Response to Reviewer

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

Reviewer: D.Quincey

We greatly appreciate the concerns raised by the Reviewer and respond to each of them below. Original comments by the reviewer are in bold, followed by our response. Note that the page and line number are always given twice, once for the document with markups which is provided at the end of the Response, and once to the revised manuscript without markups, which will be provided later.

The key take-home message is currently a bit hidden. It seems to me that the new findings are: 1. that the surge return period appears to be of the order of 20 years (whilst acknowledging that n=2); 2. that surge velocities may be even faster than previously realised – implications for erosion and sediment transport; 3. that there may be a topographic control on this particular surge (but this needs much greater discussion – see following point); 4. that the ice-marginal lake is posing a hazard to local communities.

If the abstract and the conclusions could be modified to give the key message much greater prominence the manuscript would have greater impact. 2. The relevance of the steep bed topography at 12-km needs some further discussion/ explanation. Is the suggestion that it provides a control on surge dynamics? Or even that it is responsible for the spatial imbalance in flow? Presumably it doesn't provide a bottle-neck to flow (I imagine the opposite if anything)? Is the modelled ice particularly thin above the step and potentially frozen? Some consideration of the possibilities would be a welcome addition. 3. There appear to be many more velocity datasets discussed in the text than presented in the figures. Is there a reason for not showing all of the velocity data? It would really help with visualising the evolution of the surge to have them all (or at least more than the current three) available. 4. The discussion of whether the surge is thermally or hydrologically triggered lacks real evidence so I would suggest toning it down or even removing it. It is likely that both thermal and hydrological processes will be at play as you infer in your own discussion. 5. There needs to be some uncertainty analysis of the dh/dt data. How well coregistered were the DEMs? Showing off-glacier areas of dh/dt data (and velocity data) would help here, as would the distribution of those values. This extra analysis would be a good addition to the Supplementary, with uncertainty shading added to the figures and an error range added to the values stated in the main text.

We would like to thank the reviewer for these suggestions and our response is found below.

We have adapted the abstract and especially the discussion and we have toned down the discussion on the switch hypothesis. We also extended this analysis of the steep topography section at km-12 and this reveals that ice deformation as well as hydrology may be important drivers. By now showing all velocity data of all time steps during the surge, we show the added value of these new satellite products, also for broader applications. We have also added a quantification of the DEM errors and we show this in figure S1 in the supplementary material.

Minor comments:

P1 12: 'during a surge of the Khurdopin Glacier in 2017.' (also elsewhere, glacier should be Glacier where you are referring to it by name).

Thanks for pointing this out. We have amended it throughout the manuscript.

P1 15-16: I'm not sure there is evidence for a surge front in the data you show here?

Thanks for pointing this out and as reviewer 2 has pointed out, the definition of front may have been used too subjectively here. Compared to other surges in the region and as you pointed out in (Quincey and Luckman, 2014), perhaps Khurdopin can be classified as not having a surge front. We have removed the reference to a front in the text.

P1 19-20: do you show these surface observations? It's difficult for the reader to believe the extra lubrication suggestion without seeing evidence.

In the Brief Communication format we are limited in terms of space and we have refrained from showing additional images. We agree however that this is an essential aspect and should be visualized. We have therefore included a 2-panel plot showing this distinct change in surface features in Fig 3.

P1 26: this is maybe misleading: : : has an increase in frequency been reported? Or just an increase in number? And is that not because we have better and better data? Without repeat datasets (like those presented here) we can't say for sure whether frequency is increasing or not.

We have based our statement mainly on the observation in these two papers, where especially (Copland *et al.*, 2011) argues that *"Given that our ability to detect surging using satellite imagery has remained essentially constant since the 1970s, we must therefore consider whether there have been changes in forcing over time."*. We agree however that this cannot be fully ascertained from the data we have and have therefore amended our text accordingly in P1L30 / P1L26. For Khurdopin specifically no increase in frequency can be found. If we can take the main floods from upper Shimshal as a proxy (1979, 1960, 1944, 1923, 1901 or 1904 and possibly 1882), this corresponds to return periods of 22 (19), 19 (22), 21, 16, 19, 20 and 18 years from the end of the 19th century until today (Hewitt and Liu, 2010).

P1. 34-35: what do you mean by 'understanding regional glacier behaviour'? Is 'in order to advance knowledge of basal processes, non-steady flow more generally, and erosion and sediment transport in the region' perhaps a better justification?

We agree that our explanation is too generic and we have replaced it including the suggestions made in P2L1 / P1L36.

P2 3: name the glacier here, and also specify in the next sentence that it's the Khurdopin lake (not Kyagar) that has previously caused destruction.

Thanks for the comment, we have adapted the text at P2L10 / P2L7.

P2 8: maybe 'recent' is better than 'novel' here? Novel implies something a bit different about it.

Thanks for pointing this out, we have changed this as suggested.

P2 9: do you actually quantify the mass transfer somewhere? I don't see it.

We have now provided an estimate of the volume flux based on the height changes in P4L16 / P3L26. As we do not have full glacier coverage with the DEMs (with the areas above the tongue being especially erroneous) and there is uncertainty in the DEMs, we cannot close the mass balance. It is therefore not possible to quantify the total volume/mass flux.

P2 16: was the ASTER DEM derived by USGS? Or by the authors? In either case, some further information is required about its expected vertical accuracy and how well it performs against the TDX DEM.

The ASTER DEM was generated through the AMES pipeline (Shean *et al.*, 2016) and we have now specified this in P2L27 / P2L19 and additionally added a discussion of vertical accuracy and our applied corrections in the Supplementary Material.

P2 22: can you add the value (of mass loss) here?

We have added a value of volume change in P4L16 / P3L26.

P2 23: is it subglacially sourced for sure? I've always imagined it to be plucked from the spur where the two main tributaries meet.

This may indeed also be the case. As Reviewer 1 suggested however this information is not strictly essential for this paper so we have removed the whole sentence.

P2 26-27: is there a reason why you don't show these finer resolution velocity data?

We have initially omitted showing these data for reasons of space in the Figures. However, also in accordance with Reviewer 1, and to further underline the value of the new Planet data we now show all velocity profiles during the surge in Figure 1 and provide all profile data in TableS3 in the Supplementary Material.

P2 31: maybe reword to 'does not always allow the onset, peak and termination of the surge to be accurately identified, the data suggest that'?

We have changed this as suggested.

P2 32: not sure 'build-up' needs italics (here or at line 38)?

This is indeed not necessary and we have amended it.

P2 32-40 change to past tense here ('were below… and quickly rose…increased in1998… and peaked in spring 1999… phase lasted until… glacier had reached… was characterised by… velocities had reached…had further accelerated')

Thanks for taking time for these comments, we have changed to past tense accordingly.

P3 7: I'm not sure Figure 3 really supports this statement

To support this statement we have now adapted Figure 3 to show the ponds before and crevasses after the surge.

P3 9 and 14: if the lowermost 1 km of the glacier is not impacted by the surge is the length change not zero? What is meant by length change here (if not position of the terminus)?
In Section 4 we refer to the changing part as "active tongue", which is the part of the tongue above the green line in Figure 3. Like on neighbouring Yazghil Glacier, Khurdopin has developed an ice-cored moraine at the terminus that downwastes but does not change position anymore since many years. As such it does not seem to be dynamically connected to the actual tongue anymore. We have clarified this in the text.

P3 20-21: this is a long section between the commas – consider moving 'at rates comparable to those of the quiescent phase' before the first comma

Also based on comments by Reviewer 1 we have revised and shortened this sentence.

P3 32-38: it should be a short step to calculate the volumes from the DEM data – these values would be a valuable inclusion here.

We have now added an estimate of ice volume gain in P4L16 / P3L26.

P4 21: not quite true. The recent Hispar paper (doi:10.3390/rs9090888) by Paul et al. show comparable velocities

Thanks for pointing this out, since this publication was published after our submission we have not included it. We have now referred to it accordingly in P6L5 / P4L37.

P4 25-27: as far as I can tell the Planet imagery did not contribute to the data you present here other than the overview in Figure 3.

Also following the main comment from the reviewer we have now made sure to emphasize the value of the Planet data for this study throughout this Section and in the Discussion. Additionally, we show all velocities derived from Planet pairs in figure 1 and in the Supplementary Material.

Figure 1: some co-ordinates either here or in the text would help readers not familiar with the glacier to locate it.

We now refer to figure 3 in figure 1 for a location and have provided coordinates in P2L4 / P2L1

Figure 3: I'm not sure the wiggles are best described as 'centrelines'? Are they not the contorted medial moraines that have shifted position?

Thanks for the suggestion, we have changed this.

Supplementary: can you provide the image tile names in each case?

We have now expanded table S1 in the Supplementary Material and provide details for each separate scene.

Supplementary: Table S1 should be S2 in second case (and should SRTM be included here?).

We have amended this.

Supplementary: the animation is excellent. Should it not be referred to somewhere in the text (or it may go largely un-noticed)?

We refer to this now in figure 1.

References

Copland, L. *et al.* (2011) 'Expanded and Recently Increased Glacier Surging in the Karakoram', *Arctic, Antarctic, and Alpine Research*, 43(4), pp. 503–516. doi: 10.1657/1938-4246-43.4.503.
Hewitt, K. and Liu, J. (2010) 'Ice-Dammed Lakes and Outburst Floods, Karakoram Himalaya: Historical Perspectives on Emerging Threats', *Physical Geography*, 31(6), pp. 528–551. doi: 10.2747/0272-3646.31.6.528.
Quincey, D. J. and Luckman, A. (2014) 'Brief communication: On the magnitude and frequency of Khurdopin glacier surge events', *The Cryosphere*, 8(2), pp. 571–574. doi: 10.5194/tc-8-571-2014.
Shean, D. E. *et al.* (2016) 'An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery', *ISPRS Journal of Photogrammetry and Remote Sensing*. International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS), 116, pp. 101–117. doi: 10.1016/j.isprsjprs.2016.03.012.

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

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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~~Glacier in 2017. Results reveal that an accumulation of ice ~~mass~~volume 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~~Our data reveals that velocities on the lower tongue 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~~only to then rapidly peak ~~has passed on the upper tongue. The surge~~and decrease again within a few months, which confirms earlier observations with a higher frequency of available velocity data. The surge return period 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~~ resulting in extremely high basal flow velocities, which may be further amplified by englacial hydrological processes. 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~~observed surges has been reported (Copland et al., 2011; Hewitt, 1969, 2007)~~.~~, however this has not been confirmed over larger areas and time periods and it could also be an artefact stemming from the increasing temporal availability of satellite imagery. Two general mechanisms driving surges are proposed: ~~(a)~~ a build-up of ice ~~mass~~volume during the quiescent phase in the reservoir zone of the glacier causing (a) 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~~advance our ~~understanding~~knowledge of ~~regional glacier behaviour~~ice dynamic processes as well as glacially driven erosion and sediment transport in the region. 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~~Glacier, located in the Shimshal valley in Northern Pakistan~~,~~ (36°20'18"N, 75°28'3"E), 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 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~~,~~. In the region, a similar ~~to another~~process has been observed and well documented ~~glacier in the region~~for Kyagar Glacier ~~(Round et al., 2017).~~(Round et al., 2017). Sudden drainage of ~~this lake~~the Khurdopin Lake has caused destruction to downstream villages before, 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, however lack of cloud free imagery has made it difficult to accurately characterize the most recent surge (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~~recent 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 digital elevation model (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~~2000 and 2017~~,~~ (30 m), and on Planet high~~-~~-resolution imagery (3 m) 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~~Volume changes were computed using the SRTM from 2000, a TanDEM-X DEM from 2011 and a DEM generated from ASTER imagery from May 2017. The ASTER DEM was generated using the open source Ames Stereo Pipeline software (Shean et al., 2016). We compared the DEMs in stable off-glacier terrain and corrected the products accordingly (see Supplementary Material). Using the GlabTop2 model (Frey et al., 2014) and the SRTM, 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~~Supplementary Material. The potential lake volume was calculated by intersecting the visually-derived lake perimeter with the TanDEM-X DEM.

3 Velocities during surge events

Khurdopin ~~glacier~~Glacier is approximately 41 km in length, 1.5 km in width ~~with~~and has an elevation range between 3300 m above sea level (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 equidistance 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~~were able to characterize the surge event and the surface dynamics on the lower tongue and near the glacier terminus.

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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~~, with observations of floods possibly caused by lake drainage after a surge in 1901 or 1904, 1923, 1944, 1960 (Hewitt and Liu, 2010) and observed surges in 1979, 1999 and 2017). Mean average surface velocities on the 25 km long main tongue of Khurdopin during a quiescent phase are below 5 m a^{-1}, with a small peak of 15 m a^{-1} at around 12 km along the tongue. The peak corresponds to a markedly steeper section of the profile (Figure 1). While lack of cloud-free imagery or poor image quality does not always allow accurate identification of the onset, peak and termination of the surge, the data suggest that a gradual increase of surface velocities over multiple years led to surge peaks with velocities up to 4000 m a^{-1} in 1979 and 1999 (Quincey and Luckman, 2014). The most recent quiescent phase lasted from 2000 until at least 2011. By 2013 the glacier had 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 between 2015 and 2016 was characterised by increasing surface velocities in the tongue's upper reach (Figure 1 and Table S3 in the Supplementary Material). Between early 2017 and beginning of June velocities increased up to 5200 m a^{-1} and dropped again to below 200 m a^{-1} in most parts by September. While this extreme acceleration and deceleration happened within less than 9 months, the velocity peak along the longitudinal profile remained relatively stable (Figure 1). The increased velocity and associated ice volume redistribution resulted 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 3d). 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). ~~-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}~~The gradual build-up and then relatively short surge peak support earlier findings based on less frequently available data (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 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).~~While the available Landsat images were equally able to pick up the high velocities, it was only possible to characterize the actual surge development in such detail with the high-frequency Planet imagery, which additionally increases the chances for cloud-free imagery~~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~~.

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4 ~~Mass~~Ice volume changes during surge events

Apart from increased velocities, surges logically also result in large amounts of displaced ice ~~mass~~volume. In many cases this results in a rapid extension of the positon of the glacier's snout. However, ~~for~~in the case of Khurdopin the terminus does not advance and has not done so during at least the recent surges, since it has 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~~rates for the quiescent ~~phase after the last surge to the build up~~ and surge ~~phase~~phases 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~~), an observation made earlier by (Gardelle et al., 2012), who identified this distinct behaviour for other glaciers in the region as well. This distinction is again visible exactly at the same location for the surge, 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~~ 50 to 80 m, ~~considering~~depending on whether we assume the ~~mean change between 2011 and 2017 and accounting for~~net volume loss during the ~~fact that elevation changes~~ build-up phase between 2011 and 2016 ~~were likely negative due to melt, at rates comparable~~ to ~~those of~~ be zero or equal to the volume loss during the quiescent phase~~.~~ between 2000 and 2011. Based on the elevation changes we find a net volume gain between 2011 and 2017 of $520 \cdot 10^6$ m^3 (+/- $117 \cdot 10^6$ m^3 based on the DEM accuracy) between the steep section and the part of the terminus where no more surface change is visible. Averaged over the entire glacier we estimate that the overall ~~mass~~volume loss is slightly negative~~,~~ (see surface elevation change in Figure 2), 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 km² at the beginning of May to 0.06 km² one month later and more than 0.1 km² 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 km² (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 km², possibly during the melt season of 2018 or 2019.~~

The tongue of the Khurdopin Glacier reaches across the main valley floor. As a consequence the glacier has blocked the local Vijerab river multiple times in the last century. The blockage is caused by the tongue that pushes towards the opposite headwall of the main valley (Figure 3). Most of the reported lake drainages were not catastrophic and they have rarely caused damages downstream beyond eroded fields and damaged bridges (Hewitt and Liu, 2010; Iturrizaga, 2005). 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 72000 m^3 at the beginning of May to $1 \cdot 10^6$ m^3 one month later and peaking at $2 \cdot 10^6$ m^3 on the 28th of June. The lake finally drained starting around the 21st of July and had disappeared by 5th of August. As a consequence the river washed away the road at multiple locations, destroyed at least one main bridge and eroded local agricultural land, making the valley inaccessible for a week. 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 or a corresponding $7.5 \cdot 10^6$ m^3 (Figure 3). Considering the height of the advanced glacier tongue – between 15 m at the fringe and up to 80 m on the surging tongue – and the fact that in 2000 the lake reached lake levels ca. 10 m higher than in 2017, we show potential lake extents that could reach beyond 1 km^2 or $10 \cdot 10^6$ m^3, possibly during the melt season of 2018 or 2019. Repeat floods in the one or two years after a possible surge event have been reported multiple times in the recent century as well (Hewitt and Liu, 2010). The volumes calculated could be decreased by sediments visibly deposited either by the surging glacier or the dammed Vijerab River.

6 Discussion and Conclusion

The data collected and analysed support earlier studies on Khurdopin in the observation of a relatively constant return period of a glacier surge of 20 years since the end of the 19th century, irrespective of a changing climate and surges of nearby glaciers ~~(Quincey et al., 2011; Quincey and Luckman, 2014).~~(Hewitt and Liu, 2010; 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~~between surges, 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.~~It is difficult to ascertain which are the main drivers for the regular surges on Khurdopin Glacier (Quincey and Luckman, 2014). In combination with a gradual accumulation of mass on the upper tongue during quiescence and a resulting steepening surface gradient the actual surge starts rapidly when a tipping point is reached. Ice deformation u_d (Greve and Blatter, 2009; Round et al., 2017), even when assuming a relatively small ice thickness between 150 m and 250 m, provides a velocity of 4 to 34 m a^{-1} for the 4° steep surface gradient. This is in the same order of magnitude as the measured velocities during quiescence. 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~~. As velocities increase rapidly from 2015 onwards, the contribution of deformations becomes less important and basal motion amplified by subglacial drainage plays a dominant role. The sudden absence of supraglacial ponds on the terminus during the surge (Figure 3) 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 (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~~profiles as was observed during the quiescent phase (Kamb et al., 1985). ~~The surface velocities observed during the peak surge in May 2017 on Khurdopin glacier are~~As previously suggested the surge on Khurdopin is hence likely a combination of the thermal and hydrological switch (Quincey and Luckman, 2014).

similar to Kyagar Glacier (Round et al., 2017). Future field observations should focus on finding possible evidence for these processes and possible feedback processes, especially related to the deformation of water-saturated granular base material that could explain these extreme acceleration rates and peak velocities (Damsgaard et al., 2015). The surface velocities observed during the peak surge in May 2017 on Khurdopin Glacier are, together with the recently observed surge on the neighbouring Hispar Glacier (Paul et al., 2017), 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)~~.~~, where observations with even higher temporal resolution were available. We can show that newly available satellite imagery with multiple cloud-free sub-weekly image pairs makes the characterization of such a rapid surge cycle possible and confirms high peak velocities that are easily missed by less frequently available Landsat imagery. 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.

8 Acknowledgements

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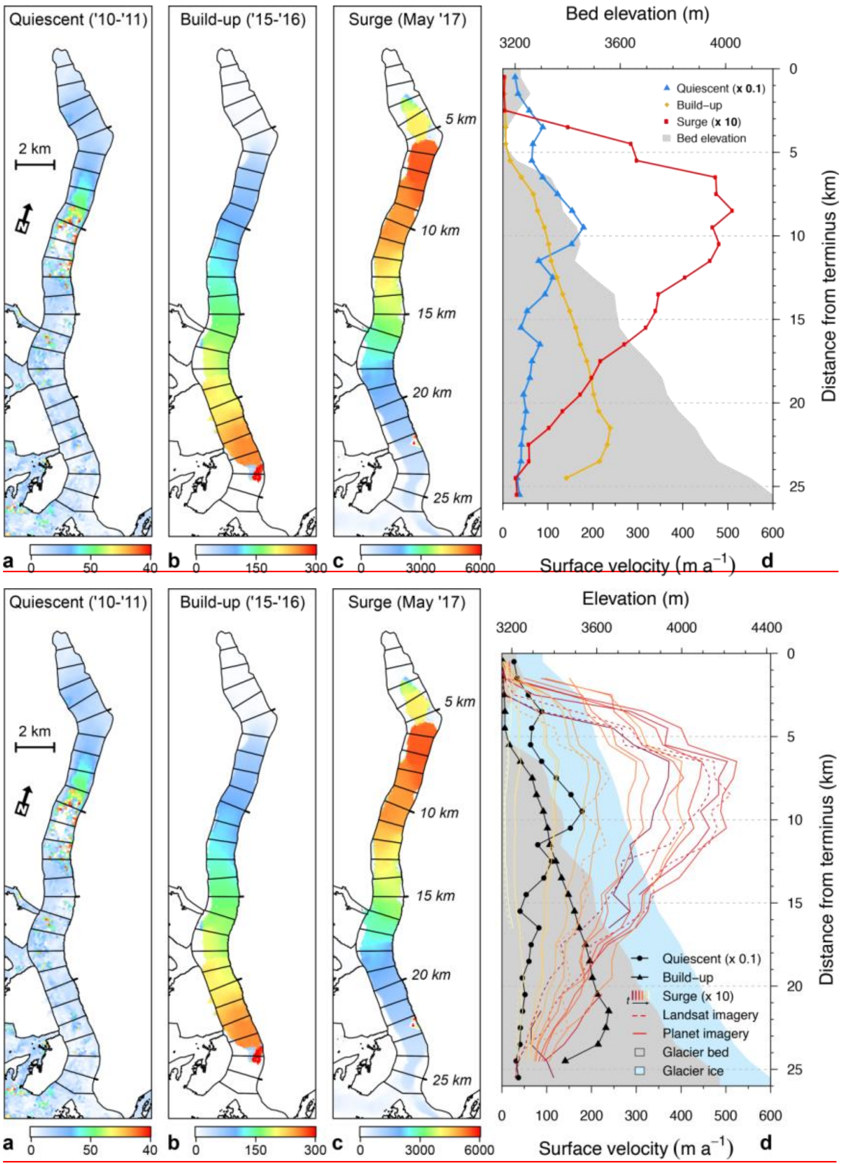
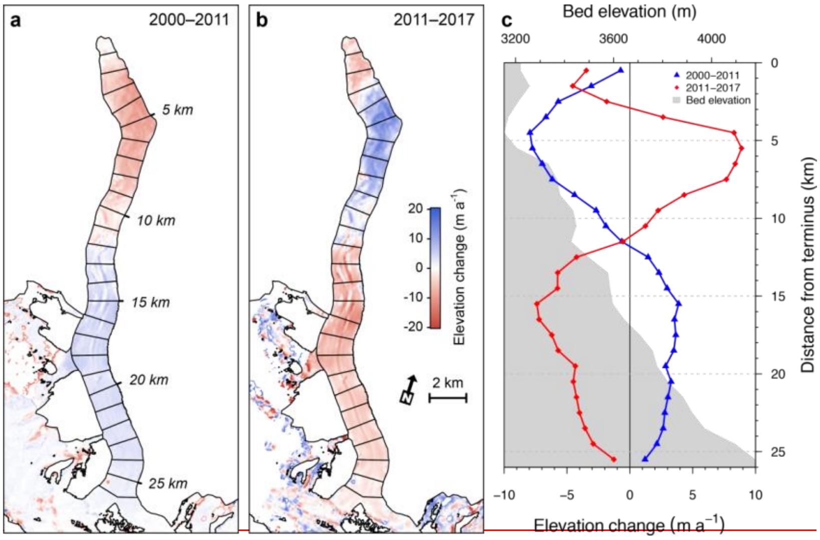


Figure 1: Velocities measured from cross correlating Landsat~~ 7 and 8~~ imagery of one year of the quiescent phase (a; 17th of October 2010 – 18th of September 2011), the last year of the build-up (b; 28th of August 2015 – 10th of May 2016) and the surge peak in May 2017 (c; 13th to 29th of May, 2017). Panel (d) shows mean values of the bins compared against bed elevation~~.~~ and all available velocity pairs for 2017, between December 2016 (dark red) and September (yellow). Note the difference in scales for the different phases. An animation of the images used to derive the velocities can be found in the Supplementary Material.



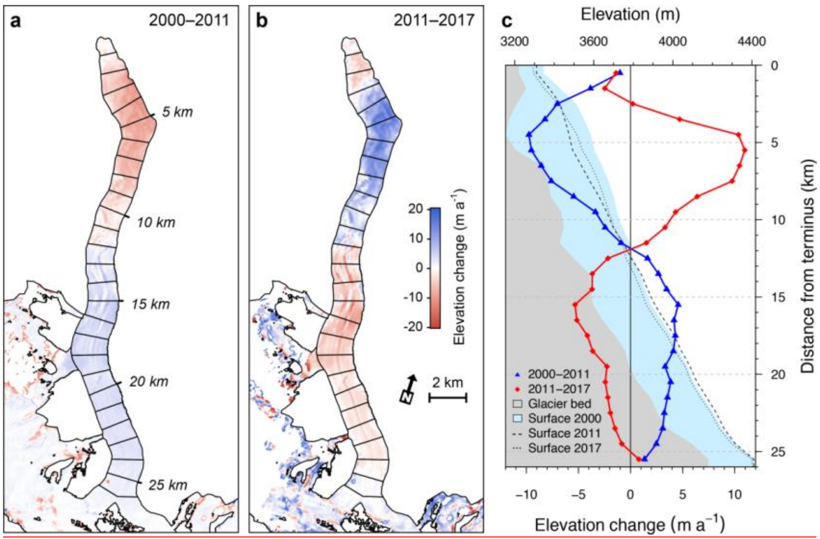
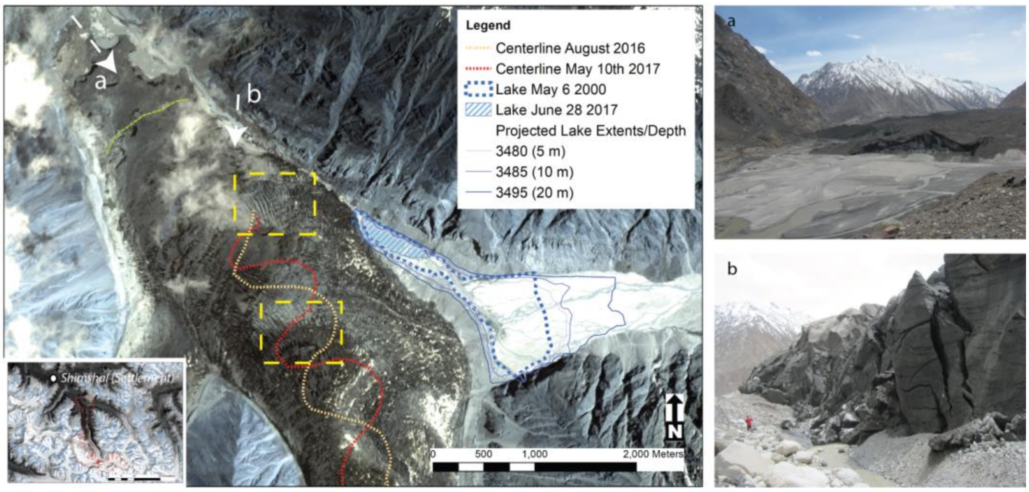


Figure 2: Elevation change rates during the quiescent phase (a), and during the build-up and surge phase (b). Mean values per bin are shown in panel (c). Note that the change ~~that is~~ due to the surge specifically (occurring only in a few months in 2017) is much larger than what is shown, as the difference 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.



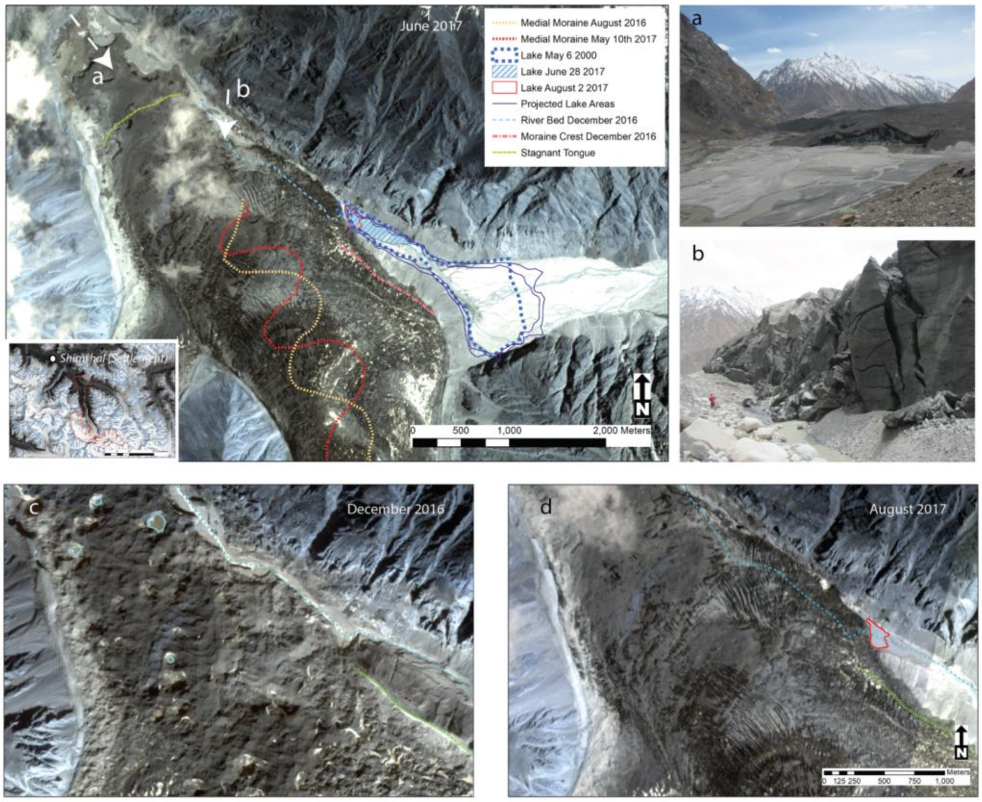


Figure 3: Evidence from the surge event visible at the tongue. The ~~left~~main panel is based on a Planet image from the 28th of June 2017 (Planet Team, 2017)**~~, the centrelines and~~. The medial moraines, the lake extent in 2017, the original river bed and moraine crest are also mapped from Planet 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~~TanDEM-X. 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~~showed no change during the surge. Panels (c) and (d) show the tongue surface before and after the surge. (Photos: Waheed Anwar, May 2017)

Supplementary Material to *Brief Communication: The Khurdopin surge revisited – extreme surge velocities and formation of a dammed lake in 2017*

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1 Data

Table S1: LANDSAT/Planet Data for Velocity Datasets and Animation. All scenes ~~within the years given in the last column~~ were acquired and visually pre-selected for cloud cover, snow cover and image quality over the glacier outline. The numbers in the first column refer to the actual pairing to derive velocities in Table S3.

COSI-Corr pair (Table S3)	Satellite / Scene	Band	Resolution	Acquisition ~~Dates~~Date
1	L7 LE07_L1TP_149035_20000911_20170210_01_T1	8 (Panchr.)	15 m	11/09/2000
1 / 2 / 3 / 4	~~Landsat MSS 1-5 (351/97)~~L7 LE07_L1TP_149035_20030531_20170125_01_T2	~~7/4 (NIR)~~8 (Panchr.)	~~60~~15 m	~~1972~~ ~~1981~~31/05/2003
2 / 6	2008_0925_20161029_01_T1LT05_L1TP_149035_	7 (SWIR)	30 m	25/09/2008
3 / 5	2010_1017_20161012_01_T1LT05_L1TP_149035_	7 (SWIR)	30 m	12/10/2010
4	2011_0918_20161006_01_T1LT05_L1TP_149035_	7 (SWIR)	30 m	18/09/2011
5	2009_0928_20161025_01_T1LT05_L1TP_149035_	7 (SWIR)	30 m	28/09/2009
6 / 7	2010_1017_20161012_01_T1LT05_L1TP_149035_	7 (SWIR)	30 m	17/10/2010
~~2~~7	~~Landsat 5~~2011_0918_20161006_01_T1LT05_L1TP_149035_	7 (SWIR)	30 m	~~1989~~ 18/09/2011
8	LC08_L1TP_149035_20130518_20170504_01_T1	8 (Panchr.)	15 m	18/05/2013
~~3~~8 / 9	~~Landsat 7~~LC08_L1TP_149035_20140910_20170419_01_T1	8 (~~Panchromatic)~~Panchr.)	15 m	~~1999~~ ~~2003~~10/09/2014
9 / 10	LC08_L1TP_149035_20150828_20170405_01_T1	8 (Panchr.)	15 m	28/08/2015
10 / 11	LC08_L1TP_149035_20160510_20170325_01_T1	8 (Panchr.)	15 m	10/05/2016

11 / 12	LC08_L1TP_149035_20161001_20170320_01_T1	8 (Panchr.)	15 m	01/10/2016
12 / 13	LC08_L1TP_149035_20161220_20170315_01_T1	8 (Panchr.)	15 m	20/12/2016
~~1~~13 / 16	~~Landsat~~ ~~8~~LC08_L1TP_149035_20170427_20170515_01_T1	8 (~~Panchromatic)~~Panchr.)	15 m	~~2013~~ 27/04/2017
~~5~~14	Planet Mosaic	Optical ~~Bands~~	3 m	30/12/2016 ~~2017~~
14 / 15	Planet Mosaic	Optical	3 m	16/04/2017
15	Planet Mosaic	Optical	3 m	27/04/2017
16 / 18	LC08_L1TP_149035_20170513_20170525_01_T1	8 (Panchr.)	15 m	13/05/2017
17	Planet Mosaic	Optical	3 m	10/05/2017
17 / 19	Planet Mosaic	Optical	3 m	25/05/2017
18 / 21	LC08_L1TP_149035_20170529_20170615_01_T1	8 (Panchr.)	15 m	29/05/2017
19 / 20	Planet Mosaic	Optical	3 m	29/05/2017
20 / 22	Planet Mosaic	Optical	3 m	03/06/2017
21 / 30	LC08_L1TP_149035_20170801_20170811_01_T1	8 (Panchr.)	15 m	01/08/2017
22 / 23	Planet Mosaic	Optical	3 m	12/06/2017
23 / 24	Planet Mosaic	Optical	3 m	19/06/2017
24 / 25	Planet Mosaic	Optical	3 m	24/06/2017
25 / 26	Planet Mosaic	Optical	3 m	27/06/2017
26 / 27	Planet Mosaic	Optical	3 m	08/07/2017
27 / 28	Planet Mosaic	Optical	3 m	21/07/2017
28 / 29	Planet Mosaic	Optical	3 m	26/07/2017
29 / 31	Planet Mosaic	Optical	3 m	01/08/2017
30 / 32	LC08_L1TP_149035_20170817_20170825_01_T1	8 (Panchr.)	15 m	17/08/2017
31 / 33	Planet Mosaic	Optical	3 m	19/08/2017
32	LC08_L1TP_149035_20170918_20170929_01_T1	8 (Panchr.)	15 m	18/09/2017
33	Planet Mosaic	Optical	3 m	12/09/2017

Table ~~S1:~~S2: DEM Data

	Satellite / Product ID	Resolution	Acquisition Date	Reference
1	ASTER / AST_L1A.003:2253120815	30 m	21/05/2017~~/05/21~~	(NASA LP DAAC, 2017)
2	TanDEM-X / TDM1_DEM__04_N36E075_DEM	12 m	Multiple during 2011	DLR
3	SRTM	1 arc second (~30	02/2000	

		m)		

Table S3: Velocity values [m a^{-1}] from all data products for the period between 2000 and 2017. Rows are km along the glacier tongue starting at the terminus. Columns are time steps and associated satellite products as described in Table S1. Color code corresponds to quiescence (green), build up (yellow) and surge (red).

Location \ Time/Satellite	1 L7	L7/L5	L7/L5	L7/L5	5 L5	6 L5	7 L5	8 L8	9 L8	10 L8	11 L8	12 L8
1	4	2	2	2	3	3	3	2	1	3	2	19
2	5	2	3	2	2	2	3	2	1	3	3	17
3	8	2	2	2	2	4	6	2	2	5	4	19
4	12	2	2	2	3	6	9	9	6	7	6	16
5	6	2	2	1	1	4	7	6	4	7	9	10
6	5	2	3	2	1	3	6	5	10	16	35	82
7	9	2	2	1	2	5	9	19	28	41	129	286
8	7	3	3	2	3	9	12	42	53	68	216	401
9	6	3	4	4	5	12	15	54	62	77	250	430
10	11	2	27	11	14	16	18	83	89	92	297	435
11	13	2	11	21	14	11	29	96	96	102	296	417
12	13	1	3	18	17	6	25	96	105	107	298	384
13	28	1	2	12	6	6	15	120	125	121	314	359
14	41	1	4	11	6	8	9	140	139	133	305	330
15	52	1	13	12	5	5	6	147	152	148	306	297
16	61	2	60	38	5	2	4	162	167	162	308	272
17	70	2	29	51	4	5	9	164	185	166	332	254
18	79	2	73	43	2	5	6	76	197	206	331	232
19	111	2	65	75	21	7	6	198	204	199	296	240
20	111	1	26	33	NA	7	5	201	210	202	273	239
21	53	1	19	25	NA	12	5	144	224	213	275	240
22	57	1	2	10	NA	13	5	146	254	239	292	254
23	47	1	3	2	NA	6	4	193	246	232	279	255
24	22	1	3	2	NA	7	4	126	211	173	217	258
25	38	1	3	2	NA	9	3	41	193	197	274	292
26	51	1	3	2	NA	7	4	81	287	461	400	320

Location \ Time/Satellite	13 L8	14 P	15 P	16 L8	17 P	18 L8	19 P	20 P	21 L8	22 P	23 P	24 P	25 P	26 P	27 P	28 P	29 P	30 L8	31 P	32 L8	33 P
1	15	12	NA	12	39	45	166	55	NA	NA	NA	NA	NA	31	19	61	61	NA	40	NA	5
2	13	16	NA	10	54	28	185	80	5	880	495	1510	968	196	320	380	229	89	190	46	115
3	17	27	85	38	729	273	1523	1487	125	2452	1788	1768	2391	1036	1047	874	643	172	373	96	215
4	151	86	805	890	2892	1649	3192	2765	406	2502	2013	1879	2727	1510	1358	901	773	333	392	154	206
5	538	308	2486	2681	3701	2856	4000	3432	1188	2936	2454	2211	3089	1616	1451	992	936	381	405	147	189
6	527	304	2943	2719	3643	3145	4161	3591	1269	3124	2549	2392	3236	1723	1509	1003	943	357	355	111	140
7	1319	331	3732	4466	5034	4732	5242	4469	2145	3825	3138	3000	4018	2132	1902	1276	1200	409	421	120	153
8	1002	275	3715	4642	4836	4756	5167	4417	2392	4056	3284	2979	3972	2200	1943	1230	1203	351	361	84	120
9	1543	282	3581	4607	4837	5105	4930	4280	2149	3721	3138	2832	3903	2096	1864	1174	1113	286	304	54	81
10	1842	300	3390	4375	4435	4665	4883	4159	1766	3595	3095	2805	3943	2125	1811	1200	1139	281	285	51	68
11	684	273	3317	3980	4633	4809	5011	4288	2193	3759	3162	2887	4073	2172	1845	1235	1159	302	306	51	80
12	991	333	2860	3747	4366	4611	4526	3948	2317	3521	2937	2665	3830	2049	1703	1094	1135	285	274	44	80
13	1395	314	2924	2663	4018	3814	4247	3682	1774	3361	2792	2540	3604	1998	1628	1039	1105	281	281	48	77
14	947	318	2664	2696	3508	3350	3954	3506	1830	3157	2643	2604	3472	1952	1556	1001	1058	284	284	68	110
15	1067	310	2487	2426	3065	3400	3321	3147	1917	2819	2309	2220	3193	1753	1403	924	1006	288	299	76	129
16	1083	336	2860	2193	NA	3199	3257	3107	1772	2865	2370	2244	3160	1774	1473	948	1024	331	333	115	168
17	1029	386	2389	1816	NA	2684	2983	2844	1628	2659	2258	2092	2971	1682	1403	944	1012	378	403	194	247
18	611	346	NA	1320	NA	1998	2368	2281	1209	2142	1851	1817	2553	1419	1202	886	873	493	404	NA	NA
19	929	379	NA	1403	NA	1938	2059	2072	1447	1982	1738	1778	2452	1393	1196	923	891	NA	453	NA	NA
20	875	422	NA	1083	NA	1729	NA	1807	1523	1920	1852	1856	2459	1383	1171	887	933	492	480	NA	NA
21	571	374	NA	891	2227	1334	NA	NA	1324	1633	1753	1340	2085	1194	1001	751	852	363	431	NA	NA
22	565	328	871	784	1881	1076	NA	NA	1424	1453	1509	1247	1935	1101	940	718	817	348	462	NA	NA
23	413	305	657	626	1674	1029	NA	NA	1457	1173	1190	987	1487	928	781	616	715	330	411	NA	NA
24	279	321	654	532	1388	603	NA	NA	740	962	1019	813	1219	793	671	570	651	332	364	NA	NA
25	336	327	1004	378	947	315	NA	NA	NA	823	905	756	1058	722	638	537	642	NA	355	NA	NA
26	296	350	1155	296	NA	318	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

2 Model Settings and Uncertainties

2.1 Velocities

COSI-Corr is sensitive to chosen initial window sizes as well as window steps (Leprince et al., 2007). In this study we work with different satellite products in respect to resolution and band quality – from the 30 m bands of the initial LANDSAT MSS Satellite to the 3 m optical product of Planet – which made different setups necessary. For the 30 m bands of Landsat MSS and Landsat-5 we used an initial window (W) of 128 pixels, a final window (F) of 16 pixels and a step size of 2 pixels (d) ~~-~~(W128-F16-d2). For Landsat~~-~~ 7 and Landsat~~-~~ 8 as well as Planet imagery we used a W128-F16-d4 setting while for surge events, when displacement is substantial or imagery is far apart in time, ~~a~~ W256-F16-d8 is used. We used the Non-Local Means Filter of COSI-Corr (Ayoub et al., 2009) to smooth the gridded data. Velocities measured on stable off-glacier terrain were used to assess the validity of the on-glacier data. The Landsat-MSS off-glacier velocities are in the same range as on-glacier velocities, which makes the COSI-Corr approach not suitable for this data. Off-glacier displacement based on Landsat~~-~~ 5 data was between 2 – 5 m a^{-1}, and this is sufficiently accurate to investigate the build-up and surge phase where velocities are generally one order of magnitude higher. Landsat~~-~~ 7 and 8 as well as Planet data used in the analysis from 2013 onwards generally show off-glacier displacements of 2 - 3 m a^{-1} for imagery multiple days to weeks apart, which corresponds to the likely error identified by ~~(Luckman et al., 2007)~~(Luckman et al., 2007). To make sure that noise, resulting from errors in the co-registration process, is not included in the data analysis, we discard all pixel values with a signal-to-noise ratio smaller than 0.75, following (Kraaijenbrink et al., 2016). As large displacements during a surge are picked up as noise by the algorithm in many cases, this constraint had to be loosened for surge peaks. In these cases patches on the surface that showed erratic behaviour (no uniform direction, large variability in velocities on a small area) were discarded visually.

~~3~~ 2.2 DEMs

We compare the offset between the respective DEMs in relatively flat valley areas where all 3 DEM products are available (Figure S1a). Both TanDEM-X and the ASTER DEM are of less quality in steep terrain, however the 90th percentile of slope values on the investigated glacier surface is 10°, below which the quality is generally acceptable. We therefore exclude all values from the test areas with a slope above 10°. This results in a median offset between the TanDEM-X and the SRTM in the test areas of -24.8 m (σ = 8.5 m, Figure S1b), which is caused by the different geoids of the datasets, WGS84 and EGM96 respectively. Between the ASTER and the TanDEM-X an offset of -12.4 m (σ = 2.3 m) is found and used for correction on the ASTER (Figure S1c).

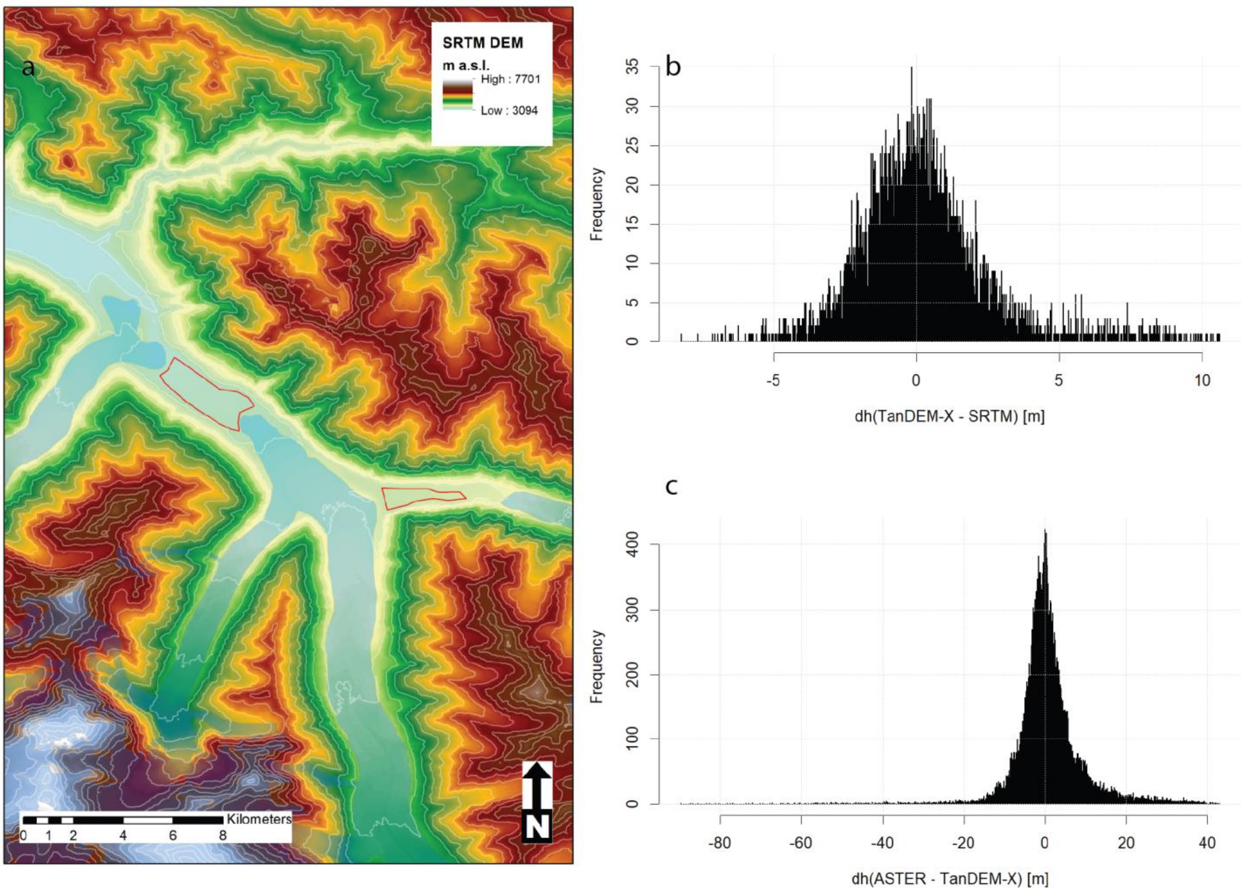

Figure S1: (a) Flat stable areas chosen in the catchment used for comparison of the DEM. Blue shaded areas are glacier tongues. (b) Difference between TanDEM-X and adjusted SRTM. (c) Difference between corrected ASTER and TanDEM-X.

3 Lake Volume Calculation

The volume of the lake was calculated by (1) deriving lake perimeters from the orthophotos, (2) draping them over the TanDEM-X digital elevation model, (3) taking the lake level as the 90th percentile of all elevation values (as the polygon of the perimeter does not have a continuous value due to the inaccuracies of the DEM), and (4) deriving the difference between this plane and the DEM (Figure S2). The lake volumes fit well with the exponential function derived by (Cook and Quincey, 2015) for lower volumes. As (Cook and Quincey, 2015) describe for ice-dammed lakes (Fig.4 therein), the curve steepens, i.e. volume increases faster than area, for larger areas, which is true for this lake as well. However for much greater extents (as observed in 2000) the relation does not hold anymore as areas increase faster due to the lake flooding a very shallow alluvial fan at the confluence of the Vijerab and the Khurdopin valley (see green and red markers in Figure S2b).

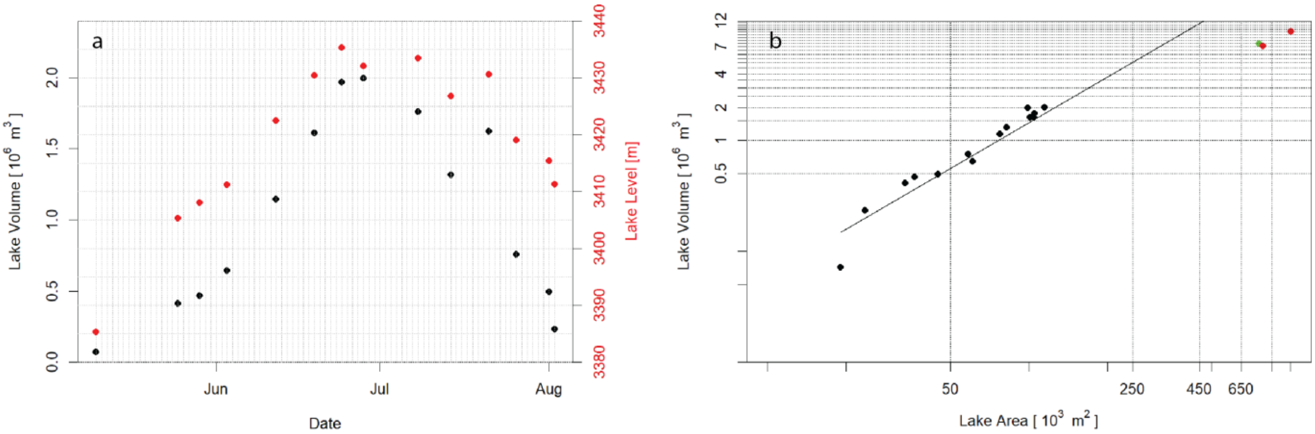

Figure S2: (a) Lake areas derived from orthophotos and associated lake levels. (b) Relating lake area to lake volume. The black dots are values from 2017, the green marker is the lake in May 2000 and the red markers are projected areas and volumes with possible increase in lake level height 10 m above the value measured in 2000. The solid line is a relation for Volume-Area scaling found by (Cook and Quincey, 2015) **which fits well for the observations in 2017, but overestimates for larger lake areas.**

4 Supplementary Animation of all Landsat Scenes

~~Making use of~~ Using all available Landsat imagery, we compiled an animation over all scenes with suitable image quality (SupplementaryMaterial.zip). The images were not enhanced but ~~rather~~comprise the raw ~~GEOtiffs~~rasters used for the ~~analysis of~~ velocity ~~data were used~~analysis.

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