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Discussions

Interactive comment on "Surge dynamics and lake outbursts of Kyagar Glacier, Karakoram" *by* V. Round et al.

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We would like to thank Martin Truffer for the insightful and positive review. It will undoubtedly help us improve a few points in the paper. We are providing this preliminary response in the spirit of interactive discussion and to allow for further feedback if needed. We address each of his points and outline how we intend to address them in the final version of the manuscript.

The PDD analysis is a bit of a side-line to this paper. I do like something like it, because the availability of melt water is an important part of the story. A few more details would help: 1) It is stated that PDD is calculated from hourly data. Are the hourly data used to calculate a daily average, or are these actually 'positive degree hours'?

The hourly air temperature measurements were used to create the equivalent of an average daily temperature by weighting the hourly measurements by the fraction of a day which they represent. We adjusted the text to make this clearer (p.11, l.14):

"Positive degree days (PDD) at the glacier terminus were calculated as a proxy for potential melting. Positive air temperature measurements were summed with each measurement weighted by the fraction of a day which it represented (Vaughan, 2006), such that an hourly measurement of 6°C would contribute 0.25 PDD. The hourly air temperature data from the station at Kyagar Glacier terminus were used (...)"

2) What is the meaning of calculating PDD at one point? If the weather station is at the terminus than a day with very low positive temperatures would presumably cause melt at the very lowest part of the glacier tongue only, whereas a high degree day would cause melting over large parts of the glacier. So this measure would be a very non-linear measure of melt?

Yes that's true, the calculated PDD is a value representing conditions at the terminus. The elevation range of the glacier and an estimated lapse rate can be used to make a short statement about the expected melting period over the majority of the glacier rather than just at the terminus. We will rephrase the PDD section in 4.3 Meteorological observations on p.19 to clarify the points raised:

"Temperatures remained below 0°C between mid-October and late April according to data from the meteorological station at the glacier terminus (at 4800 m a.s.l.). The warmest months, July and August, experienced average daily maximum temperatures of 4–7°C and monthly PDDs exceeding 150 at the glacier terminus. By taking into account the elevation of the glacier surface and an approximate lapse rate of 0.006°C m^{-1}, it can be inferred that over the whole glacier tongue, PDDs are positive between May and October, whilst over the bulk of the accumulation area (about 900 m above the terminus) melt potential was only significant from June to August. Evidence of high-altitude melt is seen in the TanDEM-X backscatter images from August 2015 (Figure

5). Annual PDDs at the glacier terminus were 647°C, 481°C, 552°C and 528°C in 2013, 2014, 2015 and 2016, respectively."

3) Does the PDD contribute more to this paper than simply a temperature graph?

We include the PDD analysis primarily as a way to present the temperature data. We believe it gives a better overview of the temporal distribution of melt potential than a temperature plot, and it provides annual or monthly values which can easily be compared.

Eisen et al. (J.Glac., 2005) discuss surge initiation by a hydraulic switch that depends very sensitively on basal stress (p. 404/405). This discussion seems very relevant to this paper as well, and I recommend consulting it.

Thanks for this suggestion. The discussion on the sensitivity of the drainage system to increased basal stress is a very relevant reference which we shall add to p.22, l.11:

"Given the potential sensitivity of the subglacial drainage efficiency to basal stress (Eisen et al., 2005) the conditions at the end of the quiescence phase could be expected to favour the switch to an inefficient drainage system."

Also after reading Eisen et al. (2005) we intend to add this additional text to the discussion p.23, l.17, as we find the difference in seasonality of initiation and termination between many Alaskan surges and Kyagar Glacier worth noting:

"It seems that the surge is well explained by the presence of an inefficient basal drainage system facilitating high subglacial water pressure, corresponding to the mechanism proposed by Kamb et al. (1985). However, the seasonality observed at Kyagar Glacier is different to the often cited winter initiation associated with closure of subglacial channels in the hydrological switch mechanism (Eisen et al. 2005, Kamb et al., 1985). In the case of Kyagar Glacier, development of an inefficient drainage system in winter does not necessarily facilitate increased subglacial water pressure until the beginning of the melt season, due a lack of liquid water in winter. Surge initiation in winter

should not be considered a precondition of hydrologically controlled surging (see e.g., Jiskoot & Low, 2011)."

p.9, l.14/15: This is a detail, but what you're discussing is not really an error, is it? You're simply deriving the horizontal component of the velocity vector. The way you describe it you would assume that the velocity vector is surface parallel.

True, it makes more sense to use the term 'velocity difference' rather than 'velocity error'. This will be corrected in the manuscript.

p.11, l.11: delete ',' (unless this involves sticking tongues into glaciers :))

The offending comma will be removed to avoid misunderstanding!

p.12, l.22: The speed-up is not really uniform over the glacier tongue: the gradient gets much larger. An interesting feature is an apparent hinge point a little less than 1 km from the glacier terminus (Fig. 6). Does that correspond to something obvious on the ground?

What we mean to say here is that the spatial pattern of acceleration is rather uniform over the tongue – there is no 'surge front' travelling down-glacier, as has been observed in some other Karakoram Glaciers (e.g. Quincey 2011, 2015). We shall word it slightly differently, p.12, l.19–24:

" In the 2.5 years before surge onset, a gradual but clear acceleration occurred, greatest over the middle of the glacier tongue (between km 3 and km 6) with an increase in velocity from 0.1 m d^{-1} in winter 2011/12 to over 0.4 m d^{-1} in winter 2013/14 (Fig. 6). The location of the maximum velocity moved from above the confluence at km 10 at the end of 2011 to over the glacier tongue at km 5 in 2013/2014. Apart from this early shift, the spatial pattern of acceleration over the glacier tongue was quite uniform with no evidence of a 'surge front' of acceleration moving down the glacier, as observed for some other Karakoram glaciers (Mayer et al., 2011; Quincey et al. 2015)."

The almost negligible acceleration over the lowest 1km of the glacier (resulting in this apparent ‘hinge point’ above which acceleration becomes evident) arises because horizontal flow is impeded by the mountain flank against which the glacier terminus pushes. This is why we observe so much thickening at the terminus, rather than horizontal advance. There is a conversion to vertical velocity which is not visible in our horizontal velocity assessment.

Fig. 12: The depression in the Dec. 2015 profile is very interesting. Do you think it could be the result of a subglacial lake drainage? Sometimes these are quite recognizable in surface crevasse patterns.

The suggestion that the surface depression could have come about through the drainage of a subglacial lake is an interesting one. However, after looking again closely at crevasse patterns over the area, we don’t see any evidence of subglacial lake drainage. There are very distinctive transverse crevasses across the steep slope immediately up from where the depression formed after the surge. However, these are rather indicative of extensional stress in the flow direction, and their enlargement after the surge is likely a result of the rapid steepening over this part of the glacier as mass is removed from the reservoir area at the bottom of this steep slope (see Fig. 1 below).

We think that the depression forms because of the divergence in speed between the glacier tongue below and the tributary above, causing ‘emptying’ of the reservoir area during the surge. A very similar formation was observed at the Belvedere Glacier in Italy, after a surge of the glacier tongue away from the steeper upper slopes in 2000/2002 (Haeberli et al., 2002; Kääb et al., 2004, page I/70)

Could you say a bit more of the relative role of the three tributaries to the surge? The elevation change figures indicate that perhaps all tributaries are involved in the surge? Is that also borne out in velocity evolution? In Alaska, there is distinctly different behaviors of tributaries (leading to the famous looped moraines, e.g. Clarke, 1991, J.Glac.). For a reader like me it would be interesting to know whether tributaries here play a similar role or not.

Looped moraines are expected when tributaries surge into a non-surging part of the glacier, or two joining branches surge at different times. In the case of Kyagar glacier it seems to be the glacier tongue below the confluence which is surging away from the tributaries and we do not see any evidence that the tributaries themselves surge independently. The attached video (supplement to this comment) very nicely shows the lack of looped moraine formation. We will add a short explanation for the absence of looped moraines to make this clear in our discussion (see text added in response to the next comment).

p.23, l.24/25: You state that only the glacier tongue participated in the surge. This is based on the obvious velocity signature. But the elevation changes clearly show that the whole glacier is involved in the surge cycle.

The greatest acceleration was observed over the glacier tongue, but the main evidence which leads us to believe that the surge behaviour predominately occurs over the glacier tongue was the pattern of mass distribution change from the DEMs. The instability which develops during quiescence is caused in part by the buildup of mass at the top of the surging area, which in the case of Kyagar Glacier is at the bottom of the tributaries/top of the glacier tongue. It is the glacier tongue which develops the characteristic steepening during quiescence and massive redistribution during the surge. On the other hand, the tributaries don’t show such irregular behavior. They experience slight thickening all over during quiescence (and large thickening at the base of the western tributary, the main reservoir area), and slight thinning over the surge (again, large thinning only over the reservoir area). We consider the slight acceleration and thinning of the tributaries during the surge as a ‘side effect’ of the glacier tongue surge. Although we don’t consider the tributaries as primarily surging, they are involved through providing mass to the reservoir areas and are affected by the surging tongue. We will amend the text at p.23, l.24/25 to reflect this:

“The spatial pattern of acceleration and elevation change over Kyagar Glacier provides further information about the nature of the surge, in particular that it was the tongue

of the glacier which primarily underwent surging, evidenced by the velocity increase (Fig. 9) and the steepening of the profile over the glacier tongue during quiescence (Fig. 12). The build-up of an ice reservoir at the confluence represents the intersection between the tongue, which develops an unstable profile during the quiescence followed by dramatic surging, and the tributaries, which maintain more steady flow and support the recharge of the ice reservoir during the quiescence. We note also that looped moraines do not form at Kyagar Glacier because the tributaries are not surging into a non-surging part of the glacier. The actual surge activity only seems to affect the glacier tongue below the confluence."

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Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/tc-2016-236/tc-2016-236-AC1-supplement.zip

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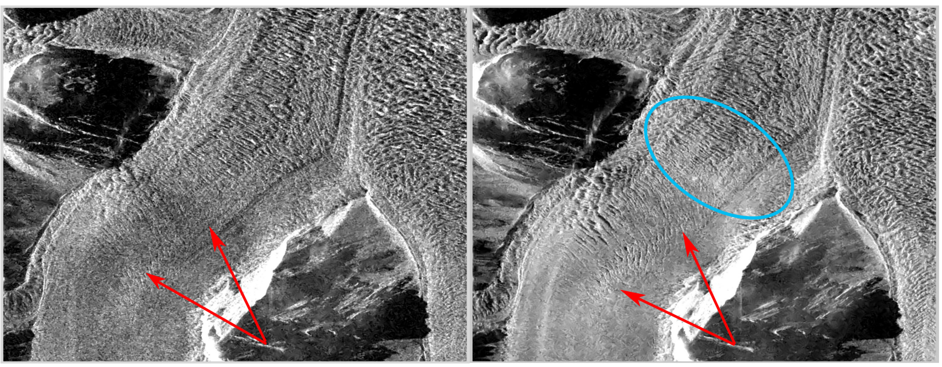

Fig. 1. TanDEM-X images showing development of transverse crevasses and circling the approximate location of the surface depression which formed at around km 8.5.