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Brief Communication: On the magnitude and frequency of Khurdopin glacier surge events

D. J. Quincey[1] **and A. Luckman**[2]

[1]School of Geography, University of Leeds, Leeds, LS2 9JT, UK
[2]Department of Geography, College of Science, Swansea University, Singleton Park, Swansea, SA2 8PP, UK

Correspondence to: D. J. Quincey (d.j.quincey@leeds.ac.uk)

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Abstract. The return periods of Karakoram glacier surges are poorly quantified. Here, we present evidence of an historic surge of the Khurdopin Glacier that began in the mid-1970s and peaked in 1979. Measured surface displacements reached $> 5\,\mathrm{km\,a^{-1}}$, two orders of magnitude faster than during quiescence. The Khurdopin Glacier next surged in the late 1990s, equating to a return period of 20 years. Surge evolution in the two events shows remarkable similarity suggesting a common trigger. Surge activity in the Karakoram needs to be better understood if accurate mass balance assessments of Hindu-Kush–Karakoram–Himalaya glaciers are to be made.

1 Introduction

Glaciers in the Karakoram experienced significant recession for the vast majority of the twentieth century, apart from some short-term advances during the 1970s (Hewitt, 2005). However, in the late 1990s and the first part of the twenty-first century many were shown to be in balance or gaining mass (Gardelle et al., 2012; Kääb et al., 2012), and the majority had either stable terminus positions or were advancing (Scherler et al., 2011; Bhambri et al., 2013). A number of studies have cited recent (decadal) climatic patterns as being responsible for this anomalous behaviour, but the picture is somewhat complicated by the large number of surging glaciers in the region (Copland et al., 2011). Surging glaciers cyclically store ice mass at elevation during periods of quiescence and discharge it down-glacier during periods of activity, making it difficult to differentiate between the influences of external climatic forcing and internal ice dynamics on individual glacier behaviour. Variations in the distribution of ice volume with elevation may also impact on short-term glacier mass balance (Tangborn, 2013), although recent work in the Pamir and Karakoram found no significant difference between the mass balances of surge-type and non-surge-type glaciers over a 10-year period (Gardelle et al., 2013).

Recent studies have quantified dramatic changes in Karakoram-wide glacier velocities (Heid and Kääb, 2012) and, more specifically, have quantified individual surge magnitudes by tracking surface features between multitemporal satellite images (Quincey et al., 2011; Mayer et al., 2011). This work has demonstrated that surface velocities may reach up to $2\,\mathrm{km\,a^{-1}}$, albeit for short periods, and that surge characteristics (e.g. presence/absence of a surge front; impact/lack of impact on the glacier terminus position; presence/absence of a debris cover) can differ greatly between individual glaciers. There remains conjecture as to the trigger mechanism behind these surges, with remote observations of their timing and evolution suggesting a change in thermal conditions may be responsible (Quincey et al., 2011), but a combined observation–modelling approach suggesting a switch in subglacial drainage may be the cause (Mayer et al., 2011). There is consensus, however, that surge events are increasing in the Karakoram, and that this is likely to reflect (either directly or indirectly) recent changes in precipitation and temperature in the region (Copland et al., 2011; Hewitt, 2007).

Despite these recent advances in knowledge, the return periods of Karakoram glaciers are poorly constrained. Some of the firmest estimates are provided by Hewitt (2007), who observed tributary glacier surges around the Panmah Glacier in the early 2000s and speculated on a recurrence interval of 50–100 years for the Drenmang Glacier, while recognising

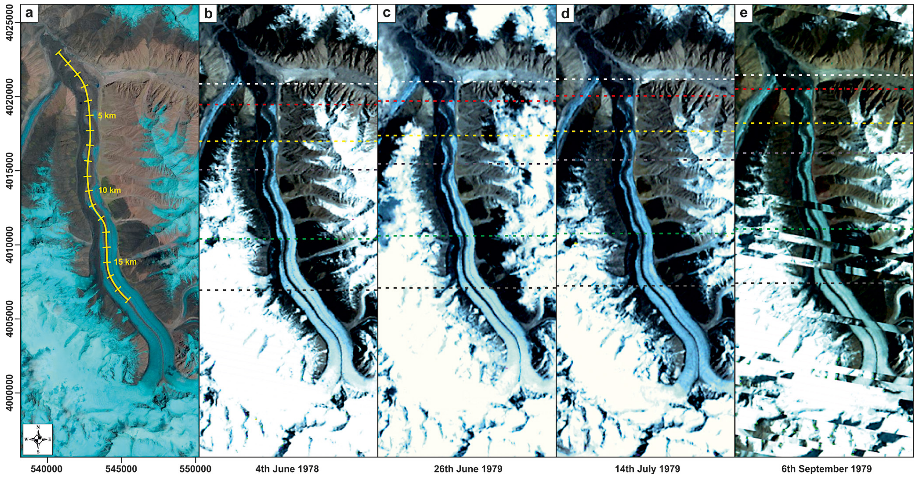

Fig. 1. (a) The Khurdopin Glacier imaged on 6 July 2013 by the Landsat Operational Land Imager, overlaid with centreline from which the data in Fig. 2 were extracted. **(b–e)** The surge of 1979 evidenced in multi-temporal Landsat MSS data. Dashed lines correlate with distinct features that can be tracked moving down-glacier (north) in each subsequent image. Note that the surge has minimal impact beyond 15 km from the terminus.

that the most recent period between surges was between 25 and 30 years. Guo et al. (2013) concluded that the return period of the recently surged Yulinchuan Glacier exceeded forty years, based on a search of satellite imagery dating back to the early 1970s. An inventory of glacier surges presented by Copland et al. (2011) identified several Karakoram glaciers that had surged more than once within the satellite era, and suggested their particular quiescent period may be 25–40 years, while historical accounts of thickening and thinning on the lower Khurdopin Glacier appear to follow an approximate 20-year cycle (Mason, 1930).

2 The Khurdopin Glacier and the surge of 1979

In this brief communication, we report on a previously undocumented surge of the Khurdopin Glacier that occurred in the late 1970s, detected in Landsat Multispectral Scanner (MSS) imagery. The Khurdopin Glacier is approximately 41 km in length, 1.5 km in width and is predominantly debris-covered for its lowermost 10 km (Fig. 1). It is situated in the Shimshal Valley in the Northern Areas of Pakistan, and is relatively well known for its surge activity, having surged most recently around 1998–99 (Copland et al., 2011; Quincey et al., 2011). Its distinctive surface morphology (large, looped moraines) is indicative of a glacier that has surged many times in the past, and reports of periodic ice dams blocking the Shimshal River (and associated outbursts from Virjerab Lake) may coincide with surge events dating back to the late 1800s (Visser, 1926; Todd, 1930; Iturrizaga, 2005).

A recent visual analysis of archive Landsat MSS imagery revealed that the glacier discharged large volumes of ice down-glacier during the late 1970s, peaking in the summer of 1979 (Fig. 1b–e). The surface features of this glacier are so distinctive and coherent that it is possible to track them using cross-correlation of image patches between repeat pairs of images, even with the relatively coarse pixel size of 60 m. The feature tracking method used here is identical to that described in previous publications (Luckman et al., 2003, 2007), with images first being co-registered using large patch sizes before surface displacements are measured using smaller patches. Robust matches were accepted based on the strength of their signal-to-noise ratio, and centreline velocity profiles (Fig. 1a) were then extracted from each velocity field. Remaining spurious matches were manually filtered from the centreline profile data. Given the large pixel size of the MSS imagery, uncertainty in the extracted velocity data is relatively high (Table S1 in the Supplement). Errors relate mostly to co-registration errors as a result of changing snow extent, variable cloud cover and varying illuminations, but in every case they are significantly lower than the magnitude of the measured displacement.

Measured velocities indicate that during the early part of the 1970s the glacier was in quiescence, with the lowermost 6 km of the glacier either stagnant or almost stagnant (Fig. 2). The velocity of the glacier began to increase sometime between 1975 and 1977, although even at this time the lowermost 4 km of ice remained inactive. Between the summers of 1978 and 1979 the surge involved the lowermost 15 km of the glacier and during the summer of 1979 the surge peaked (July–August), with surface velocity reaching $> 5\,\mathrm{km\,a^{-1}}$ at a point 5–6 km from the terminus, two orders of magnitude faster than during quiescence. By September of 1979 the peak of the surge had passed, and by 1986, pre-surge velocities had been resumed. Unfortunately, a lack of imagery precludes the extraction of any further velocity data between September 1979 and June 1986. The data we do have,

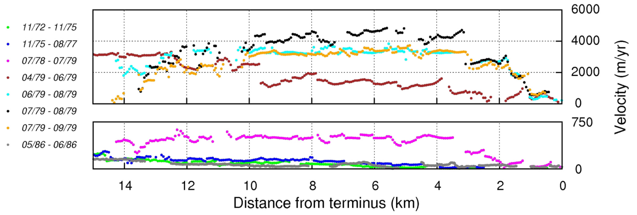

Fig. 2. Centreline surface velocities extracted from feature tracking data before, during and after the surge of 1979.

however, demonstrate that there was no clear surge front associated with the 1979 surge, nor did it impact on the glacier terminus position, similar to the event recorded in 1999.

Mean surface displacements were also extracted from small (100 pixel) patches around 5 km from the terminus in each velocity field to facilitate an analysis of the surge evolution in comparison to previously measured events (Fig. 3). These data demonstrate that the surge took of the order of two years from initiation to reach its maximum, and that the rate of initial speed-up was comparable to those events previously recorded in the region. However, the magnitude of the peak velocity is more than twice that of any previous surge velocity recorded in recent times ($\sim 2\,\mathrm{km\,a^{-1}}$ during the Kunyang surge) and more than five times the maximum displacement measured during the Khurdopin surge of 1999. It should be noted, however, that the peak of the 1999 surge may not have been fully captured by the Landsat archive. Unfortunately, the lack of post-1979 imagery also precludes any analysis of how long it took the glacier to revert to its pre-surge dynamic state. However, if the 1979 surge followed the evolution of those recorded in Quincey et al. (2011) we can estimate it would have terminated sometime during the winter of 1980–81. This leads, overall, to a surge return period of the order of 20 years for the Khurdopin Glacier.

3 Discussion and conclusion

These data suggest that the thickening and thinning cycles on the lower Khurdopin Glacier previously reported by Mason (1930) were surge events taking place over an approximate cycle of 20 years. The return period of surges on this glacier therefore appears to be unchanged since the Little Ice Age despite climatic changes in the region. Establishing patterns of dynamics on the lower glacier is particularly important given the association of terminus fluctuations with the formation and drainage of the Khurdopin–Virjerab Lake (Iturrizaga, 1997), which has been responsible for some of the largest floods in the Shimshal Valley during the last century. Neither of the surge events described here impacted on the terminus position of the glacier, or resulted in lake formation, perhaps because the lower glacier is less advanced and distinctly thinner than previously reported (Visser-Hooft, 1926). It is also noted in Iturrizaga (2005) that the lake does not only form during times of glacier advance; sealed subglacial drainage channels during times of recession can also dam the river flow.

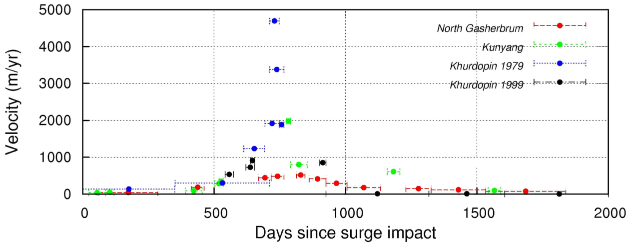

Fig. 3. Surge propagation through a point ∼ 5 km up-glacier from the terminus. Note that the shape of the 1979 surge evolution is similar to those events previously plotted by Quincey et al. (2011) (North Gasherbrum, Kunyang, Khurdopin 1999), but the magnitude of the maximum measured velocity is > 2 times greater.

Studies considering surge trigger mechanisms in the region remain inconclusive. Previous work has suggested that climatically induced changes in glacier thermal conditions may be linked to observed advances and thickening during the 1990s (Hewitt, 2005), coinciding with a period of exceptional surging. Our data show that the evolution of the 1979 Khurdopin surge is almost identical to that of the 1999 surge; the gradual acceleration of the glacier over several years before the surge maximum was reached and the maximum velocities coinciding with late summer months may therefore confirm a thermal control (Quincey et al., 2011). Equally, the relatively sudden increase in velocities during the summer of 1979, and the absence of a surge front in the velocity data, may indicate that a change in subglacial drainage is the dominant control (Mayer et al., 2011). Further observations, both in situ and from remote sensing, are required if the controls on glacier surging in the region are to be properly understood.

To identify and quantify other historic surges that may have previously gone undetected, prospects are limited by image availability and spatial resolution. The Khurdopin surge was only detected because of its distinctive surface geomorphology and its relatively large size; some surging glaciers in the region are not so heavily debris-covered (e.g. North Gasherbrum), lacking the abundance of surface features required to be able to detect a surge event, and others are much thinner (laterally; e.g. Kunyang), and therefore poorly imaged by coarse resolution sensors. However, as the satellite archive lengthens, and increasing volumes of imagery become available (e.g. through the declassification of Corona and Hexagon imagery acquired in the 1960s and 1970s), so the potential for detecting multiple events will improve. Being able to quantify Karakoram surges and their return periods is important not only for advancing glaciological knowledge, but also because of its relevance to questions of future water availability and longer term landscape evolution. This latter application will be the focus of future work.

Supplementary material related to this article is available online at http://www.the-cryosphere.net/8/571/2014/tc-8-571-2014-supplement.pdf.

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