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Brief Communication: The Khurdopin glacier surge revisited – extreme flow velocities and formation of a dammed lake in 2017

Jakob F. Steiner[1], Philip D.A. Kraaijenbrink[1], Sergiu G. Jiduc[2], Walter W. Immerzeel[1]

[1]Utrecht University, Department of Physical Geography, PO Box 80115, Utrecht, The Netherlands
[2]Imperial College London, Centre for Environmental Policy, Faculty of Natural Sciences, SW7 1NA, London, United Kingdom

Correspondence to: Jakob F. Steiner (j.f.steiner@uu.nl)

Abstract. Glacier surges occur regularly in the Karakoram but the driving mechanisms, their frequency and its relation to a changing climate remain unclear. In this study we use digital elevation models and Landsat imagery in combination with high-resolution imagery from the Planet satellite constellation to quantify surface elevation changes and flow velocities during a glacier surge in of the Khurdopin glacier in 2017. Results reveal that an accumulation of ice mass above a clearly defined steep section of the glacier tongue since the last surge in 1999 eventually leads to a rapid surge in May 2017 peaking with velocities above 5000 m a^{-1}, which is among the fastest rates globally for a mountain glacier. The time series of Landsat imagery reveals that velocities increase steadily during a four-year build-up phase prior to the actual surge and that the surge front advances towards the terminus after the peak has passed on the upper tongue. The surge frequency between the reported surges remains relatively constant at 18 (1999 to 2017) and 20 (1979 to 1999) years respectively. It is hypothesized that the surge is mainly initiated as a result of increased pressure melting caused by ice accumulation, i.e. the thermal switch hypothesis. However, surface observations show increased crevassing and disappearance of supra glacial ponds, which could have led to increased lubrication of the glacier bed. Finally, we observe that the surging glacier blocks the river in the valley and causes a lake to form, which may grow in subsequent years and could pose threats to downstream settlements and infrastructure in case of a sudden breach.

1 Introduction

Surging glaciers are not evenly distributed around the world's glaciated regions, but occur regularly under certain conditions (Sevestre and Benn, 2015). In the Karakoram, surges have been documented frequently since the end of the 19th century at numerous locations. In recent decades an increase in frequency has been reported (Copland et al., 2011; Hewitt, 1969, 2007). Two general mechanisms driving surges are proposed: (a) a build-up of ice mass during the quiescent phase in the reservoir zone of the glacier causing increased basal shear stress resulting in till deformation at the glacier bed referred to as the *thermal switch hypothesis* (Clarke et al., 1984; Quincey et al., 2011)), and (b) a collapse of hydraulic channels causing a switch from efficient surface and englacial drainage to sudden lubrication of the glacier bed referred to as the *hydrological switch hypothesis* (Kamb, 1987). Studies report surges in the region being controlled by both the first (Quincey et al., 2011) as well as the second mechanism (Mayer et al., 2011).

The Karakoram glaciers have received considerable scientific attention because of the anomalous regional mass balance (Kääb et al., 2015) and the large number of surging glaciers (Paul, 2015). Surging activity needs to be better understood in order to further our understanding of regional glacier behaviour. Moreover, understanding of glacier surges is important as they may result in natural hazards that are due to the formation of ice dams and potential blockage of rivers.

Surges on Khurdopin glacier, located in the Shimshal valley in Northern Pakistan, have been documented to occur since the late 1800s and the most recent surges have occurred in 1979 and 1999 (Copland et al., 2011; Quincey et al., 2011; Quincey and Luckman, 2014; Rankl et al., 2014). These surges were characterized by a gradual increase of velocities before the peak

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of the surge (Quincey and Luckman, 2014). During the surge events, the lower tongue is pushed further into the valley and has blocked the Vijerab River on several occasions, resulting in an ice dammed lake, similar to another well documented glacier in the region (Round et al., 2017). Sudden drainage of this lake has caused destruction to downstream villages, which led to the development of an early warning system with bonfires along the slopes of the entire Shimshal valley (Iturrizaga, 2005). So far these surges were solely described by investigating velocity data from distinct surface features of the glacier, using both coarse resolution satellite data, and field observations. Results show that the surge velocities can be up to two orders of magnitude faster than during the quiescent phase (Quincey and Luckman, 2014). In this study, we put these earlier findings into further context by investigating a new surge event in 2017 using novel satellite imagery. First we quantify surge velocities using automated feature tracking. We then quantify mass transport during quiescent and surge phases based on multi-temporal DEM analysis and we assess the potential hazard of lake formation using high-resolution optical satellite imagery. Finally, we discuss potential trigger mechanisms that may lead to the onset of the Khurdopin surge.

2 Data and Methods

To derive spatial velocities we use cross-correlation feature tracking using the COSI-Corr software (Leprince et al., 2007) on selected Landsat imagery between 1972 and 2017, and on Planet high resolution imagery between 2016 and 2017 (Planet Team, 2017) (Supplemental Table S1). Mass changes were computed using a TanDEM-X digital elevation model (DEM) from 2011 and a DEM generated from ASTER imagery from May 2017. Using the GlabTop Model (Frey et al., 2014) we computed ice thickness for the glacier and inferred the bed topography by deducting it from the SRTM DEM. Details on the specific COSI-Corr settings as well as the imagery used are provided in the supplementary material.

3 Velocities during surge events

Khurdopin glacier is approximately 41 km in length, 1.5 km in width with an elevation range between 3300 m a.s.l. in the Shimshal valley to 7760 m a.s.l. at the peak of Kanjut Sar. It is heavily debris covered on the lower 10 km of the tongue and distinct meandering debris bands typical for surge type glaciers are present up to 20 km from the terminus. While the western debris band seems to originate from the flanks of Kanjut Sar, the medial moraine is sub-glacially sourced. To investigate velocities on Khurdopin we separated the tongue into 25 bins, each spaced at 1 km along the centreline (Figure 1), and calculated the mean velocity within the bin. Using high-resolution imagery from the Planet satellites with sub-weekly overpasses (Planet Team, 2017), we are able to characterize the surge event and the surface dynamics on the lower tongue and near the glacier terminus. The surge of Khurdopin observed in 2017 confirms a recurring cycle typical for surging glaciers, ~20 years in this case (1979, 1999, 2017). Mean average surface velocities on the main tongue of Khurdopin (25 km in length) during a quiescent phase are below 5 m a^{-1}, with a small peak at 15 m a^{-1} around 12 km along the tongue, which corresponds to a markedly steeper section of the profile (Figure 1). While lack of cloud free imagery or poor image quality does not always permit to accurately date onset, peak and stop of a surge, the data suggests that a gradual increase of surface velocities between 1975 and 1979 led to a surge in July 1979. Surface velocities in the *build-up* phase are below 100 m a^{-1} until the year of the surge and quickly rise during a three-month period prior to the peak velocity of 4000 m a^{-1} (Quincey and Luckman, 2014). Visual analysis of the second surge shows that surface velocities increase in 1998 after a quiescent phase and peak in spring 1999 reaching beyond 2000 m a^{-1}, which is slightly later and faster than what is reported by Quincey and Luckman (2014). The subsequent quiescent phase lasts until at least 2011. By 2013 the glacier has reached surface velocities above 100 m a^{-1} beyond the steep section (km-12), but still smaller than 10 m a^{-1} in the lower 5 km. The *build-up* phase between the quiescent phase and the actual surge peak is characterised by increasing surface velocities in the tongue's upper reach (Figure 1). By the end of 2016, surface velocities have reached 400 m a^{-1} around km-12 and nearly 20 m a^{-1} between km-2 and km-4 and by April the glacier has further accelerated to velocities of more than 1000 m a^{-1} between km-7 and km-20. The peak velocity of the most recent surge was reached between the last days of May and the 3rd of June

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2017, with highest mean observed velocity just above 5000 m a^{-1} around km-10. Velocities near the terminus, between km-2 and km-4, were still below 300 m a^{-1} at that point. By the end of June the glacier slowed down to less than 3000 m a^{-1} between km-5 and km-15 but accelerated to > 1500 m a^{-1} just above the terminus. This advance of the surge front with a simultaneous decrease of velocities further up-glacier corresponds to observations on other surge-type glaciers in the region (Quincey et al., 2011). The increased velocity and associated ice mass redistribution result in increased strain rates, evidenced by crevasses appearing at the glacier surface since early May with a marked increase in size and number since mid-June (Figure 3). Note that the first 1 km of the tongue has remained completely unchanged during the surge as in recent decades, and melt water ponds on the surface indicate it to be likely an ice cored moraine by now (notably the area below the green line in Figure 3). This makes it difficult to discern actual length changes due to the surge.

4 Mass changes during surge events

Apart from increased velocities, surges logically also result in large amounts of displaced ice mass. In many cases this results in a rapid extension of the positon of the glacier's snout. However, for the case of Khurdopin the terminus does not advance and has not done so during at least the recent surges, since it turned into a stable moraine. This makes detection of actual length changes of the active tongue visually difficult (Figure 1). Using three DEMs (SRTM in 2000, TanDEM-X in 2011 and ASTER in 2017; Supplementary Table S2) the elevation change rate from the quiescent phase after the last surge to the build-up and surge phase are quantified (Figure 2). The transition from positive to negative elevation change during the quiescent phase is clearly notable and coincides with the steep section of bedrock around km-12 (Figure 2, panel a). This distinction is again visible exactly at the same spot in the reverse case, when elevation change is positive in the lower reach where mass is accumulating. During the surge in May 2017 the glacier surface between km-3 and 12 has likely gained height by approximately 80 m, considering the mean change between 2011 and 2017 and accounting for the fact that elevation changes between 2011 and 2016 were likely negative due to melt, at rates comparable to those of the quiescent phase. Averaged over the entire glacier we estimate that the overall mass loss is slightly negative, similar to what is reported by Bolch et al., (2017).

5 Hydrology and Hazards

The tongue of the Khurdopin glacier reaches across the main valley floor. As a consequence this glacier has blocked the local Vijerab river multiple times in recent decades, which has repeatedly caused considerable damages to settlements downstream (Iturrizaga, 2005). The blockage is caused as the tongue pushes towards the opposite headwall of the main valley (Figure 3). Most of the reported lake drainages were however not catastrophic and happened gradually as the river water slowly erodes the glacier ice similar to other regional glacier lakes (Haemmig et al., 2014). From historic Landsat imagery it is obvious that a lake formed during the melt season in two consecutive years after the surge in 1999, likely because the added mass required considerable time to be eroded. In late April 2017, the lake formed at exactly the same location, growing quickly from 0.02 km^2 at the beginning of May to 0.06 km^2 one month later and more than 0.1 km^2 on the 28th of June, reaching a lake depth of ca 2 m. Ice floes on the water surface indicate ice calving from the advancing tongue and could pose an additional threat as they could block a drainage channel temporarily and create a sudden spill upon disintegration. Projected extents based on the DEM analysis correspond well to what was observed in 2000, when the lake was 0.7 km^2 (Figure 3). Considering the height of the advanced glacier tongue – between 15 m at the fringe and up to 80 m at the centre – and a potentially large influx of sediments from Vijerab and Khurdopin subglacial drainage systems, we show potential lake extents that could reach up to 1 km^2, possibly during the melt season of 2018 or 2019.

6 Discussion and Conclusion

The data collected and analysed support earlier studies on Khurdopin in the observation of a constant return period of a glacier surge of 20 years, irrespective of a changing climate and surges of nearby glaciers (Quincey et al., 2011; Quincey and Luckman, 2014). Using distributed velocity and elevation change data we furthermore show that a division point exists at 12 km up-glacier that separates two distinct reaches of the tongue: (a) the upper reach where velocities gradually increase during the build-up phase and mass continuously accumulates during the 19 years of quiescence, and (b) the lower reach where velocities peak during the surge and the ice mass previously accumulated in the upper reach is relocated within only a number of weeks. This line likely coincides with a steep bedrock section and is located just below a tributary that possibly supplies a lot of additional mass via avalanche deposits. The surge of 2017 showed a similar four-year build-up time as the surge in 1979 over which the glacier surface in the upper reach increased by approximately 3 m a^{-1} and decreased by up to 7 m a^{-1} in the lower reach. This period is defined by constantly increasing velocities in the upper reaches. In combination with a gradual accumulation of mass during quiescence the actual surge starts rapidly when a tipping point is reached, as the increased pressure causes basal conditions to switch from cold to temperate. This points to the thermal switch hypothesis (Clarke et al., 1984) being at play, as suggested earlier for this glacier (Quincey and Luckman, 2014). However, the sudden absence of supraglacial ponds on the terminus during the surge and the formation of a supraglacial pond in May 2000 after the last surge exactly at the location of the clear line of change around km-12, could also point at a disturbed englacial network playing a role in the surge (Kamb, 1987; Mayer et al., 2011). At least the last two surges occurred at the beginning of the melt season, which could further catalyse the surge if melt water reaches the ice-bedrock interface. Basal sliding is most likely the dominant flow process as the cross profiles of surface velocity indicate plug flow, characterized by flat rather than parabolic velocity as during the quiescent phase (Kamb et al., 1985). The surface velocities observed during the peak surge in May 2017 on Khurdopin glacier are the fastest so far reported for the region. In their magnitude and rapid acceleration and deceleration they are comparable to similar bursts at the closely investigated Variegated Glacier (Kamb et al., 1985). As a consequence of the surge a lake has formed in the proglacial valley, similar to earlier surges. We quantified its evolution and potential future expansion as it is very likely that the lake will reappear during melt seasons in the following two years until the accumulated mass has sufficiently eroded for the water to drain freely. Exploiting the potential of only recently available high-resolution imagery with frequent overpasses as employed in this study, could lead to a better understanding of such surges as it provides the potential for more accurate velocity data (Altena and Kaab, 2017). Additionally, it would also enable faster assessment of risk potentials and subsequent warning of affected communities.

7 Author Contributions

JFS, PDAK and WWI designed the study, JFS and PDAK carried out the data analysis, JFS wrote the manuscript. SGJ pointed out the occurrence of the surge and provided contacts to the local authorities. PDAK, SGJ and WWI reviewed the manuscript.

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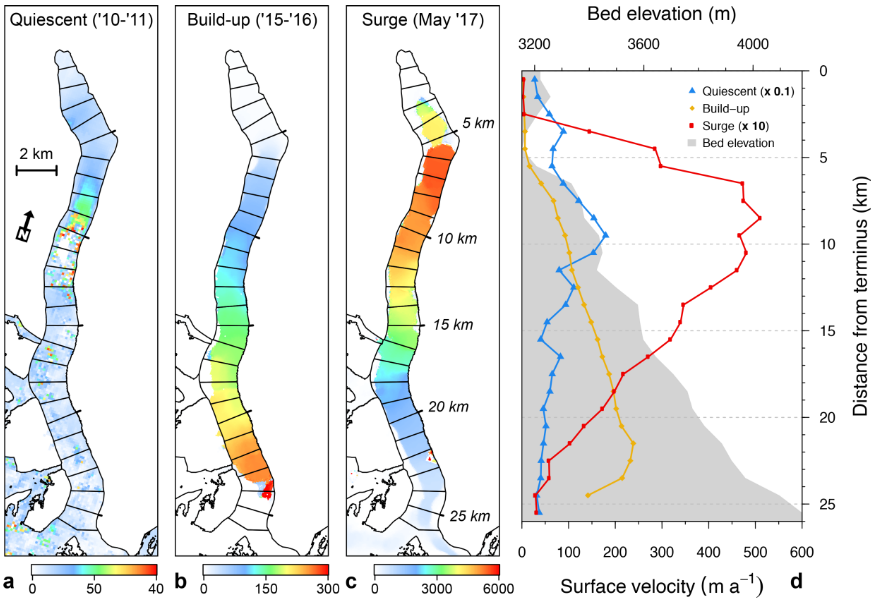

Figure 1: Velocities measured from cross correlating Landsat 7 and 8 imagery of one year of the quiescent phase (a; 17th of October 2010 – 18th of September 2011), the last year of the build-up (b; 28th of August 2015 – 10th of May 2016) and the surge peak in May 2017 (c; 13th to 29th of May, 2017). Panel (d) shows mean values of the bins compared against bed elevation. Note the difference in scales for the different phases.

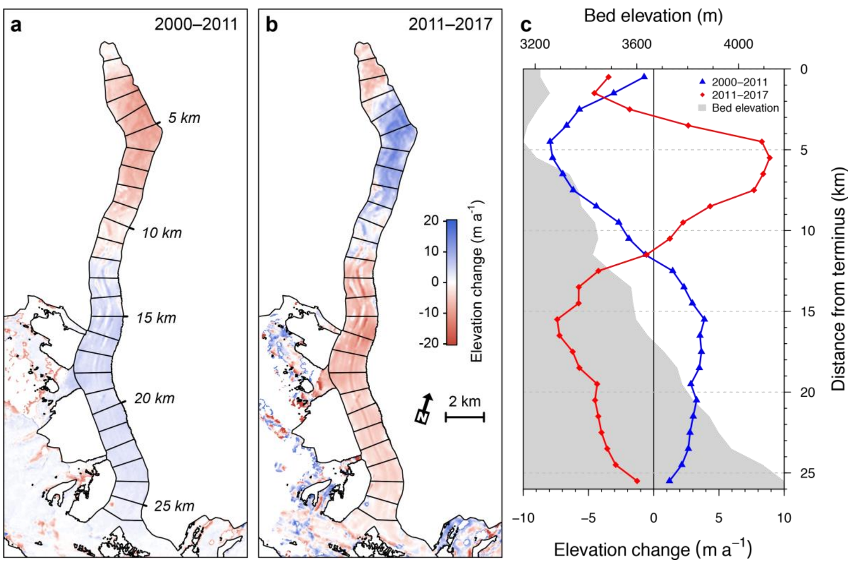

Figure 2: Elevation change rates during the quiescent phase (a), and during the build-up and surge phase (b). Mean values per bin are shown in panel (c). Note that the change that is due to the surge specifically (occurring only in a few months in 2017) is much larger than what is shown, as the difference between the 2011 and 2017 DEM includes at least 4 years of mass loss on the lower, and mass gain at the upper part of the tongue.

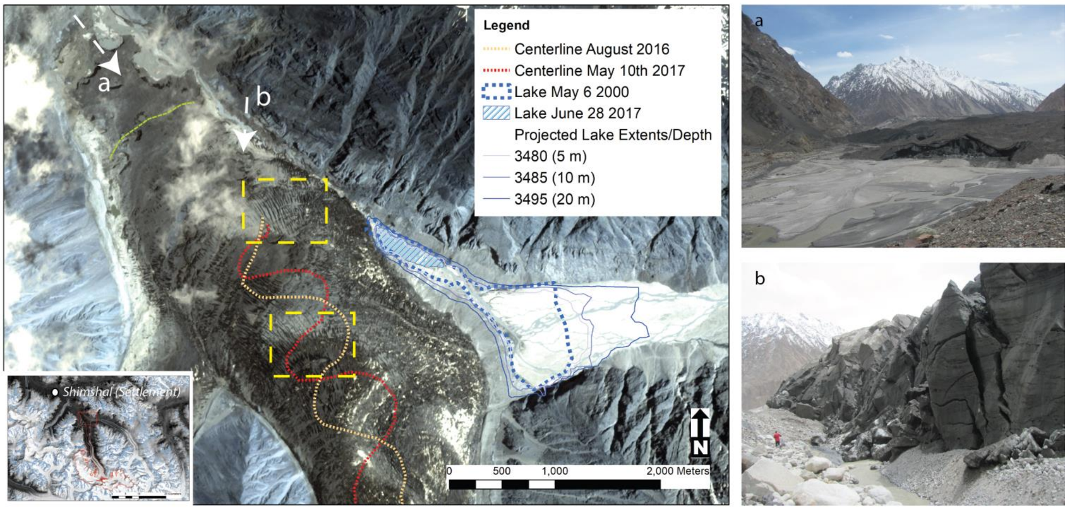

Figure 3: Evidence from the surge event visible at the tongue. The left panel is based on a Planet image from the 28th of June 2017 (Planet Team, 2017)**, the centrelines and the lake extent in 2017 are also mapped from Planet imagery. The lake extent in 2000 is mapped from the panchromatic band of Landsat-7. The projected lake extents and depths are computed based on the SRTM-DEM. The yellow rectangles show areas of heavy crevassing. Arrows at (a) and (b) denote angle of view for images on the right. Panel (a) shows an overview of the front of the tongue and panel (b) shows the front of the advance. Note the fine dark sediments often associated with a surge event. The tongue below the dashed green line remained stable during the surge. (Photos: Waheed Anwar)**