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Magnitude-frequency of Karakoram glacier surges

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On the magnitude and frequency of Karakoram Glacier surges

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The return periods of Karakoram glacier surges are almost entirely unknown. 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 $> 5 \text{ km yr}^{-1}$, two orders of magnitude faster than during quiescence and twice as large as any previously recorded velocity in the region. The Khurdopin Glacier next surged in the late-1990s, equating to a return period of 20 yr. Surge activity in the region 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. Identifying surging glaciers and quantifying their dynamics (e.g. surge magnitude-frequency) is therefore crucial if accurate assessments of the mass balance of Hindu-Kush–Karakoram–Himalaya glaciers are to be made.

Recent studies have identified a number of glaciers in the Karakoram that have surged within the previous decade and have quantified surge magnitude by track-

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ing 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 km yr^{-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, little remains known about the return periods of Karakoram surges. Of the estimates that are available, few are substantiated or robust; 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 yr, while recognising that the most recent period between surges was between 25 and 30 yr. 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 an indicative quiescent period of 25–40 yr based on these observations.

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 35 km in length and

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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). There are no other documented surges of the glacier although its distinctive surface morphology is indicative of a glacier that has surged many times in the past, and reports of periodic ice-dams blocking the Shimshal River may coincide with historic surge events (Iturrizaga, 2005).

A recent visual analysis of archive Landsat MSS imagery revealed that the glacier discharged large volumes of ice downglacier 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). 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 whole of the glacier surface and during the summer of 1979 the surge peaked (July–August), with surface velocity reaching $> 5 \text{ km yr}^{-1}$ at a point 5–6 km from the terminus, two orders of magni-

imum was reached and the maximum velocities coinciding with late summer months may 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).

A particularly interesting feature of the Khurdopin surge of 1979 is its large magnitude in comparison to previously recorded data (Fig. 3), suggesting more recent surges (1990s) may be smaller than average. A number of studies (e.g. Dowdeswell et al., 1995; Eisen et al., 2001) have suggested that surge frequency may be related to mass balance, but few have discussed whether surge frequency may itself regulate surge magnitude, as suggested by the Khurdopin data. If a specific cumulative snowfall is required for a surge to be initiated (cf. Dyurgerov et al., 1985) then it is likely that surge magnitudes will be unaltered regardless of return period; however if a change in thermal conditions reduces this snowfall threshold or alters the location and size of the ice reservoir area, it is possible that surge magnitude may also decrease through time. These ideas are difficult to test without a much more spatially and temporally comprehensive analysis of surge dynamics across the region, but certainly the data presented here would support a reduced magnitude-frequency hypothesis given continued positive mass balances.

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; other known surge glaciers in the region tend to be predominantly debris-free (e.g. North Gasherbrum), making the identification of surface features in repeat-pass imagery difficult, or 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

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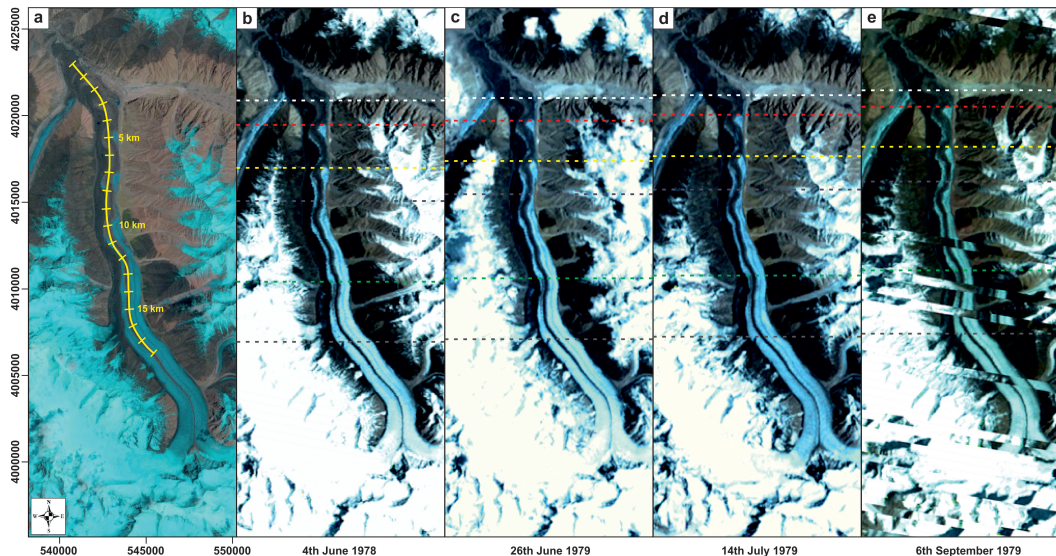


Fig. 1. (a) The Khurdopin Glacier imaged on 6th July 2013 by the Landsat Operational Land Imager, overlaid with centreline from which data in Fig. 2 were extracted. (b–e) The surge of 1979 evidenced in multi-temporal Landsat MSS data. Dashed lines correlate with distinct features that can be tracked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

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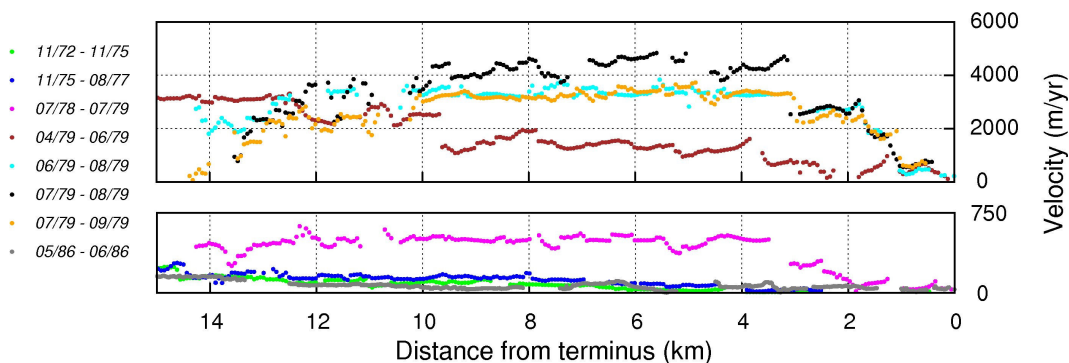


Fig. 2. Centrelines surface velocities extracted from feature tracking data before during and after the surge of 1979.

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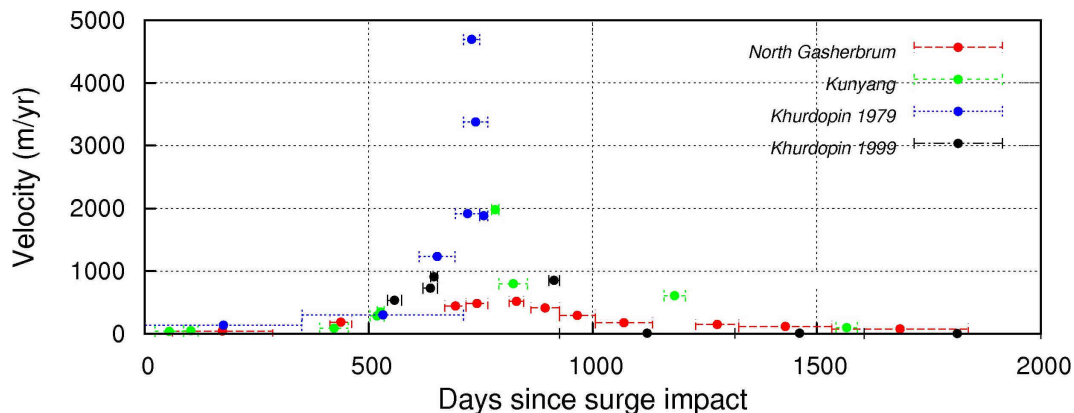


Fig. 3. Surge propagation through a point ~ 5 km up-glacier from the terminus. Note the shape of the 1979 surge evolution is similar to those events previously plotted by Quincey et al. (2011) (North Gasherbrum, Kunyang, Khurdopin, 1999), but the magnitude of the maximum measured velocity is > 2 times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

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