Landslides (2018) 15:83–98
DOI 10.1007/s10346-017-0862-3
Received: 2 February 2017
Accepted: 14 July 2017
Published online: 26 July 2017

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Debris flows triggered from non-stationary glacier lake outbursts: the case of the Teztor Lake complex (Northern Tian Shan, Kyrgyzstan)

Abstract One of the most far-reaching glacier-related hazards in the Tian Shan Mountains of Kyrgyzstan is glacial lake outburst floods (GLOFs) and related debris flows. An improved understanding of the formation and evolution of glacial lakes and debris flow susceptibility is therefore essential to assess and mitigate potential hazards and risks. Non-stationary glacier lakes may fill periodically and quickly; the potential for them to outburst increases as water volume may change dramatically over very short periods of time. After the outburst or drainage of a lake, the entire process may start again, and thus these non-stationary lakes are of particular importance in the region. In this work, the Teztor lake complex, located in Northern Kyrgyzstan, was selected for the analysis of outburst mechanisms of non-stationary glacial lakes, their formation, as well as the triggering of flows and development of debris flows and floods downstream of the lakes. The different Teztor lakes are filled with water periodically, and according to field observations, they tend to outburst every 9–10 years on average. The most important event in the area dates back to 1953, and another important event occurred on July 31, 2012. Other smaller outbursts have been recorded as well. Our study shows that the recent GLOF in 2012 was caused by a combination of intense precipitation during the days preceding the event and a rapid rise in air temperatures. Analyses of features in the entrainment and depositional zones point to a total debris flow volume of about 200,000 m^3, with discharge ranging from 145 to 340 $m^3\ s^{-1}$ and flow velocities between 5 and 7 $m\ s^{-1}$. Results of this study are key for a better design of sound river corridor planning and for the assessment and mitigation of potential GLOF hazards and risks in the region.

Keywords Moraine complex · Intra-moraine channel · Glacier lake outburst flood · Debris flow · Tian Shan

Introduction

Glacier-related hazards can have severe downstream consequences (Evans et al. 2009; Mergili et al. 2012; Westoby et al. 2014), particularly if the outburst of glacial lakes leads to debris flows and floods. Glacial lake outburst floods (GLOFs) are generally known for their potential to cause some of the largest floods known in mountain environments (Costa and Schuster 1988; Clague and Evans 2000; O'Connor and Costa 2004; Borga et al. 2014; Worni et al. 2014; Schwanghart et al. 2016). These phenomena have been largely described in all large mountain ranges around the world (e.g. Vinogradov 1977), especially in the Alps (Huggel et al. 2003), the Himalayas (Richardson and Reynolds 2000; Quincey et al. 2007; Worni et al. 2013) and the Andes (Worni et al. 2012; Schneider et al. 2014; Anacona et al. 2015). By contrast, research on glacier-related hazards, such as GLOFs and related debris flow phenomena, are still scarce in Central Asia (Baimoldaev and Vinokhodov 2007; Mergili et al. 2010; Narama et al. 2010; Zaginaev et al. 2016).

This lack of scientific research on GLOFs in Central Asia is surprising, as more than 2000 mountain lakes with surfaces larger than 0.1 ha exist within the territory of Kyrgyzstan alone (Jansky and Yerokhin 2010), and as 242 additional lakes have recently been mapped in the neighbouring Uzbekistan (Petrov et al. 2017). Nearly 20% of the Kyrgyz lakes are potentially dangerous because of their unstable dams, frequent overflows and/or as a result of the melting of buried ice inside moraine dams (Janský et al. 2008). Since 1952, more than 70 lake outburst events have been reported (Janský et al. 2010). A particularly large number of GLOFs have been observed in the northern Tian Shan between the 1950s and the 1970s (Kubrushko and Staviskiy 1978; Yafazova 2007). Some of these events were extreme events with very negative consequences, such as the GLOF in the Kishi Almaty river of the Ile Ala-Tau range, in 1973, which killed 10 people in the downstream area (Baimoldaev and Vinokhodov 2007; Yafazova 2007; Narama et al. 2010). Another extreme event occurred in July 1998 at Archa-Bashi Glacier Lake in the Alay range of the Gissar-Alay region. In this case, the GLOF was triggered by a sudden release of water from a moraine-dammed lake, which caused a flood in the local river killing more than 100 residents in the Shakhimardan settlement in Uzbekistan (Chernomorets et al. 2016). In 2008, an outburst occurred from a moraine-dammed, non-stationary lake located on the northern flank of the Terskey Ala-Too range, inundating houses, roads and fields and killing three people (Narama et al. 2010). These non-stationary lakes are lakes which are episodically filling before they drain abruptly, and are thus considered as the most dangerous lake type in the region (Janský et al. 2008, 2010). This type of lakes collects atmospheric and meltwater in enclosed, bowl-shaped moraine depressions formed by retreating glaciers. Drainage from such lakes, and hence the entire glacier, is concentrated to subsurface channels at the level of the dam (Janský et al. 2010) or intra-moraine channels. The release of lake water often triggers GLOFs and debris flows in the downstream drainage system, and these processes tend to remain extremely unpredictable because lake area and volume may change dramatically and over very short time periods (Narama et al. 2010). Developing an improved understanding of GLOFs and related downstream processes, in terms of their frequency, timing, magnitude and duration of water release from lakes (i.e. outflow hydrograph), is therefore required, even more so as changing climatic conditions might locally exacerbate hazards and risks (Stoffel and Huggel 2012).

The aim of this work is to analyse a recent GLOF event in the Teztor valley, Ala-Archa River catchment, which was triggered by the sudden drainage of a lake of the non-stationary Teztor Glacier lake system. The event occurred in 2012 and triggered a debris flow which reached the main valley upstream the capital city of

Bishkek, and caused severe damage on its downstream course. The debris flow event triggered the warning system, installed in 2011, which consists of several magnetic contact sensors (Zamai and Dobrovolsky 2012) sending radio signals to the base station. This guaranteed some minutes to evacuate people from exposed zones. Nevertheless, damage to water pipelines and the resulting inability to produce hydroelectric energy still resulted in substantial losses, estimated at almost 100,000 US $ (Zaginaev 2013).

Field and historic evidence reveals that similar, and even larger, debris flows occurred in this same area, such as the event in 1953 (described in the "Comparison of the 2012 event with a debris flow in 1953" section). The fact that at least two large GLOFs and related debris flows occurred in this catchment over the past few decades therefore calls for an in-depth analysis of this system.

In this paper, we (i) define and review existing literature on the mechanisms of non-stationary glacial lake formation and drainage; we (ii) analyse the 2012 event in detail, based on a post-event survey and analysis of the triggering factors; and (iii) compare this recent event with the catastrophic GLOF and debris flow event in 1953. Finally, (iv) we highlight implications of this study for debris flow and flood management in the wider Ala-Archa region.

Non-stationary glacier lake formation and evolution

Formation and development of glacier lakes typically depend on parent glacier behaviour, with glacier retreat usually leading to the development and expansion of proglacial lakes (Petrakov et al. 2012). Moraine-dammed and thermokarst lakes develop in ice-rich permafrost or stagnant ice (Reynolds 2000). Another known mechanism facilitating the development of lakes is glacier ablation around lake margins and the related calving and melting, which has been found to locally accelerate glacier downwasting rates (Sakai et al. 1998; Benn et al. 2001).

In the case of glacial recession, the thinning of ice dams can have implications on the amount of lake water needed to cause drainage (Costa and Schuster 1988; Evans and Clague 1994; Clague and Evans 1997, Sorg et al. 2012), which can then result in more frequent, but lower magnitude GLOFs. By contrast, during periods of glacial advance, ice dams can increase in thickness and size and, in turn, can impound greater water volumes, thereby potentially producing less frequent, but higher magnitude outburst events. Water release is, therefore, controlled by this threshold exceedance in the glacial hydraulic system (Walder and Costa 1996) and by glacier thermal conditions (Gilbert et al. 2012).

Moraine-dammed and thermokarst lakes are also common in Kyrgyz Tian Shan, they form when valley and cirque glaciers retreat from advanced positions (Clague and Evans 2000). Many of these lakes have drained suddenly in recent years, thereby generating floods and debris flows. Such lakes usually develop in areas of moraine complexes (Bennett and Evans 2012) predominantly characterized by glacial ablation. A moraine complex is a glacially formed geological body which was formed during the Little Ice Age by a receding glacier and which is composed of debris and buried ice (Bolch 2015). Lakes often form at the junction of a glacier and a moraine complex. The lake bed of such water bodies is typically formed by ice or ice and debris, whereas most parts of the lake banks are composed of debris. As a consequence, this type of lakes usually has intra-moraine outflow systems (Fig. 1). Drainage from these lakes may occur as soon as a critical depth threshold is reached and as soon as hydrostatic pressure causes yielding of the drainage conduits (Glen 1954; Tweed and Russell 1999; Roberts 2005). When seepage flow rates appear to be increased, internal erosion or piping is likely to occur. In case that the intra-moraine channels are blocked, a lake tends to evolve and fill quickly, thereby increasing outburst probabilityEmmer and Cochachin 2013). The latter process may be favoured by intense rainfall or snowmelt with high air temperatures, whereby outflow discharge incises intra-moraine channels, or in the case of freezing or blocking of intra-moraine channels (Erokhin 2011).

Drainage-event frequency and magnitude have been defined as being cyclical by Tweed and Russell (1999). In this context, Walder et al. (1997) also argued that reservoir volume probably does not exert primary control on peak discharge: other factors may influence peak discharge as well, such as site conditions at the outlet, overtopping or piping (O'Connor et al., 2013). However, they also pointed out that in the absence of complete understanding, reservoir volume may serve as a useful estimator of debris flow and flood magnitude for initial hazard assessments.

Study site: Teztor Glacier lake complex

The Tian Shan Mountains cover about 39°–46°N and 69°–95°E in Central Asia. The main ranges stretch for ≈2500 km from Northern Kyzyl-Kum in Uzbekistan, across Kazakhstan, and Kyrgyzstan, to the east of Hami in China.

Glacial and periglacial regions of the Northern Tian Shan, including the Kyrgyz Ala-Too range, host characteristics that favour the presence of glacial lakes and the development of GLOFs and debris flows, such as the presence of glacially overdeepened troughs, voluminous moraines and narrow valleys. Ala-Archa glaciers are spread through an altitudinal range of 3300–4800 m a.s.l. Approximately 83% of the Ala-Archa glacier area consists of large valley glaciers, with about 76% of the total glacier-covered areas located between 3700 and 4100 m a.s.l. The Ala-Archa glaciers receive 700 mm of annual precipitation, mainly between April and June (Aizen 1988; Aizen et al. 2000), and they feed the closed drainage basin of the Chui River, which is the major irrigation and water supply source for northern Kyrgyzstan and southern Kazakhstan (Aizen et al. 2006).

The study area, the Teztor lake complex, is located in Northern Tian Shan at an altitude of 3530–3590 m a.s.l. Teztor is a left tributary of the Adygene stream that flows into the Ala-Archa River (Fig. 2). Table 1 shows the main characteristics of the study site.

The Teztor Glacier is located in the upper part of the catchment and has receded up to 480 m over the past 60 years (Erokhin and Zaginaev 2011). As a consequence, a large depression on the left side between the Teztor Glacier and the moraine complex has formed. This complex includes a debris-covered glacier, buried ice, stagnant ice and rock glaciers, as shown in the geomorphic map of the Teztor catchment in Fig. 3. This geomorphic map was based on field surveys (i.e. geomorphic descriptions and sketches (e.g. cross sections), photographs) and satellite image interpretation as described in Viskhadzhieva et al. (2016).

Rockfall and snow avalanche deposits can be observed in the headwaters and upper parts of the catchment where the most relevant geomorphic features are however the moraines. Creep slopes prevail on the moraine ridges, and colluvial, and debris flow deposits appear along the mid and lower part of the catchment. In the central part of the catchment, the Teztor stream cuts

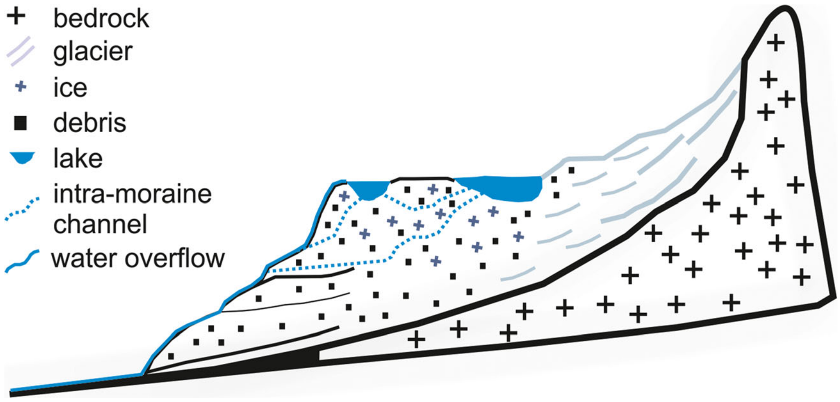

Fig. 1 Sketch of moraine complex lakes in Northern Tian Shan. Non-stationary lakes often form at the junction of a glacier and a moraine complex; a lake bed is typically formed by ice or ice and debris, whereas most parts of the lake banks are made of ice and debris

its way through bedrock and moraine deposits. At the valley bottom, the large depositional fan at the mouth of the Adygene stream (Fig. 2, Table 1) is formed by debris flow deposits, such as the deposits from the 1953 and 2012 events, which remain clearly visible on the fan surface (see Fig. 2).

Three depressions have been formed in the Teztor moraine complex, and are named Teztor-1, Teztor-2 and Teztor-3 in Fig. 4b. These lake depressions have different dynamics of development and can also be considered to have different mechanisms of origin (see Supplementary Material for details).

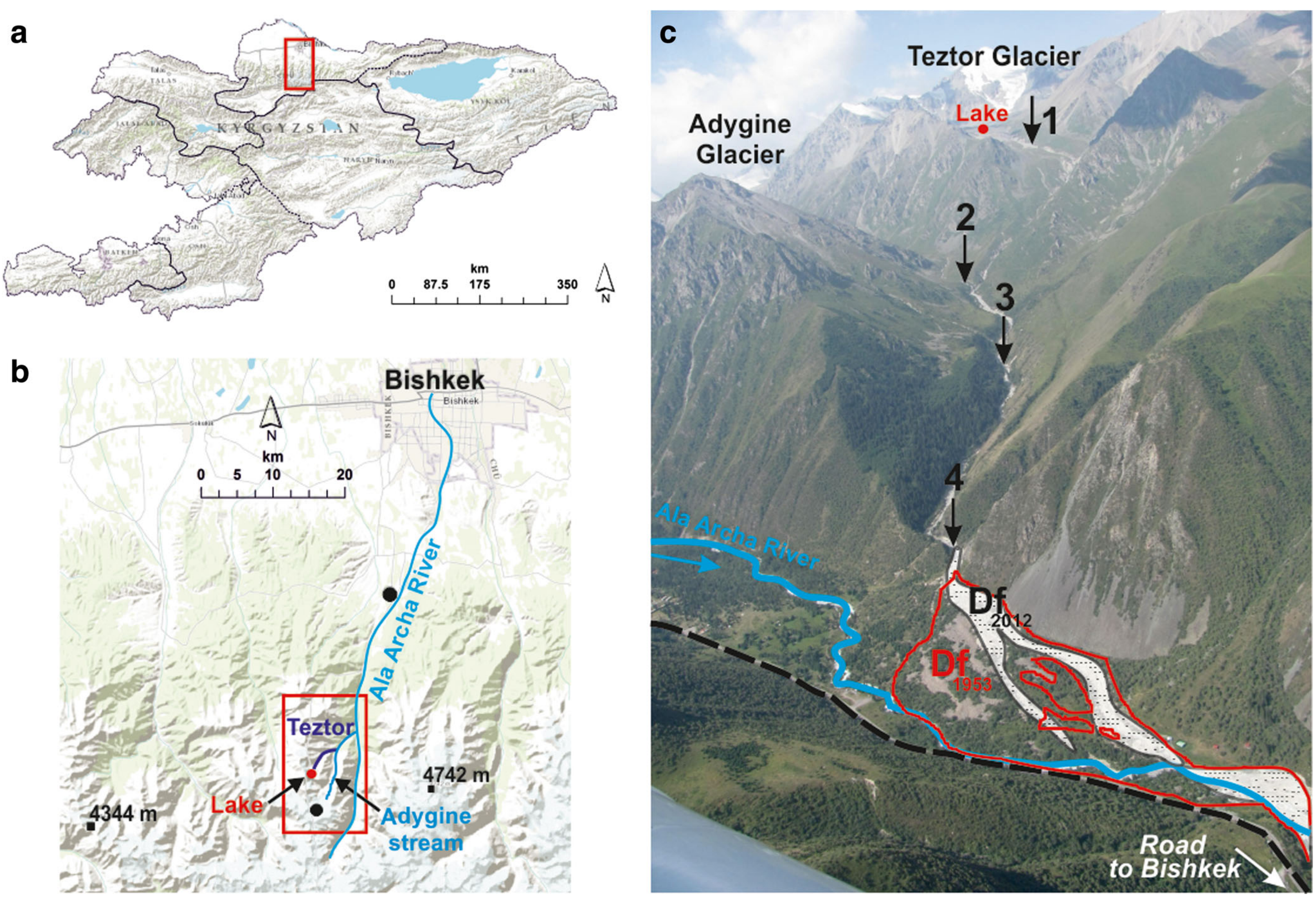

Fig. 2 **a** Location of the Ala-Archa valley in Northern Tian Shan. **b** Study site, Teztor-Adygene glaciers. *Black stars* indicate the position of the Climate Forecast System Reanalysis (CFSR) weather stations (see text for details), *black circles* show the two local meteorological stations, one located at the Adygene glacier area and one in the lower Ala-Archa valley, Baitik. **c** Oblique aerial view of the debris flow path some days after the event of July 31, 2012. *Numbers* and *black arrows* show the surveyed cross sections (see the "GLOF mechanisms and rheological parameters of the 2012 debris flow" section). *Df* debris flow fan deposits in 1953 and 2012

Table 1 Study site characteristics of the Teztor catchment

Parameter (units)	Site: Teztor at the confluence with Adygene stream	Site: Adygene at the confluence with Ala-Archa River
Drainage area (km^2)	7	40
Mean catchment slope (°)	28	27
Highest elevation (m a.s.l.)	4373	4373
Lowest elevation (m a.s.l.)	2440	2111
Channel length (km)	5	13
Mean channel bed slope (m/m)	0.204	0.165
Fan area (km^2)	–	0.245
Mean fan slope (°)	–	8
Fan longitudinal length (m)	–	954
Fan width (m)	–	350

Lakes Teztor-1 and Teztor-2 are moraine-dammed lakes formed within the intra-moraine depression. Lake Teztor-3, by contrast, originated in thermokarst funnels (Fig. 4; also see the "Introduction" section and Figure S1and S2 of the Supplementary Material).

Climate in the Ala-Archa catchment is controlled by air masses coming from the north and northwest in winter, and from the west, northwest and southwest during summer. At high altitude (i.e. from 2000 to 3500 m a.s.l.), climate is characterized by average air temperatures ranging from 11 to 18 °C in July and from −8 to −10 °C in January. The nival-glacial zone (found above 3500 m a.s.l.) is characterized by average air temperatures in July reaching up to 4.9 °C, but −22 °C in January. As a result, widespread permafrost occurs at altitudes above 3500 m a.s.l. The mean annual precipitation varies between 300 and 700 mm, with the highest precipitation observed in spring and at altitudes ranging from 2000 to 2500 m a.s.l. (Podrezov 2013). The only available precipitation and air temperature records are from the Baitik station (1579 m a.s.l.), which are shown in Fig. 5. The mean annual precipitation, according to these records, has increased by more than 130 mm (Mann-Kendall test P value is equal to 0.009) over the past 100 years, whereas the mean annual air temperature raised up to 0.8 °C (Mann-Kendall test P value <0.05).

Precipitation and air temperature records for the nival-glacial zone of the Teztor-Adygene river basin are available from the Adygene weather station situated at an elevation of 3570 m a.s.l. since early 2008. However, this time series is not complete and data are only available for the summer months. The maximum historical daily precipitation rate recorded at this station is 32 mm on June 16, 2012, and the maximum temperature was registered on July 31, 2012, when it raised up to 18 °C (Fig. 6).

Methods

Post-2012 GLOF event field survey

A post-event field survey started on August 1, 2012—immediately after GLOF, the debris flow occurred. For the assessment of the outburst volume, we used a TruPulse 360R Laser Rangefinder, which enabled measurement of the lake areas before and after the event and the drop in lake water level. Available pictures and traces in the field (i.e. water level marks in the form of silty and clayey deposits as well as the presence of algae) were used to reconstruct lake level before and after the drainage as well as to quantify water level drop and thus estimate volume of released water.

During the field reconnaissance of the debris flow path, we primarily focused on entrainment and accumulation processes in order to later divide the debris flow path into different zones with similar geomorphic effects and to determine critical gradients for entrainment. Typical valley cross sections were therefore measured in the field in order to assess the debris flow depth, flow velocity and discharge (for locations of cross sections, see Fig. 2).

Peak velocity V and peak discharge Q were estimated by empirical relation given by Eqs. (1) and (2), which combine flow depth and channel slope (Kherkheulidze 1972):

$$V = 4.83 \cdot \mathrm{H}^{0.5} \cdot \mathrm{I}^{0.25} \tag{1}$$

$$Q = \mathrm{A} \cdot \mathrm{V} \tag{2}$$

Where V is peak velocity of the debris flow (m s^{-1}); H is debris flow depth determined at the cross sections (m); I is longitudinal slope of the channel bed degree (m m^{-1}); Q is peak discharge of the debris flow (m^3 s^{-1}) and A is cross-sectional area (m^2).

Rheological properties (in terms of density) of the debris flow material were then determined in the field by collecting samples of the fine material; we measured the weight of the samples and calculate bulk density. Further rheological properties, such as viscosity, were also determined in the laboratory, but we did not use them in this work. Geomorphic observations at the selected reaches were then used to illustrate the spatial distribution of erosional and depositional features along various segments of the debris flow route. These observations focused on the area and height of deposition or erosion layers, where visible then allowed estimation of total entrained and deposited volumes.

Remote sensing and data analysis

Remotely sensed information derived from multi-temporal aerial and satellite imagery enabled the quantitative assessment of debris flow erosion and deposition by comparing images taken prior to and after the event. In addition, remote sensing allowed estimation of local

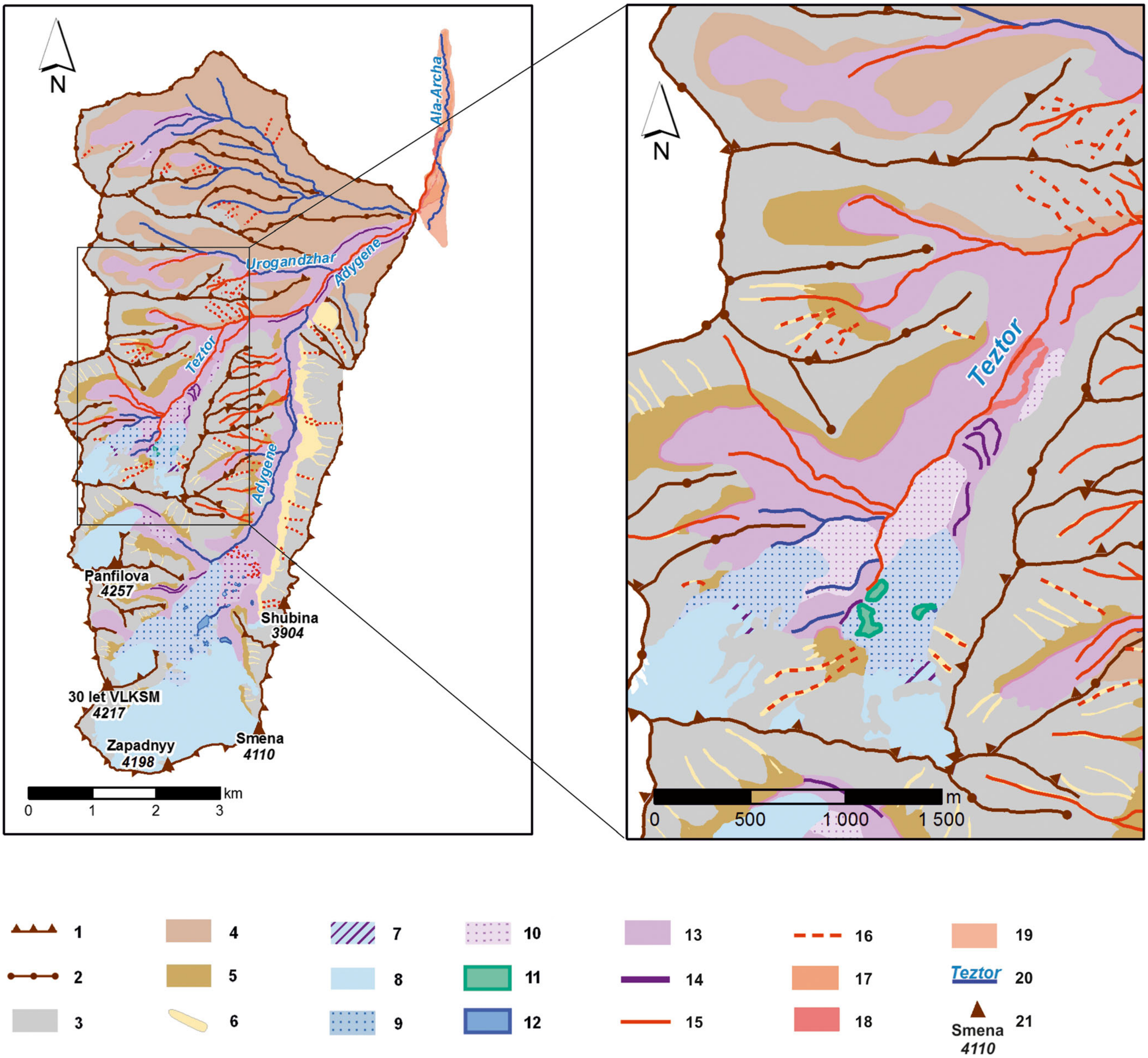

Fig. 3 Geomorphic map of the Teztor-Adygene basin. Mountain ridges: *1* sharp, *2* rounded. Slopes: *3* bedrock, *4* creep. *5* scree/avalanche/debris flow fans. *6* scree/avalanche channels. Glaciers: *7* covered by debris, *8* not covered by debris, *9* stagnant ice, *10* rock glaciers. Lake basins: *11* empty, *12* water-filled. *13* moraines. *14* moraine ridges. Debris flow channels: *15* permanent, in river channels, *16* temporary, on the slopes. Debris flow deposits: *17* of 1953, *18* after 1953, *19* older debris flow and alluvial deposits. *20* Rivers. *21* Main peaks

conditions prevailing at the glacier site before the GLOF occurrence, and therefore allowed inferences on possible triggering mechanisms (as described in Allen et al. 2016). Five high-resolution aerial and satellite images (available from Google Earth and airborne archives) were analysed for the period between 1962 and 2014. To create a longitudinal profile along the debris flow path, we used an available topographic map at a scale of 1:25,000 produced in 1980.

We also used helicopter photos taken in the months before and after the event in 2012. Historical data (i.e. oblique photographs and previous field surveys since 1998) were analysed as well, so as to reconstruct and understand previous events, such as the GLOF in 1953, and to provide data on areas and volumes of Teztor lakes.

Analysis of meteorological data was based on data from the two stations available in the region, (Baitik 42° 42.8′ N; 74° 32.6′ E; 1579 m a.s.l. covering the period from 1916 to 2012 and Adygene 42° 30.45.6″ N; 74°26.17.9″ E; 3570 m a.s.l. covering the period from 2008 to 2016). In the case of the Baitik station, although data extend back to 1916 (see Fig. 6 for details), information is not available at daily or sub-daily resolution. The station located within the Adygene catchment, on the other hand, only is operational since 2008 and covers exclusively the summer months. This station, which was installed within a joint Czech-Kyrgyz programme (Erokhin and Zaginaev 2011), is located at an elevation of 3570 m a.s.l. and records air and lake water temperature data at

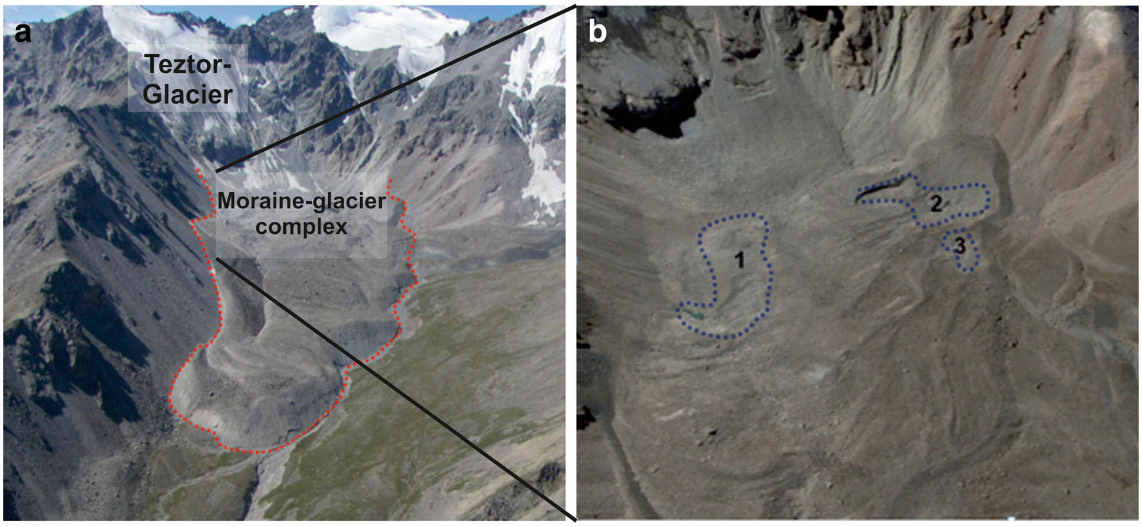

Fig. 4 a The *red dots* outline the Teztor moraine-glacier complex, with an active rock glacier in its *frontal part*. **b** The three lake basins *Teztor-1*, *Teztor-2* and *Teztor-3* are periodically filled by meltwater (helicopter image taken on August 2, 2009)

sub-hourly intervals (see Fig. 6). Conditions at Adygene Lake are assumed to be similar with those at Teztor-2 (i.e. same altitude and similar climatic, geologic and geomorphic characteristics).

To overcome the limitations related to the temporal resolution of the data Climate Forecast System Reanalysis (CFSR), data were downloaded (www.globalweather.tamu.edu) and analysed for the purpose of this study. This database is a global, high-resolution, coupled atmosphere-ocean-land surface-sea ice system; it provides the best estimate of hourly data for the 36-year period of 1979–2014 (Saha et al. 2010a, b). The CFSR weather data were obtained for a bounding box (south latitude 42.2489°; west longitude 74.2593°; north latitude 42.7833°; east longitude 74.9487°) and for rainfall, maximum and minimum air temperature, wind speed and relative humidity, based on records from two weather stations (longitude 74.375; latitude 42.619; elevation 2715 m a.s.l.; Longitude 74.687; latitude 42.619; elevation 2473 m a.s.l.; see Fig. 2).

Results and discussion

Non-stationary lakes and outburst events

Analysis and interpretation of available high-resolution satellite and aerial imagery, covering the period 1962–2014, revealed frequent changes in the number and size of lakes in the Teztor Glacier complex. An overview on changes in lake size and number is provided in Fig. 7.

The highest number of lakes was reached in 1998, when six lakes existed in the basin. By contrast, the maximum lake area (all lakes combined) was observed in 2009, and before the GLOF occurred on July 31, 2012.

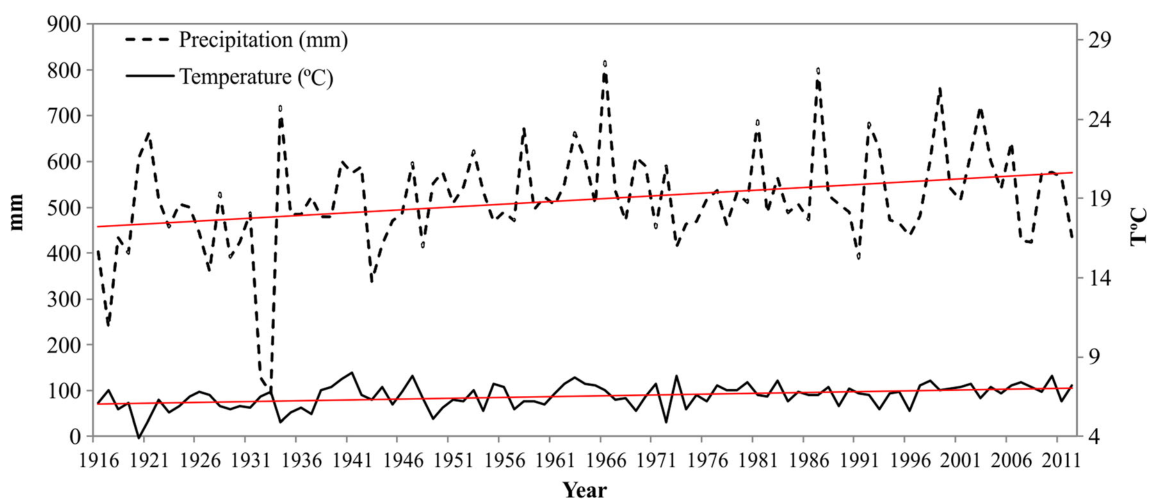

Fig. 5 The mean annual air temperature and mean annual precipitation recorded at the Baitik station (42° 42.8′ N; 74° 32.6′ E; 1579 m a.s.l.), located 12 km from the study site and covering the period from 1916 to 2012. *Red lines* show linear trend

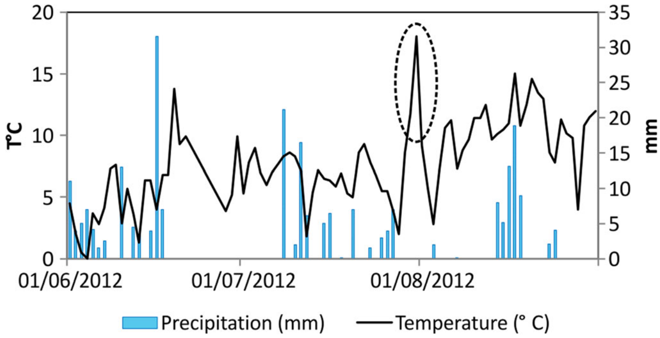

Fig. 6 Peak summer daily air temperature and summer daily precipitation recorded at the Adygene station in summer 2012. The timing of the GLOF and debris flow on July 31, 2012, is highlighted with a *black oval*

Extensive analysis of field data on the three main lakes in the Teztor complex (for the period comprised between 1953 and 2014) also allows description of their dynamics and outburst conditions:

Teztor-1: The lake basin is located at approximately 3550 m a.s.l. (Fig. S3). A sinuous stream of glacial meltwater crosses the bottom of the lake depression. At the deepest spot of the lake basin, the stream disappears at the thermokarst funnel, flowing in its intra-moraine channel down the valley. Available historical records reveal that the GLOF which occurred on June 22, 1953, was in fact triggered from Teztor-1 with a reported water volume of 80 × 10^3 m^3 (according to Erokhin and Dikih 2003) and in the form of debris flow with a discharge increasing rapidly from 50 to 400 m^3 s^{-1}, and that about 1.2 million m^3 of sediment was transported during this event (Kroshkin and Talmaza 1960). In June 1988, the same lake burst again, but the emptying process was slow and lasted for about 3 days, so that the initial discharge during lake drainage was too small to mobilize large boulders from the torrent bed, and thus prevented erosion. This event did not therefore initiate a debris flow, but rather caused a slight increase of discharge of about 8–10 m^3 s^{-1} in the Ala-Archa River (Erokhin and Dikih 2003; Zaginaev 2013). Between 1999 and 2012, the depression was almost free of water, except for the formation of 2–3 small (<500 m^2) lakes forming periodically within the lake basin, as also is illustrated by satellite data (Fig. 7).

Teztor-2 was the origin of the GLOF and related debris flows occurring on July 31, 2012. GLOFs originating from Teztor-2 are considered dangerous, not only for the inhabitants of the Ala-Archa River valley, but also for the Kyrgyz capital of Bishkek. This lake basin was filled periodically with meltwater, as observed in satellite images (Fig. 7) between 1962 and 2014. Between 1962 and 1998, only one small GLOF was recorded in the field in 1988 (as described in Erokhin and Dikih 2003 and observed in Fig. 7b by the reduction in lake area). In 2001, the degree of filling was estimated in the field to be around 20–30% of total lake capacity. Lake volume was around 25 × 10^3 m^3 and in 2003, the lake doubled in volume to reach roughly 50 × 10^3 m^3. In 2005, when the lake volume exceeded 70 × 10^3 m^3, the lake started to drain through an ice cave located at its southern margin. Drainage discharge was, however, relatively low with an estimated 6–8 m^3 s^{-1} (Zaginaev 2013). The depression then remained mostly free of water, except for two small lakes (area < 500 m^2) which formed at its bottom (see Fig. 7).

In 2009, the depression started to fill again with snowmelt and glacier meltwater. In July 2011, the volume of the lake reached again ca. 70 × 10^3 m^3. Before the outburst on July 31, 2012, the lake of irregular shape had a length of ca. 170 m and a width of 100 m, for a total area of 11.5 × 10^3 m^2. The 2012 GLOF lowered the water level by 10 m and left an oval-shaped depression with a length of 70 m and a width of 55 m. Lake area decreased to 3.2 × 10^3 m^2, with an estimated volume of water released during the outburst of approximately 74 × 10^3 m^3.

Teztor-3: The lake basin of Teztor-3 was dry and empty during the early 1990s, and water only started to fill the depression since 1996. The lake volume has been steadily increasing until July 2005 and reached up to 50 × 10^3 m^3, thereafter the lake burst in late July 2005. An exact date of the event is not available. The post-event survey showed that outburst discharge was in the order of 15–20 m^3 s^{-1} (Zaginaev 2013). Numerous gullies were carved along the flow path of the torrential flood triggered by this GLOF (Fig. S4).

It is very likely that the actively retreating glaciers in the Teztor catchment have indeed favoured the blocking of intra-moraine channels during periods of more or less stagnant glacier mass balance and as a result of the recent downwasting of regional glaciers (Sorg et al. 2012; Bolch 2015; Zaginaev et al. 2016). Our observations at Teztor are also in line with changes in nearby permafrost bodies and reconstructed rock glacier movements as a function of air temperature changes (Sorg et al. 2015). In addition, moraine dams containing ice cores or interstitial ice have been observed to be vulnerable to failure in other regions (Reynolds 1998), and thus confirm our findings.

The ice contained in these moraine bodies may melt if climate warms, causing the moraines to subside and eventually fail. The interior of the Teztor moraine complex, which obviously controls the regime of lake formation and lake drainage development, can be observed in freshly opened crevasses and natural outcrops originated from the processes of erosion and thermokarst. Based

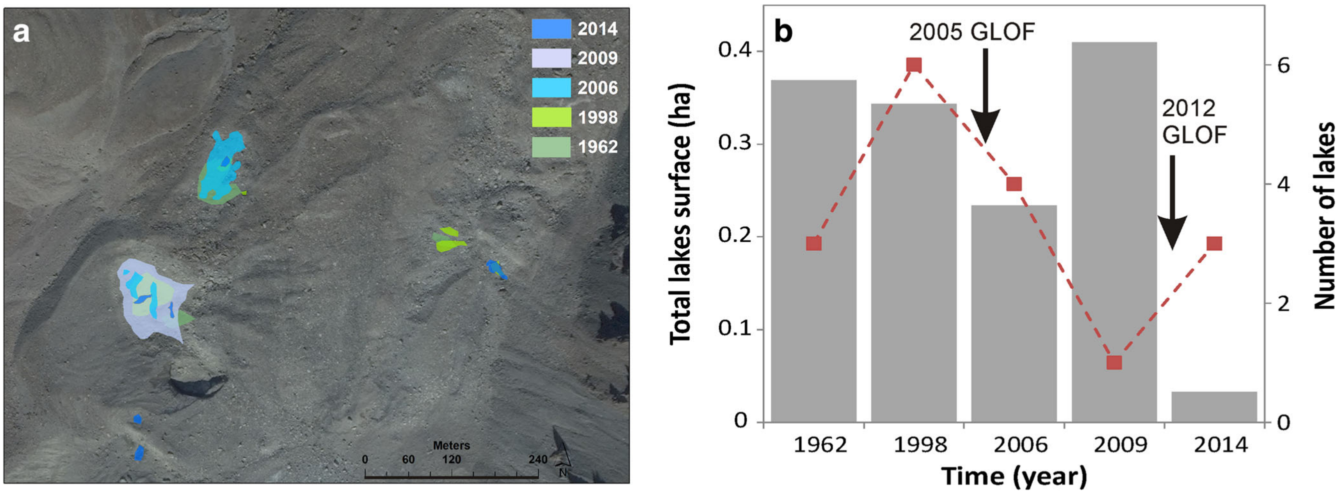

Fig. 7 **a** Dimensions of lakes at different times based on remote sensing (background image from Google Earth taken in 2014). **b** Total lake area (*grey bars*) and number of lakes (*red squares*) existing in the Teztor lake complex during the period 1962–2014 (based on high-resolution satellite imagery)

on a structural assessment of the Teztor moraine complex, we present a sketch illustrating the functioning of the Teztor moraine complex in Fig. 8. The illustration shows that the proportion of ice and debris incorporated in the Teztor moraine complex along the

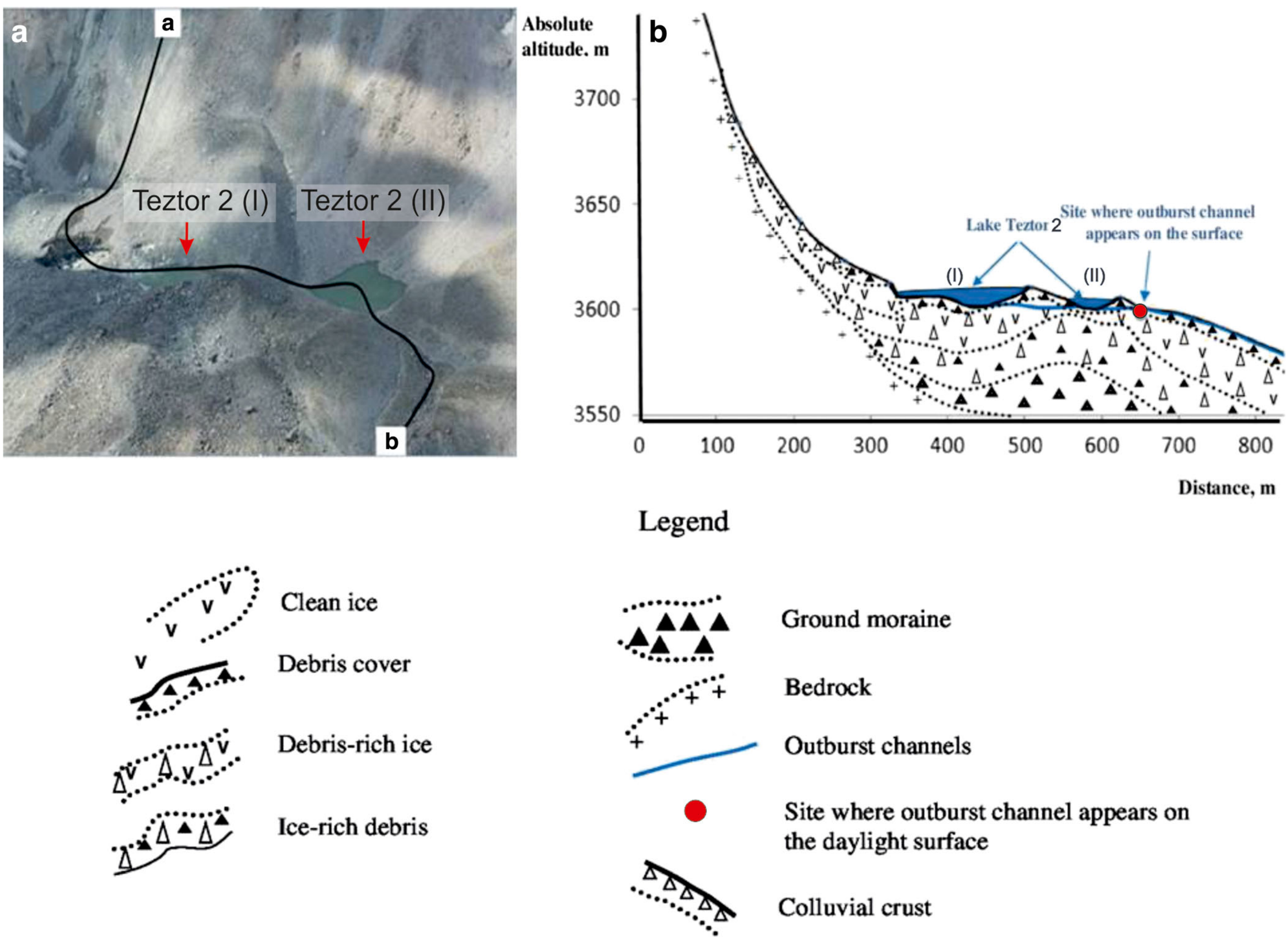

Fig. 8 a Longitudinal profile of the moraine complex Teztor 2 (separated into 2 sub-lakes as shown in Fig. 9) between *points a* and *b* (aerial helicopter picture taken on September 1, 2012). **b** Sketch of the Teztor moraine complex section along the *I-II* profile line.

Fig. 9 Helicopter photos of Lake Teztor-2 some days before the event (**a**) and at the day after the 2012 event. Lake Teztor-2 was separated into two sub-lakes: *I* and *II* (**b**) and (**c**). *Dashed arrows* show internal drainage from Teztor-2 (*I*) and Teztor-2 (*II*). *Red arrow* shows a further on-surface drainage

profile is highly variable, with an upper layer exhibiting less than 20% ice content. The sub-surficial layers of the complex are rich in debris as a result of enhanced ice melting. Debris content in some parts of this complex is estimated to be at least 50%, and locally reach up to 70–80%. Noteworthy, and in the absence of boreholes, these percentages are based on visual observations and estimates. Real values may differ from these estimates, and more studies are required to enhance the understanding of local processes. Assessment of internal structures of the Teztor complex also shows the availability of ice lenses and ice cores which play an important role in the formation and evolution of lakes and their drainage system. These processes may indeed have favoured instability of intra-moraine channels of the moraine located at Lake Teztor 2.

GLOF mechanisms and rheological parameters of the 2012 debris flow

During the course of the 2012 GLOF, Teztor-2 was separated into two parts. At the beginning of the event, the depression located down westwards from Teztor 2 (I) was empty.

As shown in Fig. 8b, drainage from Teztor 2 (I) occurred through intra-moraine channels (approximately 50 m along a straight line) in the moraine dam separating Teztor 2 (I) from the downstream depression. This depression was then filled with water and a new lake was formed Teztor-2 (II). Drainage from newly formed Teztor-2 (II) occurred through internal channels and the outbursting water reached surface only 20 m below the lower lake margin, as illustrated in Figs. 8b and 9. By contrast, no evidence of overflow was observed at the surface. At first, and similar to a well-documented case from the Patagonian Andes (Worni et al. 2012), the outflowing water propagated in the form of a debris flood or hyperconcentrated flow, before it then evolved into a debris flow on its downstream course.

The maximum velocity and discharge were estimated following Kherkheulidze (1972) during the post-event survey along with the bulk density properties of the debris flow material at different cross sections along the channel (shown in Fig. 2). For this purpose, for each reach, valley width, channel slope and height (depth) of the debris flow were determined, as shown in Table 2.

The estimated flow velocities of the 2012 debris flow are in the range of values observed for similar events, such as for instance, Worni et al. (2012) or O'Connor et al. (2001), who reported velocities in the range of 3 and 6 m s^{-1}, respectively, with maximum values of up to 15 m s^{-1}. Flow composition and characteristics have a very direct influence on velocity. These characteristics obviously changed as the flow propagated down the valley, in response to the high entrainment rates and the resulting changes in water content and debris strength. The debris flood had an initial density of less than 1100 kg m^{-3} immediately downstream of the lake, but after passing the entrainment zone, we estimated debris flow density of up to 2100 kg m^{-3}. The different samples taken at the apex of the Adygene fan along showed densities of $\rho 1$ = 2130 kg m^{-3}, $\rho 2$ = 1930 kg m^{-3} and $\rho 3$ = 2000 kg m^{-3}.

Figure 10 provides an impression of the main sectors of the debris flow system and deposits of the 2012 event, namely, the entrainment, transit and deposition zones (Fig. 11). According to field observations in the initiation (starting zone in Fig. 11) and main entrainment zones (erosion zone in Fig. 11), (which were up to 4 km long, Fig. 11), sediment and debris were incorporated into the flow through the erosion of the stream bed and adjacent valley banks. It was estimated that the entrainment of material in the erosion zone, which has stream slopes ranging from 30° to 17° (Fig. 11), was around 15 ± 10 m^3 per 1 m of the flow. Entrainment of loose material further upstream and close to the starting zone was much more limited. Along the subsequent segment of the main entrainment zone, we observe an entrainment area, in which debris was mainly entrained through side erosion of the banks: stream slopes are slightly lower here (between 14° and 20°). The entrainment rate was mostly controlled by channel slope; ground ice was observed in the uppermost part (starting zone), which in turn might have decelerated the entrainment rate.

The third zone (transit zone in Fig. 11) has a length of around 2.5 km and was characterized by the transit and partial deposition of debris flow material (17°<slope<6°). The depositional zone of the 2012 debris flow was about 1.5 km in length, with a much lower slope (2°–9°) than the previous sections; this zone also included the fan area. This sharp decrease in slopes favoured deposition of the largest proportion of material transported by the debris flow. Based on information on the depositional area and its approximate height in those parts for which an assessment was possible, the total volume deposited on the Adygene fan was estimated to ca. 200,000 m^3.

As such, debris flow deposition on the Adygene fan can be seen as a textbook example in terms of the relation between channel gradients and the deposition of GLOF-triggered debris flow material. Whereas Hungr et al. (1984) defined deposition of debris flows to start as soon as the channel gradient ranges between 10° and 14° for unconfined flows and between 8° and 12° for confined flows, O'Connor et al. (2001) still observe erosion at reaches >8°, whereas deposition occurred primarily in reaches with gradients <8°, but

Table 2 Width (W), maximum height (H), drainage area (A), slope (I), slope (°), flow velocity (V) and discharge (Q) of the debris flow as calculated during the post-event survey. The location of the reaches is indicated with arrows in Fig. 2c

Cross section	W (m)	H (m)	A (m^2)	I ($m\ m^{-1}$)	(°)	V ($m\ s^{-1}$)	Q ($m^3\ s^{-1}$)
1	15	2	30	0.33	18	5	144
2	12	4	100	0.3	17	7	341
3	23	3	115	0.27	15	6	324
4	30	2.5	112.5	0.1	6	5	285

also occurred locally in channel expansions and on fans with slopes as great as 18°. In this sense, the definition and ranges provided by O'Connor et al. (2001) match perfectly with our observations and in the context of the 2012 GLOF and debris flow.

After having deposited most of its material on the Adygene fan, the 2012 event (Fig. S5A) transformed again into a hyperconcentrated flow and reached the Ala-Archa River and the city of Bishkek hours after its initial triggering and in the form of a flood (Fig. S5). The 2012 debris flow and downstream flood did not have severe consequences; however, the potential damming of the Ala-Archa River could have triggered much more destructive flash floods in the valley and even at the level of Bishkek, as evidenced by the devastating GLOF-triggered flood in the same catchment in 1953.

Comparison of the 2012 event with a debris flow in 1953

When comparing the recent event in 2012 triggered by Teztor-2 GLOF with the debris flow in 1953 triggered by Teztor-1 GLOF (the latter is the largest event recorded in the Teztor valley), some differences become obvious in the release and process behaviour. Although volumes of both lakes were similar before the events: $80 \times 10^3\ m^3$ in 1953 and $74 \times 10^3\ m^3$ in 2012, and peak discharges of debris flows transformed from GLOFs were about 400 $m^3\ s^{-1}$ in 1953 (Kroshkin and Talmaza 1960) and around 350 $m^3\ s^{-1}$ in 2012, there is a great difference in volumes of deposited debris on the Adygene fan by the 1953 and 2012 events, as indicated in Fig. 12. While the debris volume from the 2012 GLOF was 200,000 m^3, as was mentioned before, the debris flow triggered by the glacial lake outburst in 1953 resulted in the deposition of ca. 1.2 million m^3 (Erokhin

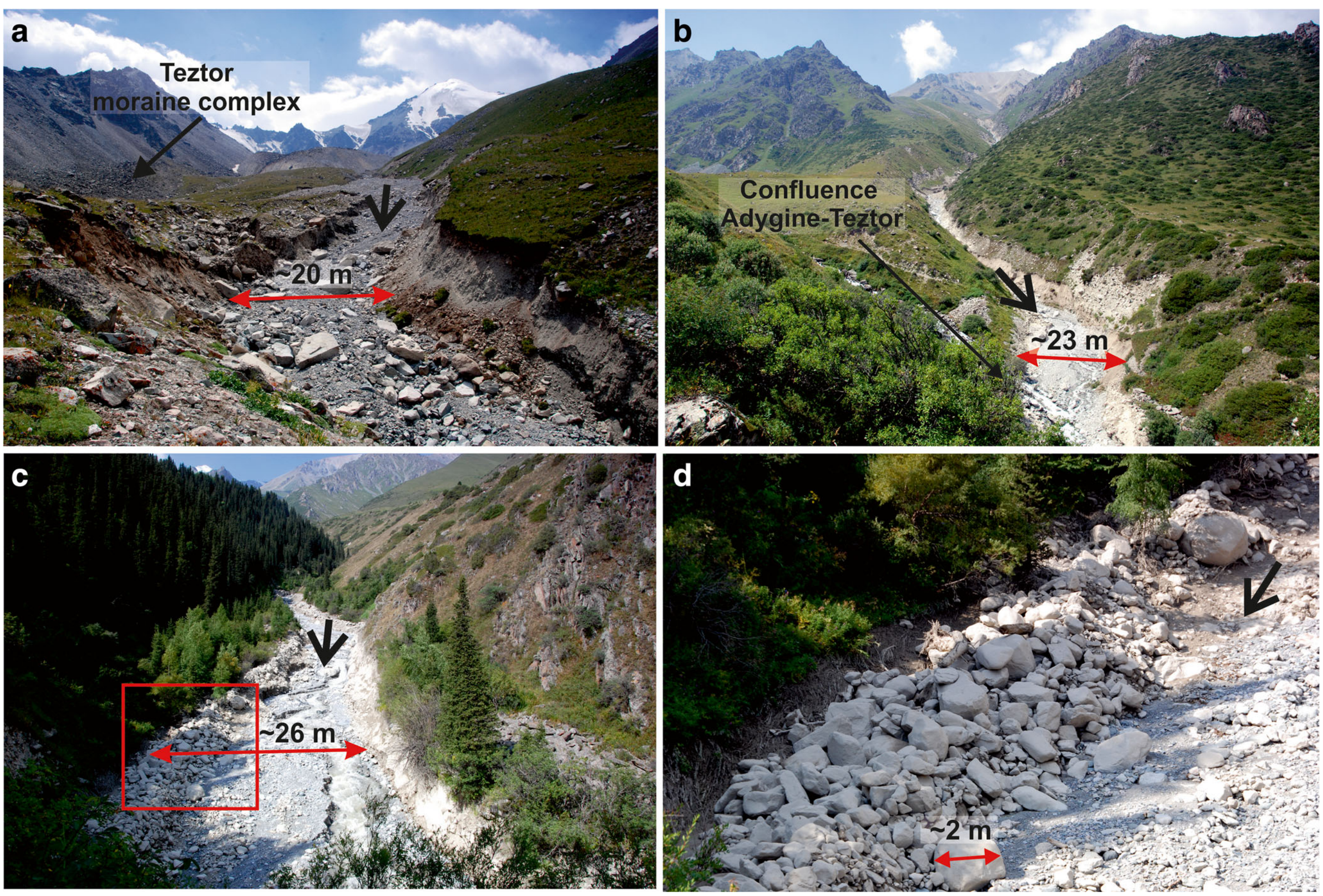

Fig. 10 **a** Main entrainment zone in the upper catchment reach (picture taken between cross sections 1 and 2 in Fig. 2c). **b** Confluence of the Teztor torrent with the Adygene stream (cross section 2 shown in Fig. 2c). **c** depositional zone upstream of the fan (Fig. 2c shows a lower channel stretch from the cross section 4 site), with the *red square* indicating the position of the (**d**) detailed view of the debris flow levee with boulders of up to 2 m in diameter. *Black arrows* indicate the flow direction

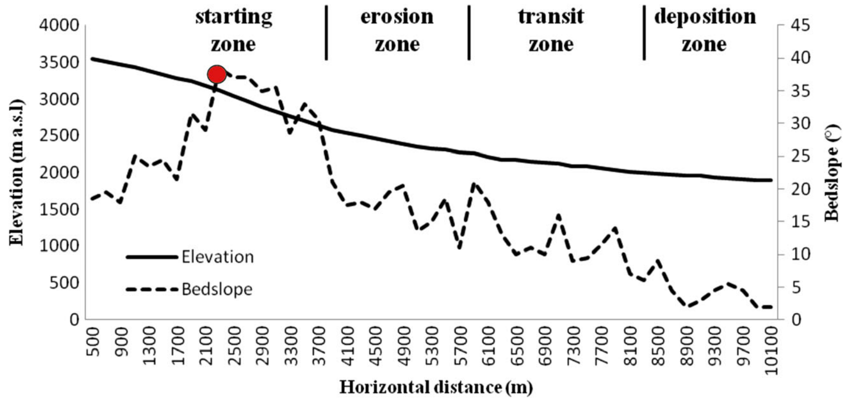

Fig. 11 Longitudinal profile and bed slope along the debris flow path. Horizontal distance refers to the distance from the snout of Teztor Glacier to the lower fan margin. The main process zones are shown in the *upper part* of the graph (described in the text). The *red dot* shows the location of the lake outburst

and Dikikh, 2003), which is six times larger than that in 2012. The maximum flow height was observed to be around 3–4 m along the straight sections and between 6 and 8 m in bends. Such a big difference may be explained by the depletion of debris availability in the entrainment zone after the powerful debris flow in 1953, which incorporated and carried away much of the available debris flow material. Moreover, and as an additional reason, the debris flow discharge in 2012 was also 50 $m^3 s^{-1}$ smaller than that in 1953.

Unlike the 2012 event, deposition of the 1953 debris flow spilled out sufficient material into the Ala-Archa River to temporarily dam the river and to give origin to the disastrous flood. This large event damaged the Ala-Archa road, electric power lines and resulted in a flashflood in Bishkek city (Erokhin and Dikikh, 2003). We assume that the deposits of the 1953 and other past events may have influenced the depositional area and the trajectory of the 2012 event on the Adygene fan and, together with the lower discharge of the debris flow, prevented river damming.

Meteorological triggers of the 2012 GLOF

It is apparent that hydrometeorological conditions, such as seasonal temperature rise, high solar radiation, which increases the snow and ice melting and thus the lake water level, also caused by heavy precipitations, are a common trigger of GLOFs. Analysis of debris flow event triggered by Lake Teztor 2 outburst requires an in-depth understanding of meteorological triggers. Available meteorological data obtained from the Adygene research station show significantly increased air temperature values (from 8 to 18 °C) and lake water temperature values (from 2 to 4 °C) between July 29 and July 31, 2012 (Fig. 6, Fig. 13).

Analysis of the recorded precipitation totals and values derived from reanalysis data points to cumulative precipitation sums for July 2012 of 80 and 173 mm, respectively (Fig. 14a), with a first series of precipitation events recorded between July 8 and 12, 2012, and another just before the occurrence of the GLOF between July 24 and 30, 2012. This latter event was important according to the CFSR data with daily values exceeding 30 mm (Fig. 14a); however, only 16 mm was recorded at Adygene station which is located just across the ridge of the moraine complex and therefore very close to the site of the event (Fig. 14c). According to the data from CFSR, solar radiation dropped significantly during both storms, but was relatively high during the GLOF event with values above 30 W/m^2 (Fig. 14b). Relative humidity was also low the day before and the day of the GLOF, and exhibited the lowest values of the month of July 2012 (45%; Fig. 14d).

We hypothesise that the high radiation, in combination with the low humidity, may have led to an abrupt increase of air temperatures. The maximum air temperature as provided by the CFSR data series showed values of 19–20 °C on July 31, 2012 (i.e. the day of the GLOF), with an increase with respect to the previous days of about 3–5 °C. Analysis of CFSR data also revealed that the minimum and maximum air temperatures were slightly higher than the normal (when compared to the period 1979–2014) day of the GLOF event. Moreover, from July 25 to 30, 2012, rainfall totals were much higher than usual for this season as well (Fig. 15).

The CSFR data, as any reanalysis dataset, has some limitations (Fuka et al. 2013) and potential inconsistencies, and these issues are not only related to the fact that the stations are not exactly located in the area where the GLOF indeed occurred (see Fig. 2). The absolute values and observed anomalies should therefore be seen as a proxy and therefore serve as one set of possible explanation of the processes which have taken place in the upper part of the Teztor lakes complex. Despite these limitations, we believe that this data can be used—and that they in fact are representative—to describe the overall climate before and during the event. As such, and in the absence of field-based evidence, they can help to better understand the anomalous meteorological conditions that may have triggered the most recent GLOF on record in the catchment.

The postulated temperature increase in the CSFR dataset is confirmed by the values recorded at the Adygene station (Fig. 13). In view of this additional line of evidence, we argue that the outburst of Teztor-2 was indeed conditioned by excessive antecedent precipitation during the month of July 2012, and by the rapid rise in air temperatures towards the end of the month, which could have favoured rapid melting of residual winter snow and snow accumulated in early summer, considering that June and early July in 2012 were characterized by the highest historical precipitation amounts since 2008 (Fig. 6), and would thus have intensified runoff into the lake. The rapid rise of air temperatures and the consequent rise of lake level and water temperatures would have favoured accelerated wasting of buried ice in moraine dam (according to the potential increase in lake water density at 4 °C as described by Greenwood and Earnshaw 1997) and the drainage of lake water through intra-moraine channels.

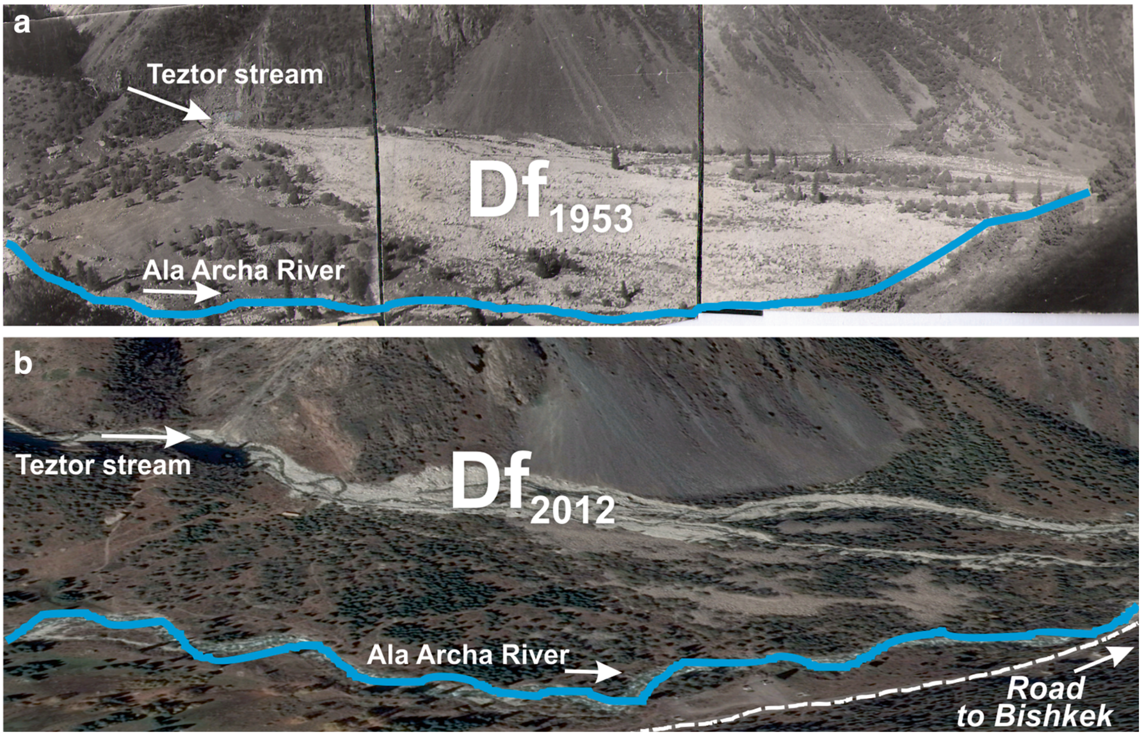

Fig. 12 Oblique aerial view of the debris flow path some days after the event in 1953 (**a**) and 2012 (**b**). Df_{2012} debris flow 2012 depositional fan, Df_{1953} debris flow 1953 depositional fan

Concluding remarks and implications for debris flow and flood hazards

The stability of glacial lakes, the possibility of catastrophic failure as well as the occurrence of subsequent outburst floods and debris flows have received much attention in the past in various high-mountain environments of the world. GLOFs and glacial debris flows are important hazards in Central Asia and the Tian Shan region in particular, with potentially large risks for downstream population centres.

The case study presented here differs from others for a number of reasons: first, it presents one in only a few cases for which substantive field-based evidence and reliable data are available within the Tian Shan region (Zaginaev et al. 2016). In addition, the process leading to the release of the GLOF was through intra-moraine channels, and not related to the breaching of a moraine-dammed lake. According to our observations and previous work (Narama et al. 2010), the outburst floods passing through englacial and intra-moraine channels exhibit lower peak discharges than those observed during the mechanical and/or sudden failure of ice-and moraine-dammed lakes (Walder and Costa 1996; Huggel et al. 2004a, b). However, intra-moraine drainage from small lakes can also lead to serious damage, as was shown in the case of the Teztor Glacier lakes, because even small outburst volumes may

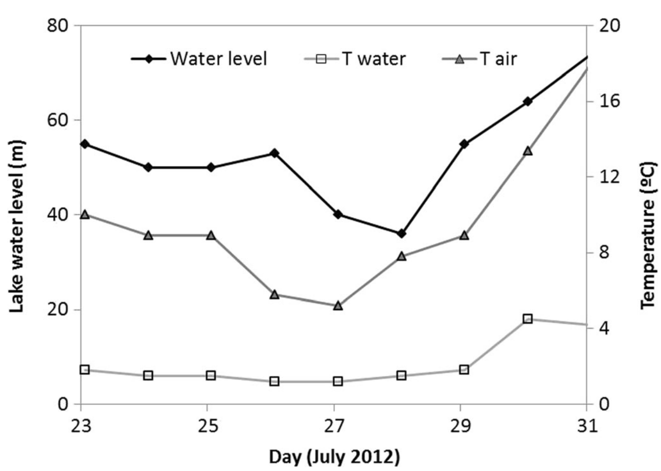

Fig. 13 Adygene Lake water level, lake water temperature and air temperature as recorded at Adygene research station during the final week of July 2012 and before the outburst on July 31, 2012

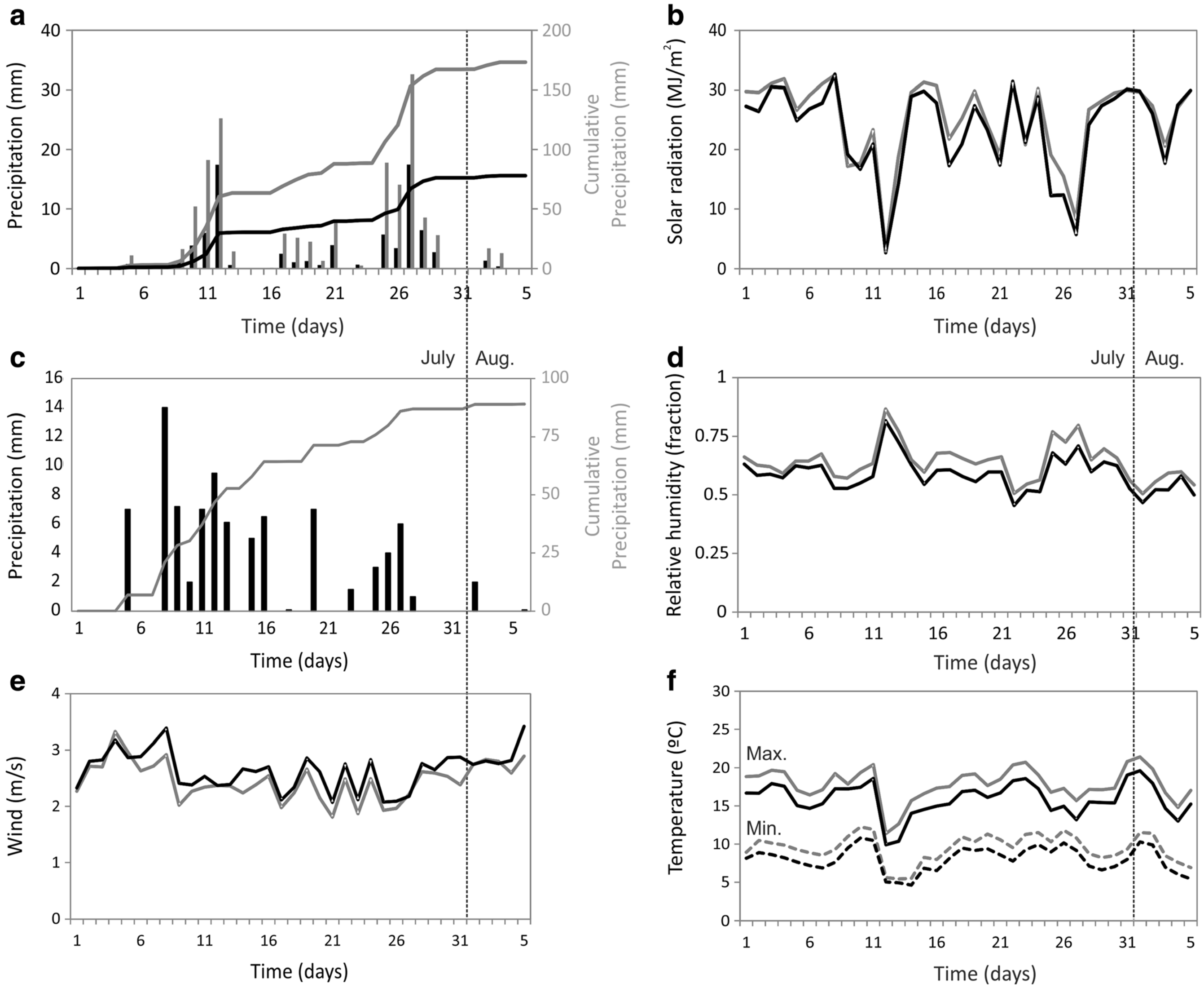

Fig. 14 **a** CFSR-extracted daily precipitation. **b** CFSR-extracted solar radiation. **c** Recorded daily precipitation at Adygene station. **d** CFSR-extracted relative humidity for the month of July and the first days of August 2012. **e** CFSR-extracted wind velocity; **f** CFSR-extracted maximum and minimum temperature (*grey* and *black lines* in graphs **a**, **b**, **d**, **e** and **f** as provided by CFSR at two available weather stations (see Fig. 2): longitude 74.375; latitude 42.619; elevation 2715 m a.s.l.; longitude 74.687; latitude 42.619; elevation 2473 m a.s.l. within the bounding box)

ultimately result in hazardous debris flows (Haeberli 1983; Yafazova 2007). Even if the development of non-stationary glacier lakes discussed in this paper represents an exceptional situation internationally, lakes like the ones described here tend to be very frequent in Kyrgyzstan and can lead to the repeated occurrence of GLOFs from the same system (Kubrushko and Staviskiy 1978; Zaginaev et al. 2016). The hazard assessment for this type of lakes is possibly more challenging than that of conventional high-elevation lakes, and cannot rely solely on morphological or physical properties (Haeberli 1983; Huggel et al., 2004).

As shown in this work, exhaustive field surveys provide valuable data to better understand the processes driving GLOFs from these environments, but this effort must be combined with a continuous monitoring and has to be complemented by remotely sensed approaches. The event in 2012 showed that the outburst of Teztor-2 was conditioned by the abundant antecedent precipitation and by the rapid rise in air temperatures, which could have favoured rapid melting of snow and glacier ice and rapid water level and water temperature rises. Therefore, at the sites where such lakes exist, continuous and accurate recoding of meteorological conditions is required to monitor potential triggering conditions. In addition, the monitoring of lake temperature might be of great value as well, and in particular to forecast thermokarst and melting processes that eventually may lead to lake outburst (Walder and Costa 1996). The hydrometeorological conditions that can trigger catastrophic GLOFs may also change in the future (Singh et al. 2014; Allen et al. 2015), yet knowledge on how such conditions can affect GLOF hazard is very limited (Allen et al. 2016).

The results obtained in this study provide information related to the initiation, entrainment and deposition sites in that basin, as well as on debris flow magnitude and volumes. All these aspects are fundamental for hazard assessments. The comparison of the event in 2012 with the larger debris flow that occurred in 1953 highlighted an additional hazard, the damming of the main Ala-Archa River. The geometry of the fan, the sediment stored in the

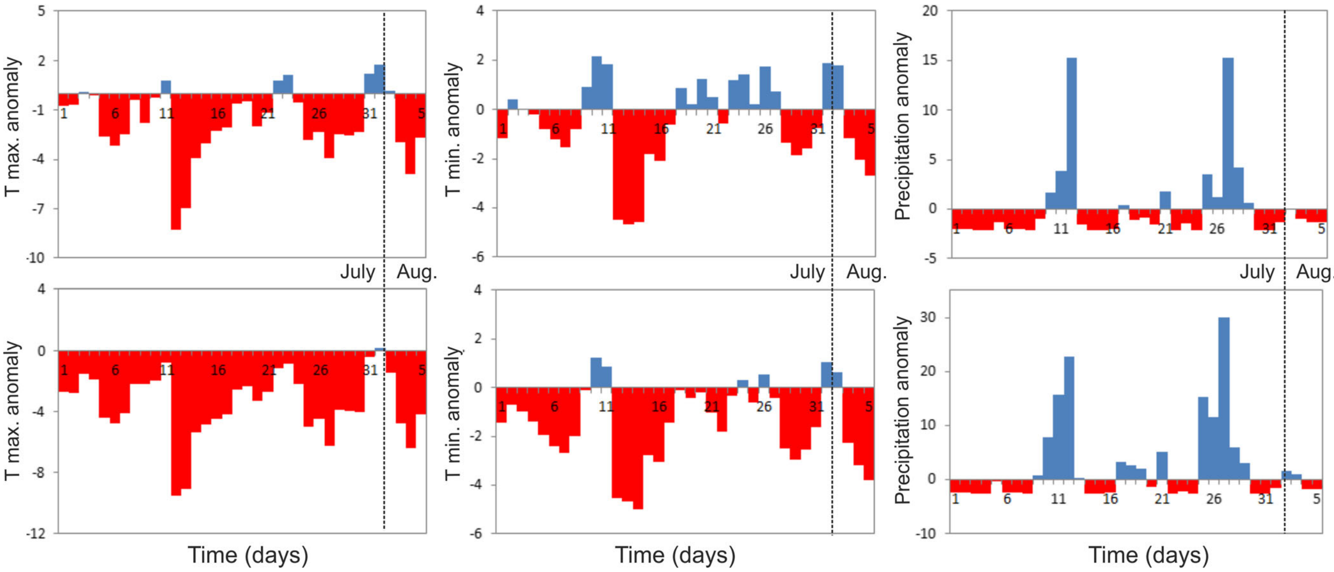

Fig. 15 Daily maximum and minimum temperatures and precipitation anomalies as provided by CFSR at two available weather stations (Longitude 74.375; Latitude 42.619; elevation 2715 m a.s.l.; Longitude 74.687; Latitude 42.619; elevation 2473 m a.s.l.; see Fig. 2) within the bounding box and in comparison to the period 1979–2014 for the month of July and the first days of August 2012

catchment and the persistence of the lakes in the moraine complex at Teztor catchment remain such that the main river can indeed be blocked again in the future, thus requiring further considerations and studies (Ruiz-Villanueva et al. 2016).

During the event in 2012, debris flow travel time between the location of the sensors and the frequented parts of the National Park was 6–8 min (Zaginaev 2013). This may not be enough to warn people and for them to escape exposed sectors. Therefore, more efforts are still needed to better understand the triggering conditions and the evolution of these processes at Teztor, but also in other locations within the Tian Shan range. GLOF hazard and risk reduction measures may therefore focus on disaster preparedness and response, combining a better understanding of triggering mechanisms, monitoring of hydrometeorological conditions and designing proper land use plans and early warning systems.

Acknowledgments
This work has been supported by the Swiss National Science Foundation, through the joint SCOPES research project "Debris flow and outburst flood hazard in Tian Shan under impact of changing climate" (DEFENCC; grant no. IZ73Z0_152301), and partially supported by the Russian Foundation for Basic Research (projects 14-05-00768 and 15-05-08694). We thank the contributions by Arjen Stroeven, Nat Lifton, Maxim Petrov, Irina Tomashevskaya, Mikhail Ivanov, Leonid Sokolov, Ryskyl Usubaliev and Eleonora Gygax. The paper has benefitted greatly from comments and suggestions from two anonymous referees.

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Electronic supplementary material The online version of this article (doi:10.1007/s10346-017-0862-3) contains supplementary material, which is available to authorized users.

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