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Karakoram glacier surge dynamics

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[1] We examine the surges of five glaciers in the Pakistan Karakoram using satellite remote sensing to investigate the dynamic nature of surges in this region and how they may be affected by climate. Surface velocity maps derived by feature-tracking quantify the surge development spatially in relation to the terminus position, and temporally with reference to seasonal weather. We find that the season of surge initiation varies, that each surge develops gradually over several years, and that maximum velocities are recorded within the lowermost 10 km of the glacier. Measured peak surge velocities are between one and two orders of magnitude greater than during quiescence. We also note that two of the glaciers are of a type not previously reported to surge. The evidence points towards recent Karakoram surges being controlled by thermal rather than hydrological conditions, coinciding with high-altitude warming from long-term precipitation and accumulation patterns. **Citation:** Quincey, D. J., M. Braun, N. F. Glasser, M. P. Bishop, K. Hewitt, and A. Luckman (2011), Karakoram glacier surge dynamics, *Geophys. Res. Lett.*, *38*, L18504, doi:10.1029/2011GL049004.

1. Introduction

[2] Surging glaciers oscillate between long periods of quiescence, during which time ice volume accumulates in a reservoir area, and short periods of activity, when ice is rapidly discharged down-glacier into a receiving area. The cycle is internally regulated, and reflects a spatial imbalance in flow. Two main hypotheses exist to describe the trigger mechanism that initiates an active phase. The thermal switch hypothesis invokes a change in basal thermal temperature and thus increased sediment deformation and porosity as the fundamental driving force [*Clarke et al.*, 1984; *Truffer et al.*, 2000; *Murray et al.*, 2000]. The hydrological switch hypothesis suggests changes in basal hydrology, specifically from a channelized to a distributed system, are responsible [*Kamb et al.*, 1985; *Björnsson*, 1998]. Previous studies have identified contrasting dynamics between the two mechanisms, with thermally regulated surges initiating and terminating at varying times of the year and hydrologically-controlled surges tending to initiate during winter months and terminate during summer months [*Jiskoot*, 2011]. Multi-temporal surface velocity data, derived by remote sensing, can therefore be useful for inferring surge mechanisms where field data do not exist.

[3] Glaciers in the Karakoram region of Pakistan are well known for their previous surge activity [*Hewitt*, 2007]. These surges have particular importance for local communities that are under threat from outburst flooding associated with glacier hydrological changes, and from ice-dammed lake failure where glacier termini have advanced across trunk valley rivers. Climatologically, valley weather stations suggest that winter precipitation is dominant while, except in Ladakh, the south west monsoon has a small role [*Lüdecke and Kuhle*, 1991]. Data on snowfall in glacier accumulation zones shows that summer precipitation between 4800 and 5600 m a.s.l. averages almost half of the annual totals, much of it with an Indian Ocean chemical signature [*Wake*, 1987], and that more than 90% of the annual precipitation is deposited as snow at elevations >5000 m a.s.l. [*Winiger et al.*, 2005]. Essentially, therefore, Karakoram glaciers have an 'all-year' accumulation regime [*Hewitt*, 2006, 2011]. Increased snowfall and summer storminess are associated with the observed advance of many Karakoram glaciers [*Scherler et al.*, 2011], which is anomalous in the wider context of Himalayan glacier recession.

[4] Previous work has suggested that surges in the Karakoram are characterized by relatively short active phases (lasting for several months or years [*Copland et al.*, 2009]), and decadal quiescent phases [*Belò et al.*, 2008]. Surge velocities have been measured higher than 7.5 m d^{-1} (2.77 km a^{-1} [*Gardner and Hewitt*, 1990]) and verbal reports suggest advances an order of magnitude or more faster [*Hewitt*, 2006], but data are limited in spatial and temporal resolution. All known surging glaciers in the Karakoram are largely or wholly avalanche nourished leading to extensive debris mantles on the lower tongues. Multivariate analysis indicates that surge-type glaciers are characteristically long, wide and debris-covered [*Barrand and Murray*, 2006].

[5] Here we present satellite-derived velocity data measured before, during, and after recent surge events on five Karakoram glaciers (Figure 1). We selected these five glaciers to be representative of the range of glacier sizes and surface characteristics found in the region. Of these five, the Khurdopin, North Gasherbrum and Kunyang glaciers are of intermediate length for the Karakoram (>20 km), predominantly debris-covered, and with evidence of previous surge activity although the timing of previous surge events is unknown [*Hewitt*, 2007]. The Sughet and Tatulu Gou [*Li*, 2003] glaciers are shorter ice masses that are predominantly debris-free. Although there are no records of previous surges of these two glaciers, heavy crevassing and major frontal

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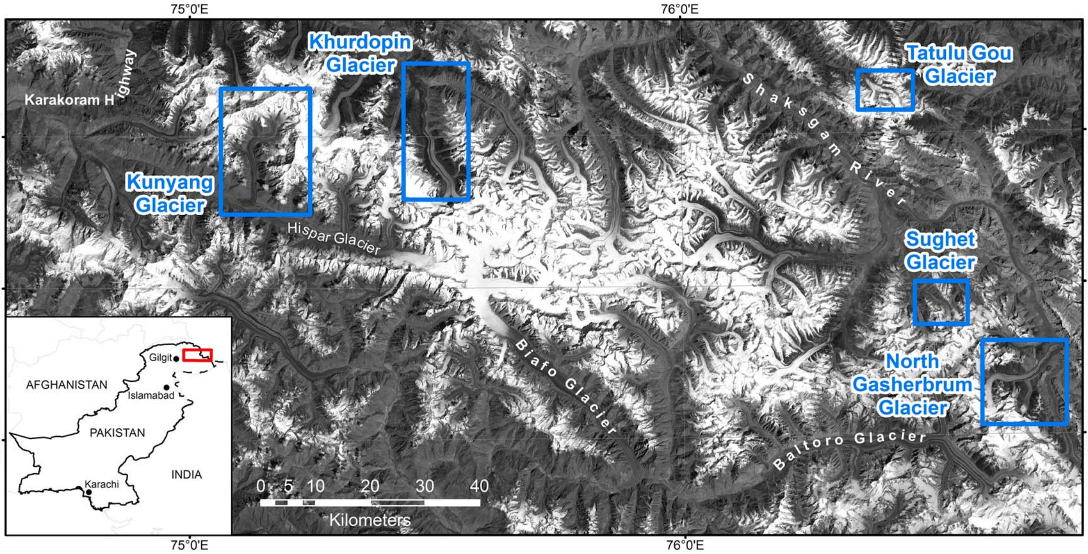

Figure 1. The Karakoram region, highlighting the five glaciers in the current study and indicating major glaciers in the area. Landsat background imagery © USGS, 2009+2010.

advances indicated that surges had recently occurred, and they were thus investigated further.

2. Cross-Correlation Feature Tracking

[6] Surface displacements between repeat-pass satellite imagery were used to derive glacier surface velocities using normalized cross-correlation feature tracking. This method has been well described elsewhere for use with both radar imagery [*Strozzi et al.*, 2002; *Luckman et al.*, 2003] and optical datasets [*Scambos et al.*, 1992]. It is particularly appropriate for Himalayan-style glaciers, which often exhibit an abundance of surface features that move coherently with the glacier ice [*Luckman et al.*, 2007]. Features on the Khurdopin, North Gasherbrum and Kunyang glaciers were tracked between pairs of 30/15 m spatial resolution Landsat

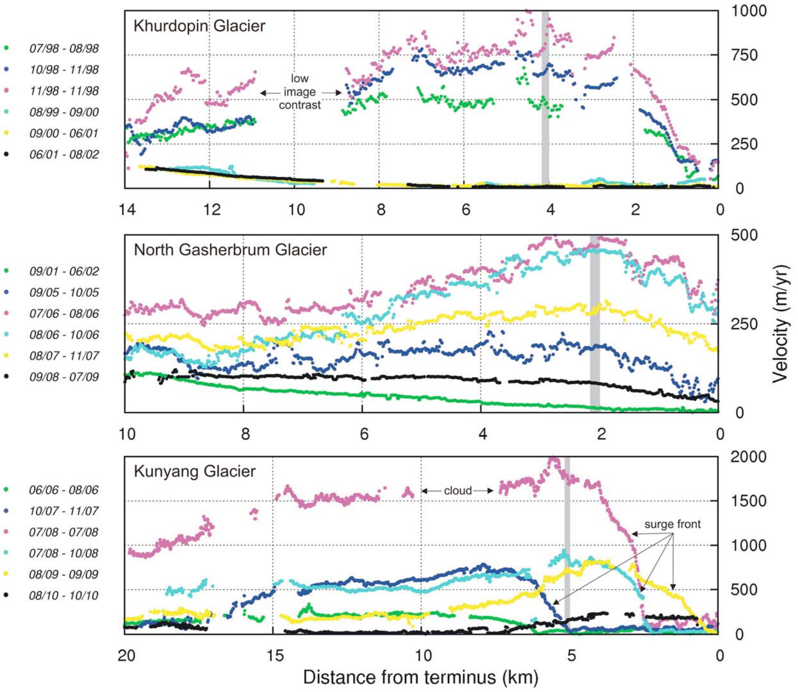

Figure 2. Centerline velocity profiles characterizing the dynamic evolution of surges on the Khurdopin, North Gasherbrum and Kunyang glaciers. For error estimation see Table S1. Note that surge velocities are between one and two orders of magnitude greater than quiescent velocities in each case, and the clear down-glacier migration of a surge front in the Kunyang dataset (labeled). Axes scales are not directly comparable and grey bars indicate the locations of temporal analyses presented in Figure 3.

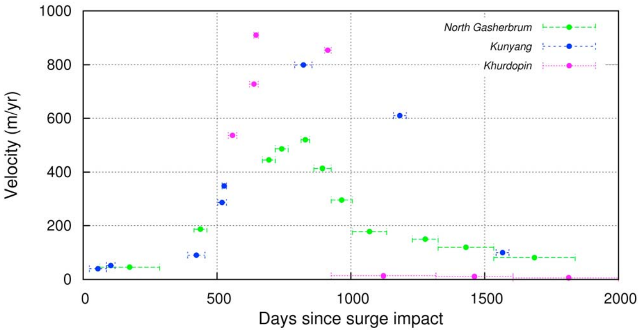

Figure 3. Temporal evolution of surge velocity for the three large glaciers in the study area. Whiskers denote period over which velocity measurement is acquired. Measurements are taken at the point of peak velocity in each case as indicated on Figure 2. A single measurement on the Kunyang Glacier, which reached almost 2 km a^{-1} at the peak of the surge, has been omitted here for clarity, and the start of the Khurdopin surge impact has been estimated as two years prior to the first measurement.

TM (Band 3)/ETM+ imagery, and measurements on the Sughet and Tatulu Gou glaciers were made using 4.6 × 3.1 m spatially sampled Single Look Complex PALSAR (Fine Beam, single polarization) imagery (Table S1 in the auxiliary material). The finer spatial resolution of the PALSAR data was required to distinguish surface features on these smaller glaciers. We used a procedure similar to that described by *Luckman et al.* [2003], but with adjusted patch dimensions tailored to the magnitude of the expected displacement. Image pairs were first co-registered to sub-pixel precision and local offsets were measured based on the peak of the cross-correlation function. The resulting displacement fields were filtered to remove extreme and poor quality offsets, the latter being flagged by a low signal-to-noise ratio.

[7] Uncertainty in the final displacement data resulted from errors related to the image co-registration procedure and from changes in the surface features through time. Previous studies have shown that by using well-separated image pairs (of the order of twelve months or more), uncertainty in the offset measurements can be as low as 2–3 m a^{-1} [*Luckman et al.*, 2007], but in the case of fast-flowing (or here, surging) glaciers the surface features evolve so rapidly that such temporal baselines can often not be used. During the peak of the North Gasherbrum and Kunyang surges, features were

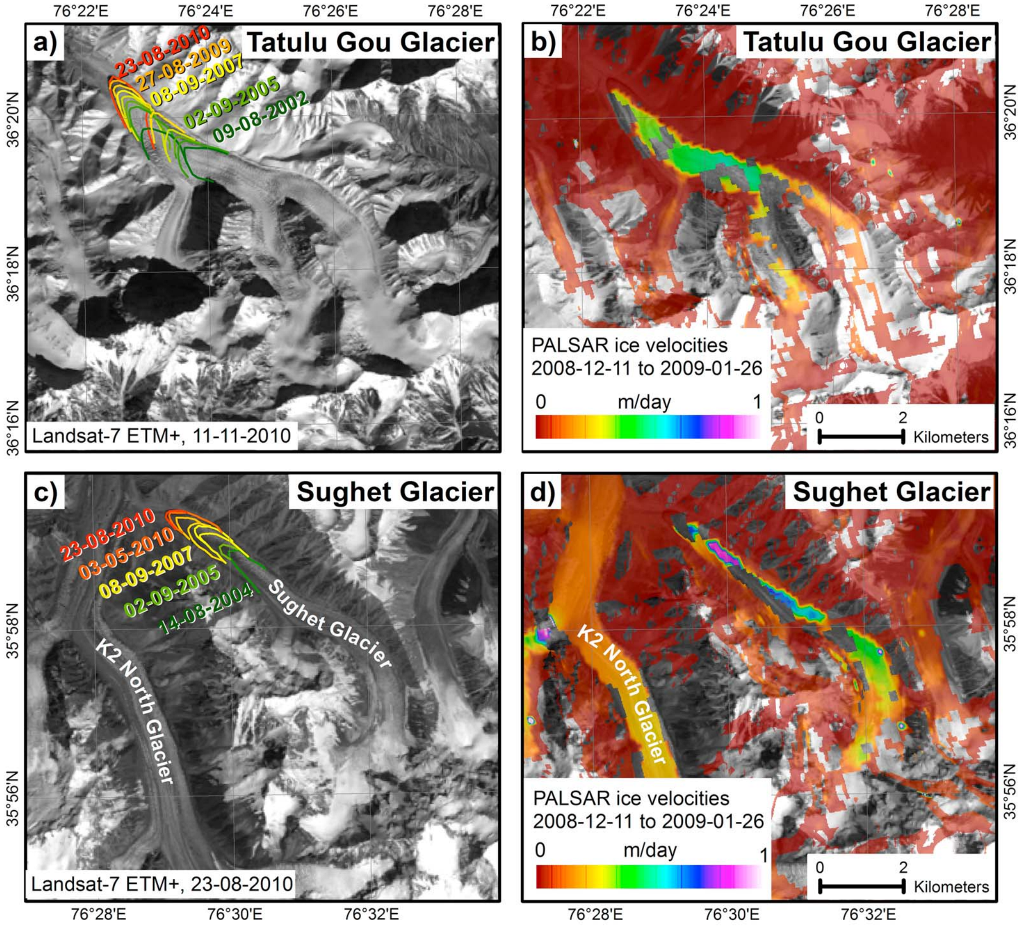

Figure 4. Measured surface velocities during the ongoing surge of the Sughet Glacier and during the latter part of the Tatulu Gou Glacier surge. Velocity fields are measured over 46 days using PALSAR fine beam, single polarization imagery. Surges on both glaciers resulted in an increase in length of >20%, and measured velocities in excess of 300 m a^{-1} in the case of the Sughet Glacier. Many other small glaciers in the region have exhibited similar behavior during this time.

unrecognizable between pairs separated by more than sixteen days. Displacement data collected over areas of known stability (e.g. bedrock) suggest an uncertainty of approximately ±5 m a^{-1} for the PALSAR data and ±10 m a^{-1} for Landsat pairs with long (annual) temporal separation. Uncertainties are ±90 m a^{-1} for image pairs with the shortest (sixteen day) separation. Surface patterns on the glaciers studied are sufficiently large and distinct such that the use of coarser resolution Landsat TM imagery does not significantly degrade the measurement accuracy. The magnitude of the uncertainty is far exceeded by the velocity of the glaciers, even at the peak of the surge when uncertainties are greatest.

3. Measured Surface Velocities

[8] Twenty-eight velocity fields were derived through the surges of the North Gasherbrum, Kunyang and Khurdopin glaciers. Selected centerline profiles demonstrate the magnitude and timing of each event (Figure 2). The Khurdopin surge had already entered its surge phase by the first measurement in 1998 and remained in surge for less than one year. It reached a maximum recorded velocity of ~1 km a^{-1} during November 1998, two orders of magnitude faster than post-surge. The North Gasherbrum surge initiated in the autumn of 2005 and reached a peak velocity of ~0.5 km a^{-1} during the summer of 2006, more than ten times as fast as the measured quiescent velocity. The Kunyang surge initiated during late summer in 2007 and reached its peak in July 2008. This velocity, of approximately 2 km a^{-1}, is more than two orders of magnitude faster than those measured during quiescence. An active surge front propagating down-glacier is clearly visible in the Kunyang event. All three surge events are characterized by an acceleration phase lasting ~2 years before peak velocity is reached (Figure 3). Quiescent velocities are resumed within 2–3 years of the surge peak.

[9] Individual velocity fields were extracted during the surges of the Sughet and Tatulu Gou glaciers, giving an insight into the spatial velocity characteristics of smaller surging ice masses (Figure 4). Maximum velocities on these glaciers were 350 m a^{-1} and 180 m a^{-1} respectively, within two kilometers of the advancing terminus. Velocities higher up on the glacier were <100 m a^{-1}, which is comparable with neighboring non-surging glaciers (Figure 4d). These glaciers also underwent rapid frontal advances. The Tatulu Gou Glacier advanced 2.5 km (28% of its pre-surge length) and the Sughet Glacier advanced 1.7 km (20%) over an eight year period. In the case of the Tatulu Gou Glacier, surges of the different tributaries merged to create one major advance starting at approximately the same time. The surge of the western-most branch had ceased by 2009, but the surges of the main and eastern branches are still on-going, as the most recent (2 August 2011; Path/Row 148/035) Landsat ETM+ imagery indicates (not shown here).

4. Discussion

[10] The initiation and termination phases of the Karakoram surges that we investigated vary in their relation to the seasonal cycle. This is significant because it indicates that these Karakoram surges are more likely to be thermally than hydrologically controlled. Previous studies have shown that hydrologically-controlled surges tend to initiate during winter months when meltwater is scarce and the subglacial hydrological system is distributed and inefficient, and terminate during summer months when there is an abundance of surface meltwater available to re-establish efficient channelized flow [*Harrison and Post*, 2003; *Björnsson*, 1998]. In contrast, thermally regulated surges can initiate and terminate at any time [*Jiskoot*, 2011], as the switch from cold- to warm-based ice occurs at a critical ice thickness and with increasing frictional heat, rather than depending on any seasonal control. Instability occurs as a result of a restricted outflow at the boundary between areas of melted and frozen bed [*Clarke et al.*, 1984; *Murray et al.*, 2000]. Although there are few data available on the thermal regime of Karakoram glaciers, cold-based ice is thought to predominate at lower elevations and at the glacier margins, with thicker warm-based ice up-glacier and again cold-based at high elevations in the source zones above about 5000 m elevation [*Quincey et al.*, 2009; *Copland et al.*, 2009]. It is possible, therefore, that these most recent surges have been triggered by an upward shift in thermal conditions, with long-term increases in winter precipitation [*Treydte et al.*, 2006] and increased summer storminess patterns leading to high-altitude warming of snow and ice [*Hewitt*, 2005]. Climate therefore seems to play a crucial, if indirect, role in regulating these recent events [*Hewitt*, 2007].

[11] The Karakoram glaciers that we studied accelerated gradually for several years before peak surge velocities were attained (Figure 3). This behavior also favors the thermally-controlled (Svalbard-type) instability mechanism. Thermally regulated surges initiate with an expansion and thickening of warm-based ice in the reservoir area during quiescence, which leads to increased basal meltwater and elevated pore-water pressures. Consequently, the stability of any underlying sediment is reduced by dilation leading to increased deformation, and a positive feedback between pore water pressure, deformation and basal motion. Full surge development can take several years or more once initiated as increasing areas of ice in the reservoir area reach the pressure melting point [*Murray et al.*, 2003], and this accounts for the year-on-year acceleration observed in the Karakoram velocity data. It is likely that the boundary between the reservoir and receiving areas coincides approximately with the location of the surge peak measured in the centerline velocity profiles, which is within 10 kilometers of the glacier terminus in each case. The reduction of this peak velocity with distance up-glacier (almost to a point where surge and quiescent velocities equate) demonstrates that the upper regions of the glacier experience a 'normal' velocity regime despite the binge-purge cycle that affects the lowermost sections of ice.

[12] The clear propagation of a surge front down-glacier in the Kunyang velocity dataset (Figure 2) contrasts markedly with the more uniform velocity pattern observed on the North Gasherbrum and Khurdopin glaciers. *Fowler et al.* [2001] suggested that the presence or absence of a surge front may be related to the relative speed of the thermal activation wave (i.e., the transition between warm and cold ice), a model which may be applicable to our observations in the Karakoram. In cases where the activation wave is slow relative to ice speed, a rapidly moving surge front may propagate down-glacier, and ultimately impact on the terminus, continuing forward as a shockwave. In the case of the Kunyang Glacier, ice speed was fast compared to the other observed surges, and the surge front caused a significant terminal advance. The surge front is therefore likely to indicate the

boundary between the melted and frozen bed [*Murray et al.*, 2000]. In cases where the activation wave is faster than ice flow, velocities are suppressed by the thermal control, and a surge front does not develop. Rapid acceleration only occurs if the thermal front reaches the terminus and the forefield is warm. These characteristics (lower measured velocity, absence of a surge front, minimal terminus impact) are all observed on the surges of North Gasherbrum and Khurdopin glaciers. It may be, therefore, that more than a single thermal mechanism is required to explain the different characteristics of the three major glaciers studied here.

[13] Surge events on relatively clean-ice Karakoram glaciers such as the Sughet and Tatulu Gou have not been reported before. Previously documented surges have occurred on longer, wider and predominantly debris-covered glaciers [*Barrand and Murray*, 2006]. Indeed, of the five glaciers studied here, only the Khurdopin is known to have surged previously. The smaller, clean-ice glaciers of the region tend to be sourced and terminate at high-elevation (>5000 m a.s.l.) where cold ice is likely to predominate, and their rapid recent expansion may indicate that glacier thermal conditions are changing across the Karakoram regionally. The onset of surging on short, steep glaciers also suggests a different picture from findings elsewhere, where surge behavior has been positively correlated with length [*Jiskoot et al.*, 2000] and shallow surface gradients, at least in the ablation zone [*Clarke et al.*, 1986].

5. Conclusions

[14] In this study we have quantified spatial and temporal variabilities in glacier velocity during five surges in the Karakoram. The data presented demonstrate that the surges are characterized by 1) initiation and termination at varying times of the year, 2) increasing velocity for several years prior to the surge peak, and 3) maximum velocities within the lowermost 10 km of the glacier, reducing with distance up-glacier. In addition, surges have now been observed on relatively clean-ice glaciers, which were not previously reported to be part of the surge-type family. This evidence points towards recent Karakoram surges being controlled by thermal, rather than hydrological, conditions, coinciding with high-altitude warming from long-term precipitation and accumulation patterns. Results from this type of study have the potential to better constrain physically-based models aimed at understanding non-steady flow in glaciers across all glacierised regions of the world, and to help understand the impact of changing climate on Himalayan landscapes.

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