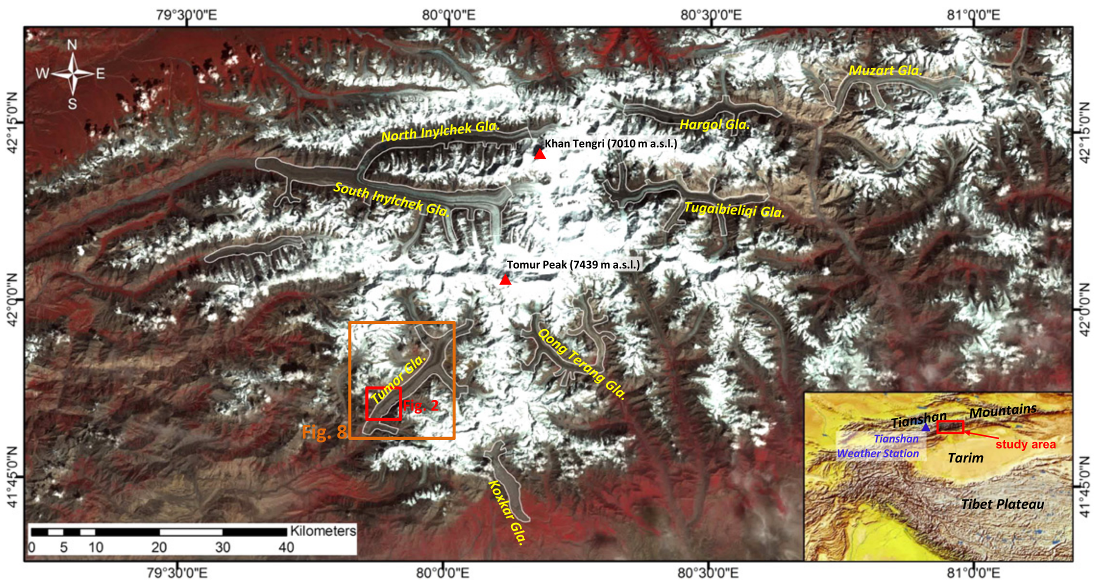

Figure 1. The eight investigated glaciers with their names marked and white polygons are used as the image mask in lake mapping. Background: Landsat TM acquired on 24 August 2007. Inset: location of the Khan Tengri-Tumor Mountains; blue triangle indicates the Tianshan Weather Station.

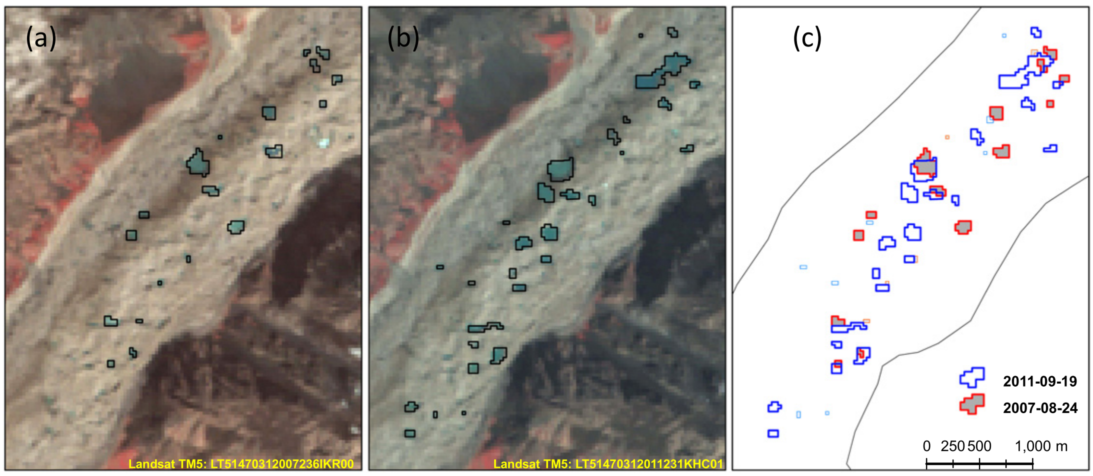

Figure 2. Examples showing the mapping of supraglacial lakes on the lower part of the Tumor Glacier (figure 1). Background: combination of band 432 for Landsat TM images. Note that some coalescences of supraglacial lakes can be seen.

acquired on 24 August 2007. The margins of the debris-covered part were visually delineated since the surface features of these big glaciers are distinct compared to other nearby lower landforms. Snow and clean ice (debris free) inside these modified glacier boundaries were mapped using previously widely used band ratio approach (e.g., Paul *et al* 2002, Paul and Andreassen 2009).

To map supraglacial lakes, we created a mask which includes all supraglacial lakes and marginal lakes (figure 1). Lake outlines were semi-automatically extracted from the masked Landsat images using the ENVI object-based Feature Extraction Module (IDL 2008; see supplementary methodological information). For most Landsat images used, the spatial resolution is about 30 m and therefore an area threshold of 3600 m^2 was set for the final mapping and the analysis of supraglacial lake distribution and changes (Wessels *et al* 2002, Gardelle *et al* 2011). The uncertainty in the measurement of the lake area was estimated by assuming an error of ±0.5 pixel on the outlines of the shape (Fujita *et al* 2009, Salerno *et al* 2012). Figure 2 shows examples for the supraglacial lakes mapping results, for a lower part of the Tumor Glacier (figure 1).

In order to exploit the geomorphological characteristics (hypsography) of the glaciers and supraglacial lakes, we applied the Shuttle Radar Topography Mission digital elevation model (SRTM DEM, see the supplementary material). Statistics on the area-elevation distributions (zones with 100 m altitude interval)

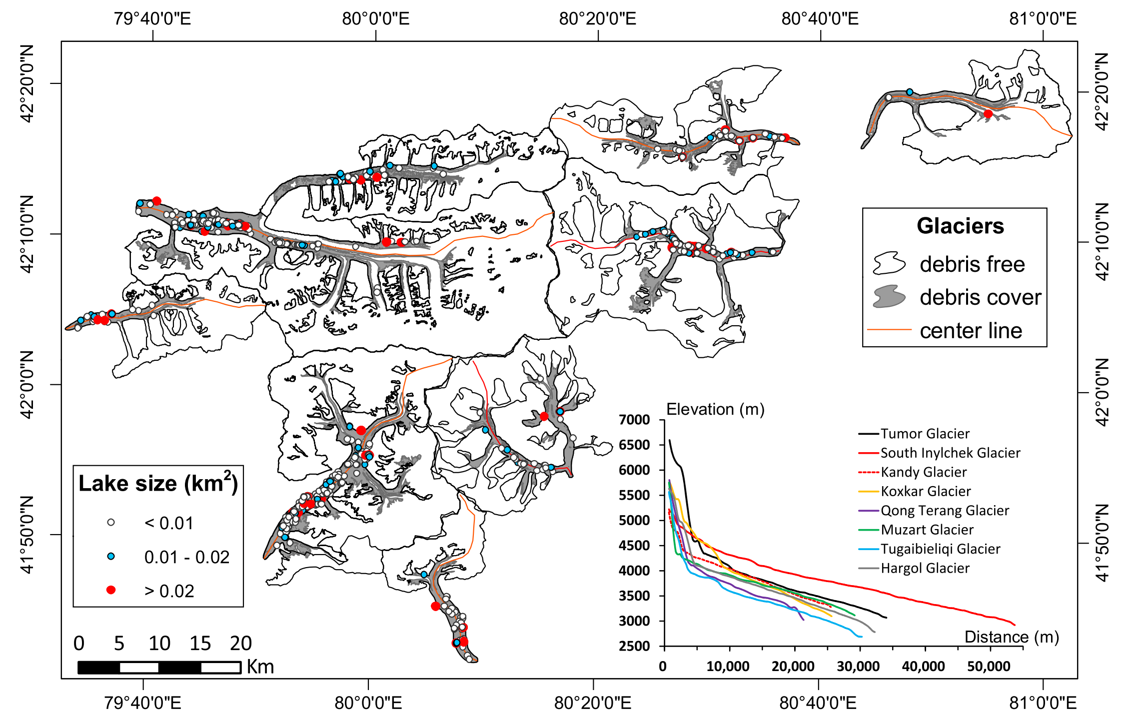

Figure 3. Distribution of all mapped supraglacial lakes on the eight glaciers over the inventory period 1990–2011 (with their sizes classified). Lower right inset: glacier surface profiles along their central flow lines (for glacier names see figure 1).

of glaciers and supraglacial lakes were based on the SRTM DEM.

4. Results

4.1. Glaciers and supraglacial lakes distribution

We mapped a total of 775 supraglacial lakes and 38 marginal lakes on the selected eight glaciers (see the supplementary material for their geomorphological characteristics). Figure 3 shows their distributions with lake sizes in three categories (<0.01 km^2, 0.01–0.02 km^2 and >0.02 km^2). Both the debris mantle, which occupies about 17.2% of the total glacier area, and supraglacial lakes are distributed in the lower part of the glaciers, where the surface slopes along their central flow lines are normally gentle. The majority of supraglacial lakes are located on the Tumor Glacier (TG) and the South Inylchek Glacier (SIG), the two largest glaciers in the KTTM region. Total area of supraglacial lakes on the TG and SIG occupies from 43.9% (in 1990) to 72.6% (in 2005) of all mapped lakes in the KTTM region. In addition to the TG and SIG, the Tugaibieliqi Glacier, Koxkar Glacier and Hargol Glacier are also found with many well developed supraglacial lakes (with total area larger than 0.1 km^2; see the supplementary material).

Figure 4 displays the altitudinal-area distributions of debris free, debris cover and supraglacial lakes in the whole KTTM, the TG and the SIG. Debris-free glacier surface mostly occurs above ∼4000 m a.s.l. (90.1%) and reach their maximum at ∼4750 m a.s.l. Debris-covered areas are mostly distributed below ∼4000 m a.s.l. (89.1%) and reach their maximum at ∼3750 m a.s.l. Supraglacial lakes (areas > 3600 m^2) can be found at as high as ∼3950 m a.s.l, ∼700 m lower than the upper extent of surface debris (∼4650 m a.s.l.). Most supraglacial lakes are concentrated at ∼3250 m a.s.l., as high as the lowest reach of clean ice where surface debris begins to appear.

4.2. Interannual variation of supraglacial lakes in late summer seasons of 1990–2011

Figure 5 shows the interannual variations of supraglacial lakes on the TG, the SIG and the whole KTTM during 1990–2011 (results are also shown in table S3 in the supplementary material). Supraglacial lake area in the whole KTTM region has not experienced a general trend of change but undergone substantial variability in both total and mean area. Over the investigation period, the total area of supraglacial lakes (figure 5(a)) varied between 0.628 ± 0.063 km^2 (in 2005) and 1.400 ± 0.224 km^2 (in 1990), with a mean value of 0.918 ± 0.149 km^2. The mean area of all investigated supraglacial lakes (figure 5(b)) varied between 0.007 ± 0.001 km^2 (for the SIG in 2005) and 0.018 ± 0.002 km^2 (for the TG in 2010). For both the KTTM region and the two glaciers, the averaged multi-year mean area of supraglacial lakes is close to the same value (0.010 ± 0.002 km^2, see supplementary material). The minimum mean area of supraglacial lakes also occurred in 2005 (0.008 ± 0.001 km^2), while the maximum mean area occurred in 1990 and then in 2010.

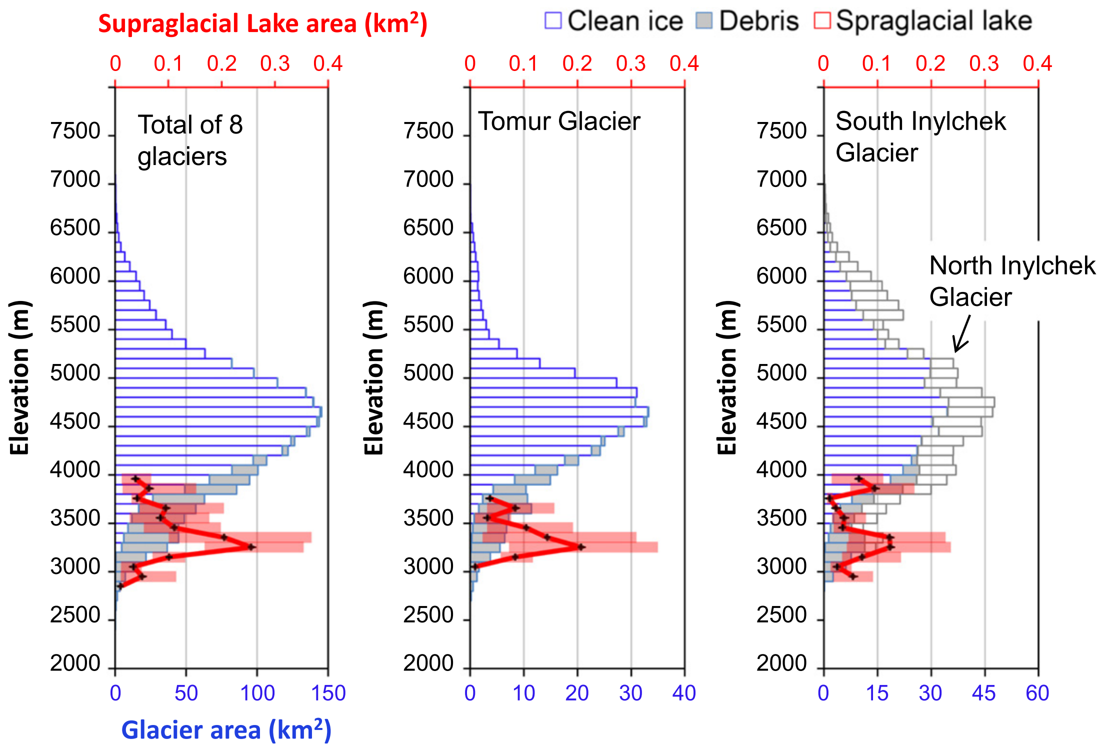

Figure 4. Altitudinal area distributions of the debris-free, debris-covered and mean supraglacial lakes in the KTTM region, with the Tomur Glacier and South Inylchek Glacier plotted independently. Bold red lines show the mean value and light red bars indicate the boundary of minimum and maximum lake areas over the inventory period 1990–2011 (for a year by year plots please see supplementary materials).

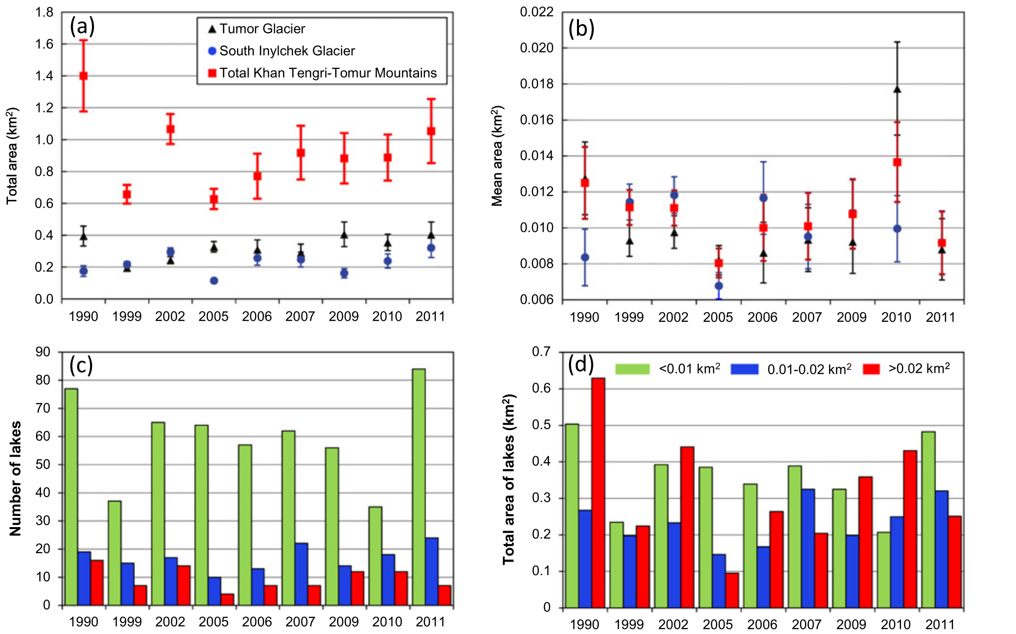

Figure 5. Interannual variation in (a) total and (b) mean area of supraglacial lakes between 1990–2011; and changes in (c) numbers and (d) total area for three area classes of supraglacial lakes.

For different area classes of supraglacial lakes, their year-by-year variations of number and total area are shown in figures 5(c) and (d). There are many more small lakes (area < 0.01 km^2) than big lakes (area > 0.02 km^2). On average between 1990 and 2011, the numbers of supraglacial lakes were 60, 17 and 9 for areas <0.01 km^2, 0.01 km^2 ~ 0.02 km^2 and >0.02 km^2, respectively. The total area of supraglacial lakes for the three classes, however, contributed nearly equally to their annual sums, which the mean values are

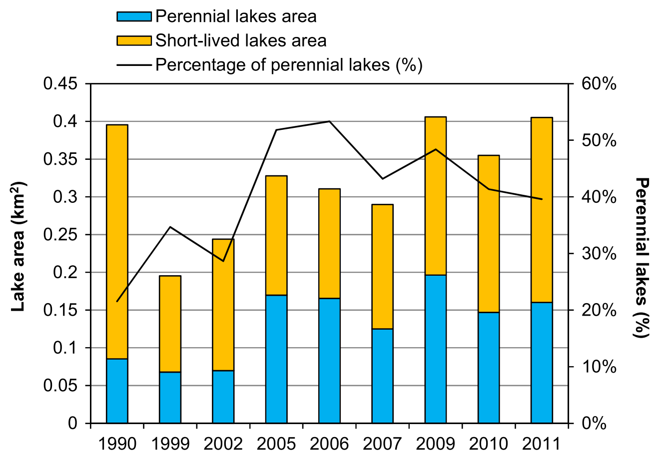

Figure 6. Changes of 'perennial' lakes and short-lived lakes on the Tumor glacier during 1990–2011.

0.36 km^2, 0.23 km^2 and 0.32 km^2, respectively. Generally, the large supraglacial lakes show greater variation in area than the small ones. Standard deviations (SD) for total area of the three size classes are 0.0098 (areas < 0.01 km^2), 0.0035 (0.01 km^2 < area < 0.02 km^2) and 0.0256 (area > 0.02 km^2). Thus, year to year variation of total area is dominated by the large supraglacial lakes. As a consequence, the year-by-year fluctuations in total area and area of large lakes are similar. The total area anomalies which occurred in 1990, 2002 and 2005 were due predominantly to the area changes of large lakes. In 2010, the total area of large lakes was more than double that of small ones, therefore, 2010 was the year with the highest mean lake area (figure 5(d)).

4.3. The 'perennial' and short-lived supraglacial lakes: a detailed investigation on the Tumor Glacier

We carried out a detailed lake investigation on the Tumor Glacier and classified all mapped lakes into two types: perennial and short-lived lakes. Most supraglacial lakes are short-lived as they were found to be ephemeral during the inventory period, appearing at particular locations but not remaining in those same locations from year to year. Conversely, some lakes we term the 'perennial' lakes, as they were identified on at least two images with the same location. In some cases, their locations shifted slightly due to the ice flow but their shapes remained similar. We used 'perennial' to discriminate against 'short-lived' for the repeatedly mapped lakes although it should be kept in mind that all or some of them may have drained and refilled again over the investigation period.

A total of 30 'perennial' lakes (including 3 ice marginal lakes) were identified on the lower part of Tumor Glacier during the investigation period (see supplementary material). Comparing the total area of 'perennial' lakes and short-lived lakes indicates that the former have experienced an overall increase in size between 2002 and 2005 (figure 6). As a result, the area of the 'perennial' lakes increased around 2005, from ~30% of the total lake areas in 1990, 1999 and 2002 to > 40% for the following years. This may be interpreted by the increased number of 'perennial' lakes and a higher filling frequency of previously existing lakes since 2005 (figure S5 in the supplementary material).

5. Discussions

5.1. Glacio-geomorphological control on the supraglacial lake distribution

The formation and existence of supraglacial lakes is strongly related to the local surface slope (Sakai and Fujita 2010). According to Reynolds (2000), at a surface gradient less than 10°, supraglacial lakes can form and exist for a longer duration than at slopes > 10°. All mapped supraglacial lakes in the KTTM region are detected in the lower flat part of the investigated glaciers, although their locations and sizes show remarkable fluctuations year by year. This flatter part of the glaciers (the average slope of the upper part is ~42.1° and the lower is ~8.9°) is also the region with extensive debris cover (figure 3). A large portion of lake area in the KTTM is distributed in the regions with surface gradient between 2° and 6°, which could be explained by the frequency distribution of surface slope of the entire debris-covered area in the region (figure S2 in the supplementary material).

We have identified some supraglacial lakes reappearing at nearly the same locations in different years, but it can not be confirmed whether these lakes have experienced drainage and refilling between successive pairs of satellite images. On the Koxkar Glacier, which has been well monitored recently, Han Haidong (personal communication) suggested that some 'perennial' supraglacial lakes usually experience one or more times of drainage and refilling throughout one year. Glacier surface velocity also influences the existence and lifespan of a supraglacial lake

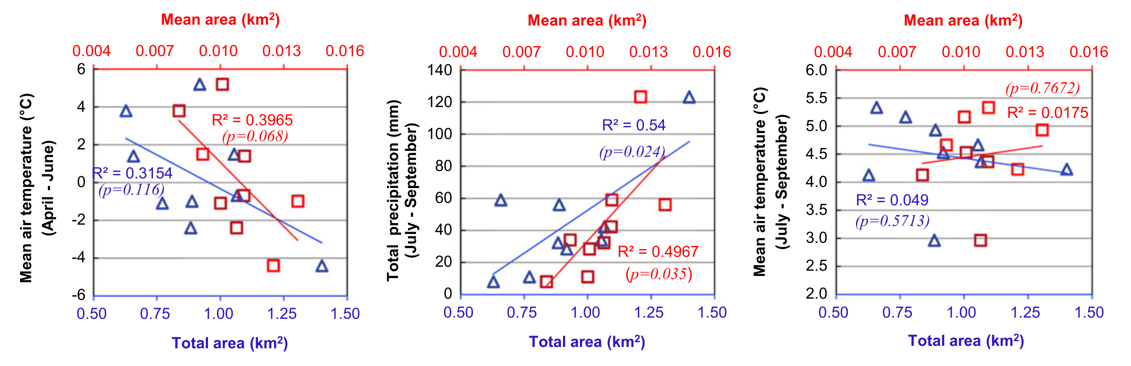

Figure 7. Comparison of the supraglacial lake area (blue triangle: total area; red square: mean area) and the seasonal climatic conditions (measured at Tianshan Station).

(Bolch et al 2008, Benn et al 2012). Further investigations on depicting the region-wide spatial distribution pattern of glacier surface velocity fields are necessary. Although the flow velocity of a glacier is inherently related to its surface slope (Paterson 1994), it will be useful to illustrate the possible reasons for the less frequent existence of supraglacial lakes on some glaciers or in some regions on the same glacier.

5.2. Relationship between supraglacial lakes variation and climatic conditions in summer and spring

The size of supraglacial lakes varies with the lake water balance (Benn et al 2000, Reynolds 2000, Benn et al 2001). Generally, sources of lake water include (1) melting of snow and ice around the lake and within the lake itself, (2) melt water transported through englacial channels or inflow from supraglacial streams and (3) water directly supplied by rainfall or snow fall. Conversely, lake water may be lost via outflow and evaporation. Regarding outflow, continuous lateral calving and melt at the water-line and subsurface down-cutting may lead to the drainage of the lake (Fountain and Walder 1998, Irvine-Fynn et al 2011). In some cases, lake level overtopping its basin rim will be followed by subsequent downcutting of a supraglacial channel (Benn et al 2001) and lake water filling will also cause hydro-fracture to an existing englacial crevasse/channel (Fountain and Walder 1998). Repeated observations of supraglacial lakes on the Ngozumpa Glacier in the Khumbu Himalaya (Benn et al 2001) and also on the Koxkar Glacier during the 2010 expedition (figure S9 in the supplementary material) indicate the established connections between supraglacial lakes and glacial drainage systems before the lake drainage.

Figure 7 shows the relationships between supraglacial lake area and seasonal climatic conditions, which were recorded at the Tianshan Station, Kyrgyz (figure 1; also see the supplementary material). It suggests that the area of supraglacial lakes is positively correlated with the summer total precipitation and negatively correlated with the spring mean air temperature. A higher negative correlation ($R^2 = 0.3154$, $p = 0.116$) between supraglacial lake area and mean air temperature for spring (April to June) but much less ($R^2 = 0.049$, $p = 0.5713$) for summer (July to September) suggests that most connected drainage systems may have been developed between April and June. In some years, such as in 1990, the drainage of supraglacial lakes is likely to be limited by the relatively cool ablation season and a superimposed precipitation (if snow then it will melt soon during the ablation season; figure S7 in the supplementary material) contributes water input to the lake expansions. In 2005, in contrast, limited precipitation (especially over summer) together with a warmer spring were the likely reasons for the observed minimum total and mean lake area. The mean area of supraglacial lakes also decreased with the increase of mean air temperature during spring ($R^2 = 0.397$, $p = 0.068$), which suggests that more drainage events occur on the larger lakes, and therefore induce a general decrease of mean lake area.

Since liquid precipitation acts as the direct input of liquid water into the supraglacial lakes, its total amount over summer is positively correlated ($R^2 = 0.54$, $p = 0.024$) to the total area of supraglacial lakes. Air temperature increase, however, has a dual function in the development of supraglacial lakes: more melt water due to enhanced ablation enlarges the supraglacial lakes but, conversely, it may also accelerate the drainage of lakes by the conversion of unconnected to connected glacial drainage systems (Irvine-Fynn et al 2011). Therefore, the development of glacial drainage systems during spring seems crucial for the later summer drainage of supraglacial lakes, resulting in the fluctuations of total or mean area of lakes as we have observed.

5.3. Future evolution of supraglacial lakes in the KTTM region

It has been confirmed that most of the reported moraine dammed lakes are the result of expansion and merging of supraglacial lakes that periodically fill up on the extensive debris-covered parts of glaciers

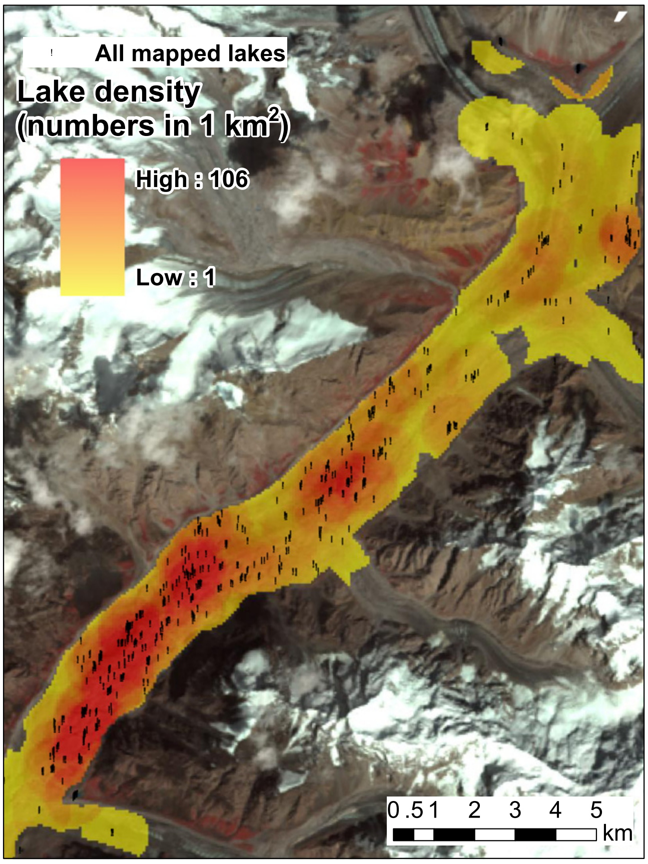

Figure 8. Lake density calculated from all mapped supraglacial lakes (black dots) on the Tumor Glacier.

(Reynolds 2000), e.g., as those have been observed in the Himalayas (Benn *et al* 2012) and South Alps (Kirkbride and Warren 1999). In contrast to many moraine dammed glacial lakes formed on debris-covered glaciers in the Himalaya (Richardson and Reynolds 2000, Komori 2008), the southern Alps (Kirkbride and Warren 1999, Warren and Kirkbride 2003) and the Patagonian Andes (Reynolds 1992, Dussaillant *et al* 2009), none has been found in the KTTM region. In the lower part of the dendritic-type glaciers in the KTTM, however, we can identify that supraglacial lakes are more likely to develop in some regions than in others (figure 3).

Based on all mapped lakes, a lake density map of the Tumor Glacier shows some regions where supraglacial lakes are more likely to develop (figure 8). An area with high spatial density ($n > 100\ km^{-2}$) of supraglacial lakes can be found in the lower part of ice tongue. The concentration of supraglacial lakes in this region will result in locally enhanced ice ablation and consequently accelerated ice surface downwasting as more energy for melt gained due to the higher thermal capacity of lake water than those non-water areas (Sakai *et al* 2000). Hence, as a result of positive feedback, these regions are prone to supraglacial lake coalescence and growth (figure 2), lending the potential for larger lake development. Furthermore, based on the current investigation, most supraglacial lakes with an area larger than $0.02\ km^2$, as well as some 'perennial' supraglacial lakes, are located in these regions. Regarding water storage, flood hazards and also the influence of lakes on the glacier ablation, these concentrated water ponded areas are much more important than the other part of the ice surface for detailed monitoring or observation in future studies.

6. Conclusions

We have presented a Landsat based multi-year investigation on the late summer conditions of supraglacial lakes on several debris-covered glaciers in the KTTM region, the largest glacierized mountain range in the Tianshan mountains. A total of 775 supraglacial lakes and 38 marginal glacial lakes were mapped on nine Landsat images acquired between August and September during 1990–2011. This relates to a mean number of 86 supraglacial lakes detected on these glaciers in the later ablation seasons of each year.

It is difficult to make an assessment on the trend of supraglacial lakes' evolution during the past decades, due to the large seasonal/annual variability of supraglacial lakes and the limited temporal cover of Landsat images we have used. However, this is the first regional investigation of supraglacial lakes on the debris-covered glaciers in the central Tianshan. Our results have demonstrated that the distribution of supraglacial lakes shows some spatial relationship with regional glacial geomorphology characters, i.e., debris-cover and ice surface slope. Total area of supraglacial lakes in the KTTM region shows great variability year to year. The majority of the investigated supraglacial lakes were located on the surface of two biggest dendritic-type glaciers (TG and SIG) in the KTTM region. Although most supraglacial lakes are short-lived, there are a number of 'perennial' lakes that can be repeatedly identified between different Landsat images. Some regions in the lower part of the TG and SIG are found to be more favorable for the supraglacial lakes' development and their future coalescing and growth may lead to the formation of larger lakes. A continued monitoring is necessary to assess the future evolution of supraglacial lakes in the KTTM region.

In addition, we found the area of supraglacial lakes was positively correlated with the total precipitation in summer (July to September) while correlated negatively to the mean air temperature over pre-summer (April to June). It has been suggested that high air temperature during the spring would likely impact on the development of glacial drainage from unconnected to connected systems allowing some supraglacial lakes to drain.

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