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Expanded and Recently Increased Glacier Surging in the Karakoram

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Abstract

A review of published literature and satellite imagery from the late 1960s onwards has revealed 90 surge-type glaciers in the Karakoram mountains, of which 50 have not previously been described in detail. These glaciers were identified by a number of surface features indicative of surge-type behavior such as looped moraines, rapid terminus advance, strandlines and rapid changes in surface crevassing. These observations indicate that surge-type behavior is more common and widespread than previously believed on Karakoram glaciers. There is strong spatial clustering of the surge-type glaciers, and a doubling in the number of new surges in the 14 years after 1990 (26 surges) than in the 14 years before 1990 (13 surges). This is coincident with a period of increased precipitation and positive glacier mass balance in this region, and supports previous studies which have found that mass balance has an important control on the frequency of glacier surging.

Introduction

The Karakoram mountains of Pakistan, India, Afghanistan, and China contain some of the largest non-polar glaciers in the world, with nine glaciers >50 km in length. These ice masses exist at high altitude (~2500–8600 m above sea level [a.s.l.]), and provide a crucial source of water for nearby communities. A sound understanding of the dynamics and recent variations of these glaciers is important for evaluating whether changes in their terminus position are driven by factors such as external climate forcing or internal ice dynamics (Yde and Paasche, 2010). Previous studies have indicated that there are many surge-type glaciers in the Karakoram (e.g., Mason, 1935; Hewitt, 1969, 1998, 2007; Kotlyakov, 1997; Barrand and Murray, 2006). However, logistical and political constraints mean that to date there have been only limited studies of many of these glaciers, and until now a full regional inventory has not been undertaken with satellite imagery.

Surge-type glaciers experience well-defined cyclical non-steady flow, with alternation between short active phases (months to years) typically characterized by a rapid terminus advance, and a longer quiescent phase (years to decades) typically characterized by terminus stagnation or retreat (e.g., Meier and Post, 1969; Kamb et al., 1985; Eisen et al., 2001). Surges typically involve the rapid movement of glacier mass from high to low elevations, and associated rapid increase in glacier velocities and surface crevassing. The global distribution of surge-type glaciers is distinctly non-random, with some glaciated areas having numerous examples (e.g., Alaska-Yukon, Canadian High Arctic, Svalbard, Russian High Arctic), while others have few or none (e.g., Rockies, European Alps) (Benn and Evans, 2010). Overall, it is estimated that <1% of all glaciers worldwide are surge-type (Jiskoot et al., 2000).

The aim of this paper is to identify and assess the occurrence of surge-type glaciers in the Karakoram. This study significantly expands on previous work by using a combination of previously published literature and repeat satellite imagery to catalogue surge-type glaciers and monitor their distribution, surge history, and physical characteristics across the entire mountain range. Using this information, a new inventory of surge-type glaciers is presented and an assessment is made of the links between changes in glacier mass balance and changes in the total number of surges over time.

Study Area

The Karakoram mountain range extends ~500 km in a NW to SE orientation, with about half of its surface area >5000 m

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a.s.l. (Searle, 1991). The climate of the Karakoram is strongly influenced by its inland location far from oceanic moisture sources, so that it is sharply continental and mostly semi-arid (Hewitt, 1969). Southern slopes are exposed to the humidifying influences of monsoonal flow from the Indian Ocean, but because of the orographic effect, northern slopes are drier. Consequently, the largest glaciers tend to flow in a southerly and westerly direction from the mountains. There are no direct measurements of the basal thermal regime of the glaciers in this region, but Hewitt (2007) suggested that all thermal regimes (cold, warm, polythermal) are likely present over the wide range of elevations (<3000 to >8000 m a.s.l.) at which glaciers exist in the Karakoram.

There have been generally minor recent changes of non-surging glaciers in this region, with Hewitt (2005) reporting recent thickening of some Karakoram ice masses. Similarly, studies of the non-surging Baltoro Glacier (~ 58 km long) have shown that its terminus position has been remarkably stable and varied by no more than ± 200 m since the 1850s (Pecci and Smiraglia, 2000; Mayer et al., 2006). The termini of debris-covered glaciers typically respond in a more muted way to external forcing than non-debris covered glaciers, but the relative stability of Karakoram glaciers still contrasts with a more widespread decay and retreat of similarly debris covered glaciers in the central and eastern Himalaya (e.g., Fujita et al., 1997; Ren et al., 2004). This suggests that generally favorable glacier mass balance conditions have existed in the Karakoram over the past few decades.

PREVIOUS STUDIES OF SURGE-TYPE GLACIERS IN THE KARAKORAM

Significant observations on Karakoram glaciers began during the advent of European exploration in the late 19th and early 20th centuries, and many of these early reports focused on unusual features such as rapid glacier advances and outburst floods. For example, Hewitt (1998) attributed a surge as the probable cause of the pushing aside of adjacent glaciers and overriding of lateral moraines by Maedan Glacier in 1860–1861 that was reported by Godwin-Austen (1864) and Schlagintweit et al. (1861–1866) (#36 in Table 1 and Figs. 1 and 2). Other significant early reports include those of Aktash Glacier, which moved forward by 1.6 km over 3 months in 1868–1869 (Shaw, 1871; #58 in Table 1 and Fig. 1), and Hassanabad Glacier, which advanced by 9.7 km over 2.5 months in 1904–1905 (Hayden, 1907; #8 in Table 1 and Fig. 1).

The greatest reported glacier surge in the Karakoram was that of Kutiàh Glacier, which advanced by 12 km over an approximately 3 month period in 1953, an average of 113 m day^{-1} (Desio, 1954; #1 in Table 1 and Fig. 1). This advance left the local inhabitants '*terror-stricken*' as the advancing ice covered villages, fields, and forests. The fastest observed surge appears to have been that of Yengutz Har Glacier, which advanced by 3.2 km in eight days in 1902–1903, reported by Hayden (1907) (#17 in Table 1 and Fig. 1). Many other early rapid glacier advances are also reported in the literature and are listed fully in Table 1.

The first comprehensive reviews of glacier surges in the Karakoram were undertaken by Mason (1935) and Hewitt (1969). Mason (1935) basically equated outburst floods arising from river damming with "accidental" glacier advances (i.e., surges), describing more than 50 cases since the early 1800s. However, Hewitt (1969) pointed out that this direct relationship is unlikely for all floods as there are many other potential causes of river dams, such as the gradual advance of a glacier due to positive mass balance conditions unrelated to surging. At the time of publication, Hewitt (1969) described 11 instances of known surge-type glaciers in the Karakoram, with possible evidence of many more. Hewitt (1998) updated this inventory, reporting known surges of 17 different glaciers over the previous century (many of which had surged several times), and surge features on 12 more.

Kotlyakov (1997) provided a 1:500,000-scale map which outlines the distribution of surge-type glaciers across the Karakoram, with classifications defined as: (a) '*surging with identified repeated surges*'; (b) '*with morphological features of instability*'; and (c) '*with some indications of pulses.*' Almost every major outlet glacier across the mountain range falls into one of these categories, equating to many hundreds of individual ice masses, although there is no associated text to describe the evidence for these surges or their characteristics. The map also differs from other published inventories in that entire drainage basins are typically classified as one single category, whereas other studies (including this one) define surges based on individual tributaries.

The most recent inventory was presented by Barrand and Murray (2006), who analyzed 150 glaciers in the central Karakoram and classified 19 of them (12.6%) as surge-type based on previously published reports and satellite image analysis. Using logit analysis they found that the largest glaciers (in terms of both length and perimeter) tended to surge the most, which is consistent with studies of surging in other regions such as Yukon (Clarke et al., 1986), Svalbard (Jiskoot et al., 2000), and the Russian High Arctic (Grant et al., 2009). Barrand and Murray (2006) attributed the significance of large perimeters to the fact that avalanches commonly provide a major source of mass gain for these ice bodies, a point also discussed by Gardner and Hewitt (1990) and Hewitt (1998). However, in some regions such as Iceland (Hayes, 2001) and East Greenland (Jiskoot et al., 2003), glacier length does not appear to relate to surge propensity. In East Greenland, for example, Jiskoot et al. (2003) found that glacier complexity (a size-independent factor derived from glacier perimeter and area) provides a better predictor, suggesting that valley shape could be an important control on the surge potential of glaciers.

Methods and Data Sources

IDENTIFICATION OF GLACIER SURGING

In this study an initial list of surge-type glaciers was created from a literature review of all previously reported surges in the Karakoram. This was mainly based on the inventories (and references therein) of Hewitt (1969, 1998) and Barrand and Murray (2006), as well as descriptions of individual surge events such as Desio (1954), Wang et al. (1984), Gardner and Hewitt (1990), Diolaiuti et al. (2003), Copland et al. (2009), and others listed in Table 1. Further identification of glacier surges was undertaken from field observations by the authors during various trips to northern Pakistan in the 1990s and 2000s, and from a systematic visual interpretation of satellite imagery of the entire Karakoram. Satellite imagery is particularly useful for this purpose as there are several distinctive morphological features that are commonly associated with glacier surges and can be readily observed in satellite scenes (Meier and Post, 1969; Clarke et al., 1986; Copland et al., 2003; Barrand and Murray, 2006):

(1) Looped/folded medial moraines and surface foliation. These are perhaps the most diagnostic indicator of glacier surging (Meier and Post, 1969) and form from the movement of surging ice past adjacent less active or stagnant ice.

TABLE 1

List of Karakoram surge-type glaciers identified in this study. First column refers to locations shown in Figure 1. Latitude/longitude values are based on WGS84 datum. 'Surge date' indicates that a glacier surged at some point during the years listed, although the surge did not necessarily last for that entire period. Columns '1976–1990?' and '1990–2004?' indicate glaciers that definitely surged during these periods (i.e., Index 1).

No.	Name (alternate names in brackets)	Lat.	Long.	Index[a]	Description of surge features	Surge date	1976–1990?	1990–2004?	References[b]
1	Kutiàh	35.779	75.043	1	Rapid 12 km advance in 3 months, March–May 1953.	1953			D54,K58, H69, M79, H98
2	Shigar-Basha	35.779	75.266	1	Rapid advance of several miles in 1902–1903.	1902–1903			W10, H69, H98
3	Unnamed	36.757	74.409	3	Looped moraines across ablation area.	Unknown			New
4	Karambar	36.630	74.128	1	Surge blocked river in 1955. Surge which started in April 1993 caused glacier advance of 7–10 m day^{-1} by June 1993 (H98).	1860s, 1895–1905, 1930, 1955, 1993		x	M31, H69, H98
5	Mani	35.891	74.862	3	Looped moraines across ablation area.	Unknown			B06
6	Balt Bare	36.340	74.933	1	2 km rapid advance 1976–1977, after large debris flow in 1974.	1976–1977	x		W84, H98
7	Minapin	36.207	74.568	1	1.3 km advance 1892–1893.	1892–1893			M35, M79, H98
8	Hassanabad	36.388	74.609	1	Advanced 9.7 km within 2.5 months in 1904–1905 (H07), distorted moraines. Had broken into several tributaries by 1954 due to 7 km retreat (P56).	1904–1905			H07, N07, P56, K58, H69, M79, H98
9	Taura West	36.254	74.946	3	Distorted moraines over ablation area, and increase in size of northern tributary 1990–2000.	Unknown			New
10	Bualtar	36.179	74.759	1	Surge 1986–1987 after landslides onto glacier (G90), second 2 km advance 1989–1990 (H98), ~5 km advance 1990–2000 (possibly continuation of 1989–1990 surge?), distorted moraines.	1986–1987, 1989–1990	x		G90, H98
11	Sumaiyar Bur–Burpu	36.130	74.888	1	Advanced ~9 km to join Bualtar in late 1800s. Sudden, massive thickening reported in 1992.	late 1800s, 1990–2000		x	C94, H98, B06
12	Hispar	36.086	75.284	2	Extensive looped and folded moraines in upper ablation area.	Unknown			New
13	Unnamed	36.103	75.163	2	Terminus advance ~0.6 km between 1990 and 2000, bulbous terminus.	1990–2000			New
14	Pumarikish (Chur)	36.128	75.208	1	Rapid 1 km advance and 20 m thickening 1988–1989 (W93), surge in late 1800s? (C94).	late 1800s, 1988–1989	x		W93, C94, H98
15	Hopar	36.146	74.979	1	Rapid 550 m advance and further 150 m advance during summer.	1929–1930			M31, H69
16	Garumbar	36.118	75.100	1	Report of 2.5 km advance sometime between 1892 and 1925.	1892–1925			M31, H69, M79
17	Yengutz Har	36.117	74.711	1	Report of 2 mile advance in 8 days between 1902 and 1903 (H07), 2.6 km advance in spring (M31, H98).	1901–1902			H07, M31, K58, H69, M79, H98
18	Khurdopin	36.249	75.486	1	Extensive looped and folded moraines throughout 13 km long terminus. Rapid advance of right–hand side of terminus 1992–2001.	1992–2001		x	I05
19	Virjerab	36.263	75.661	2	Extensive looped and folded moraines throughout terminus region.	Unknown			H98
20	Unnamed	36.240	75.757	3	Distorted moraines at terminus, advanced position and heavily crevassed in 1973, much smoother surface by 2000.	Unknown			New
21	Braldu	36.143	75.865	2	Extensive looped and folded moraines throughout terminus region.	Unknown			H98, B06
22	Unnamed	36.191	76.181	1	Rapid terminus advance of 3.2 km from 1978 to 1990, associated change in surface from smooth to crevassed.	1978–1990	x		H07
23	Bei Yengisogat	36.101	76.149	3	Extensively looped and folded terminal moraines.	Unknown			New
24	Unnamed	36.122	76.134	1	Terminus advance of ~1.2 km 1990–1995, looped terminal moraine.	1990–1995		x	New
25	Unnamed	36.128	76.126	1	Terminus advance of ~1.5 km 1990–1995, looped terminal moraine.	1990–1995		x	New

TABLE 1

Continued.

No.	Name (alternate names in brackets)	Lat.	Long.	Index[a]	Description of surge features	Surge date	1976–1990?	1990–2004?	References[b]
26	Unnamed	36.145	76.093	1	Terminus advance of ~3 km 1977–1990, looped terminal moraine.	1977–1990	x		New
27	Unnamed	36.093	76.071	3	Folded and distorted moraines, advanced position with bulbous terminus in 1977.	Unknown			New
28	South Skamri	36.039	76.196	1	Rapid terminus advance 1978–1990, looped and distorted terminal moraine.	1978–1990	x		C09
29	Skamri (Yengisogat, Insgaiti)	36.055	76.178	2	Extensive looped and folded terminal moraines.	Unknown			C09
30	Masherbrum	35.543	76.324	2	"Thickening and surge–like behavior of upper glacier" (H98), although no rapid terminus advance observed.	1990–2000			H98
31	Gondokoro	35.558	76.391	2	Advance of white ice areas by up to 1 km 1990–2000, thickening across terminus, terminus advance ~0.5 km.	1990–2000			New
32	Lokpar	35.495	76.255	1	Surge of Lokpar tributary followed by steepening and >1.5 km advance of main terminus.	1989–1993			H98
33	Liligo	35.705	76.223	1	Rapid terminus advance observed on ground and in satellite images, extensive strandlines observed in field in summer 2005.	1909–1929, 1990–2000		x	H98, D03, B08
34	1st Feriole	35.845	76.012	2	Glacier in forward (surged) position in 1977, rapid retreat of 2.8 km 1977–1990 when nearby glaciers advancing.	Unknown			C09
35	2nd Feriole (Shingchukpi)	35.889	76.033	1	Rapid terminus advance.	2004–2007			B06, H07, C09
36	South Chiring (Shirchapbi Biaho, Maedan)	35.917	76.040	1	Rapid terminus advance, field observations, looped moraines at terminus.	1860–1861, 2002–2003		x	S61, GA64, H98, B06, H07, C09
37	Drenmang	35.976	76.021	1	Previous surge in 1930–1931 (and adjacent Little Skamri in 1977–1978) (H98). Rapid terminus advance and acceleration since 2006, looping of terminal moraines, change from smooth to heavily crevassed surface with recent surge.	1930–1931, 2005–2007			H98, B06, H07, C09
38	Little Skamri	35.980	76.024	1	Rapid terminus advance (4.8 km in late 1970s) observed in satellite images, looping of terminal moraines.	1977–1978	x		H98
39	Panmah (Nobande Sobonde)	35.913	76.007	2	Looped moraines with stagnant/downwasting ice at terminus.	Unknown			B06
40	Chiring	35.928	76.029	1	Rapid terminus advance coincident with increase in crevassing in upper ablation area, folded moraines at terminus, field observations by H98.	1886–1887, 1994–1996		x	Y96, H98, B06, H07
41	Hind Hainabrakk	35.767	76.130	1	Rapid advance 1990–2000 as it merges with Trango Glacier, distorted moraines, change in surface from uncrevassed (1990) to crevassed (2000).	1990–2000		x	New
42	Chagaran	35.771	76.311	3	Folded and looping of terminal moraines.	Unknown			New
43	Moni	35.900	76.299	1	Rapid advance of terminus into tributary Sarpo Laggo (by ~1.5 km) in 1980s, including deformation of medial moraines. Continued ~1.1 km advance in 1990s.	1980s	x		H98
44	Unnamed	35.982	76.325	1	Terminus advance of ~4 km between 1995 and 2000, associated change from smooth to crevassed surface.	1995–2000		x	H98, H07
45	Unnamed	35.918	76.273	1	Two rapid terminus advances of ~1.1 km each between 1977–1990 and 2004–2007, associated surface crevassing during surges.	1977–1990, 2004–2007	x		New
46	Unnamed	35.907	76.255	1	Rapid terminus advance, bulbous terminus and distortion of moraines as surge occurred in to Sarpo Laggo Glacier.	2004–2007			New

TABLE 1

Continued.

No.	Name (alternate names in brackets)	Lat.	Long.	Index[a]	Description of surge features	Surge date	1976–1990?	1990–2004?	References[b]
47	West Chang Tok	35.898	76.232	1	Distortion of medial moraine due to advance 1978–1990.	1978–1990	x		New
48	East Chang Tok	35.899	76.237	2	Distortion of medial moraine.	Unknown			New
49	Sarpo Laggo (Yulin)	35.928	76.309	3	Extensive folding and looping of old terminal moraines.	Unknown			New
50	Unnamed	35.941	76.310	3	Glacier in forward position in 1977, with some folding of terminal moraines; rapid retreat of ~2 km between 1977 and 1990 when nearby glaciers advancing.	<1977			New
51	West Qogori	35.967	76.456	1	Forward movement of terminus 1990–2000, distortion of medial moraines.	1990–2000		x	New
52	Sagan	35.778	76.739	1	Bulbous terminus in 1990, 3 km advance 1990–2000, folded moraines.	1990–2000		x	New
53	Unknown	35.712	76.941	1	Advanced position in 1978, retreated 1.5 km by 1990, advanced again 1.5 km by 2000.	<1978, 1990–2000		x	H98
54	Unknown	35.689	76.995	2	Terminus advance of ~1.1 km between 1990 and 2000.	1990–2000			New
55	Chong Kumdun	35.183	77.679	2	Folded moraines on surface, reported blockage of Shyok River in 1927–1928 after advance.	1927–1928			S29
56	Unnamed	35.199	77.649	3	Folded moraines on surface.	Unknown			New
57	Kichik Kumdun	35.125	77.743	1	Reports of advances in 1920s (S29). Terminus advance of 2.4 km in 7 months in 1935–1936 (M40). Rapid terminus advance 1990–2000, with new crevassing.	1920s, 1935–1936, 1990–2000		x	S29, M40, M79
58	Aktash	35.095	77.757	1	Previous reports of surges: 1.6 km in 3 months (1868–1869); sudden, rapid advance (1902–1903); 2.5 km in 7 months (1935–1936); rapid advance (1958).	1868–1869, 1902–1903, 1935–1936, 1958			L10, LG40, H69, H98
59	Unnamed	35.020	77.784	1	Rapid terminus advance of 2.3 km between 1990 and 2000, associated change from smooth to crevassed glacier surface.	1990–2000		x	New
60	Sultan Chhussku	34.899	77.972	2	Report of "*enormous push forward… 200–300 million meters of ice*" (V35).	1930			V35, H69
61	West Tughmo (Zarpo)	34.923	77.856	1	1.0 km terminus advance 1990–2000, associated change from smooth to crevassed glacier surface.	1990–2000		x	H98
62	East Chamshing	34.946	77.771	1	1.4 km terminus advance 1978–1990, heavily crevassed surface.	1978–1990	x		New
63	Unnamed	34.817	77.927	1	2.4 km terminus advance 1976–1990, distorted medial moraine, bulbous terminus.	1976–1990	x		New
64	Unnamed	34.594	78.381	1	1.5 km terminus advance 1990–2000, looped moraines, associated change from smooth to crevassed surface.	1990–2000		x	New
65	Unnamed	34.565	78.347	2	Terminus retreat of 2.9 km between 1990 and 2000 while surrounding glaciers stable or advancing.	Unknown			New
66	Unnamed	34.514	78.508	1	Terminus advance ~0.6 km between 1990 and 2000, deformed medial and lateral moraines.	1990–2000		x	New
67	Unnamed	34.421	78.551	3	Folding of moraines over ablation area.	Unknown			New
68	West Chamshing	34.956	77.720	3	Rapid terminus retreat ~3.2 km between 1990 and 2000 while surrounding glaciers stable or advancing, distorted moraines.	Unknown			New
69	South Rimo	35.341	77.590	2	Extensive folded moraines at terminus, potholes on surface.	Unknown			New
70	Unnamed	35.355	77.514	1	Terminus advance ~2.2 km 1980–1990, distortion of medial moraine.	1980–1990	x		New
71	Central Rimo	35.361	77.613	1	Terminus advance ~1.3 km 1993–2000, increase in crevassing, folded moraines.	1993–2000		x	New
72	North Rimo	35.473	77.505	3	Folding of moraines over ablation area.	Unknown			New
73	Unnamed	35.553	77.438	3	Folding of moraines over ablation area.	Unknown			New

TABLE 1

Continued.

No.	Name (alternate names in brackets)	Lat.	Long.	Index[a]	Description of surge features	Surge date	1976–1990?	1990–2004?	References[b]
74	Gasherbrum	35.884	76.747	1	Folded moraines in ablation area, thickening and surge–like behavior of upper glacier (H98).	1990–2000		x	H98
75	NW Skyang (Dong Qogori)	35.984	76.498	2	Advanced position and folded moraines in 1971, retreated by 1979.	~1971			New
76	Chongtar (Dong Yulin)	35.931	76.325	2	Advanced position in 1973 with bulbous terminus, deformed moraines.	Unknown			New
77	Unnamed	35.834	75.912	2	Rapid terminus advance of ~1 km into tributary between 1990 and 2000.	1990–2000			New
78	Uzun Brak	35.885	75.748	2	Advance of ~1 km between 1990 and 2001 into Biafo Glacier.	1990–2000			New
79	Tonga	35.830	75.628	1	Rapid terminus advance ~1.2 km 2001–2005, increase in surface crevassing.	2001–2005		x	New
80	Nang Brok	35.651	75.714	1	Terminus advance ~1.8 km 1990–2000, large increase in surface crevassing.	1990–2000		x	New
81	Skoro La Gans	35.616	74.783	3	Advanced position in 1977; rapid retreat by 1990 compared to surrounding glaciers.	Unknown			New
82	Unnamed	35.556	76.001	2	Terminus advance ~0.6 km 1990–2000, bulbous terminus.	1990–2000			New
83	West Ching Kang	35.549	76.006	1	Advance of white ice areas by up to 2 km 1990–2000, folded moraines across terminus.	1990–2000		x	New
84	Unnamed	35.291	76.548	1	Terminus advance ~0.8 km 1990–2000, change from debris–covered terminus to bare ice.	1990–2000		x	New
85	Unnamed	35.227	77.099	1	Terminus advance ~0.9 km 1990–2000, push of tributary into main trunk glacier.	1990–2000		x	New
86	Teram Shehr	35.495	77.035	3	Folded moraines along glacier terminus.	Unknown			New
87	Unnamed	35.364	76.791	2	Terminus advance ~0.5 km, increase in crevassing, bulbous terminus.	1990–2000			New
88	Unnamed	36.117	76.047	1	Terminus advance ~1.4 km into tributary 1990–2001, distortion of moraines.	1990–2001		x	New
89	Baltar	36.465	74.348	3	Rapid advance of ~10 km by 1915 to join Kukuar Glacier (S33), compared to retreated position in 1830s. Retreat of ~8 km between 1930s and today.	~1915			S33, P56, M05
90	Kukuar	36.479	74.249	3	Rapid advance of ~10 km by 1915 to join Baltar Glacier (S33), compared to retreated position in 1830s. Retreat of ~8 km between 1930s and today.	~1915			S33, P56, M05

[a] Surge Index: 1 = Confirmed, 2 = Likely, 3 = Possible.

[b] References to previously published descriptions/inventories: B06 = Barrand and Murray (2006); B08 = Belò et al. (2008); C94 = Conway (1894); C09 = Copland et al. (2009); D54 = Desio (1954); D03 = Diolaiuti et al. (2003); GA64 = Godwin–Austen (1864); G90 = Gardner and Hewitt (1990); H07 = Hayden (1907); H69 = Hewitt (1969); H98 = Hewitt (1998); H07 = Hewitt (2007); I05 = Iturrizaga (2005); K58 = Kick (1958); L10 = Longstaff (1910); LG40 = Lyall–Grant and Mason (1940); M05 = Meiners (2005); M31 = Mason (1931); M35 = Mason (1935); M40 = Mason (1940); M79 = Mayewski and Jeschke (1979); N07 = Neve (1907); P56 = Paffen et al. (1956); S29 = Sinclair (1929); S33 = Schomberg (1933); S61 = Schlagintweit et al. (1861–1866); S71 = Shaw (1871); V35 = Visser and Visser–Hooft (1935–1938); W10 = Workman (1910); W84 = Wang et al. (1984); W93 = Wake and Searle (1993); Y96 = Younghusband (1896).

(2) Terminus advance. Surges can be characterized by a rapid terminus advance in relation to surrounding glaciers.
(3) Terminus steepening and thickening. Glaciers often undergo a dramatic change in the form of their terminus during a surge, including the development of a distinctive bulbous (i.e., steep convex) shape as the ice is advancing.
(4) Surface velocities. These can increase by an order of magnitude or more during a surge compared to motion during the quiescent phase. This acceleration can also result in extensive surface crevassing over regions where there was previously little or none.
(5) Strandlines. These can form after a surge as remnants of the previous glacier surface are left as a rim of ice on valley side-walls in the accumulation area. In the ablation area, valley side-walls can contain distinctive lines of polished bedrock and/or disturbed sediment due to a rapid reduction in glacier surface elevation after surging.

Out of the above list, the presence of looped/folded medial moraines is the most distinctive feature of surge-type glaciers. They act as particularly useful indicators as they are readily

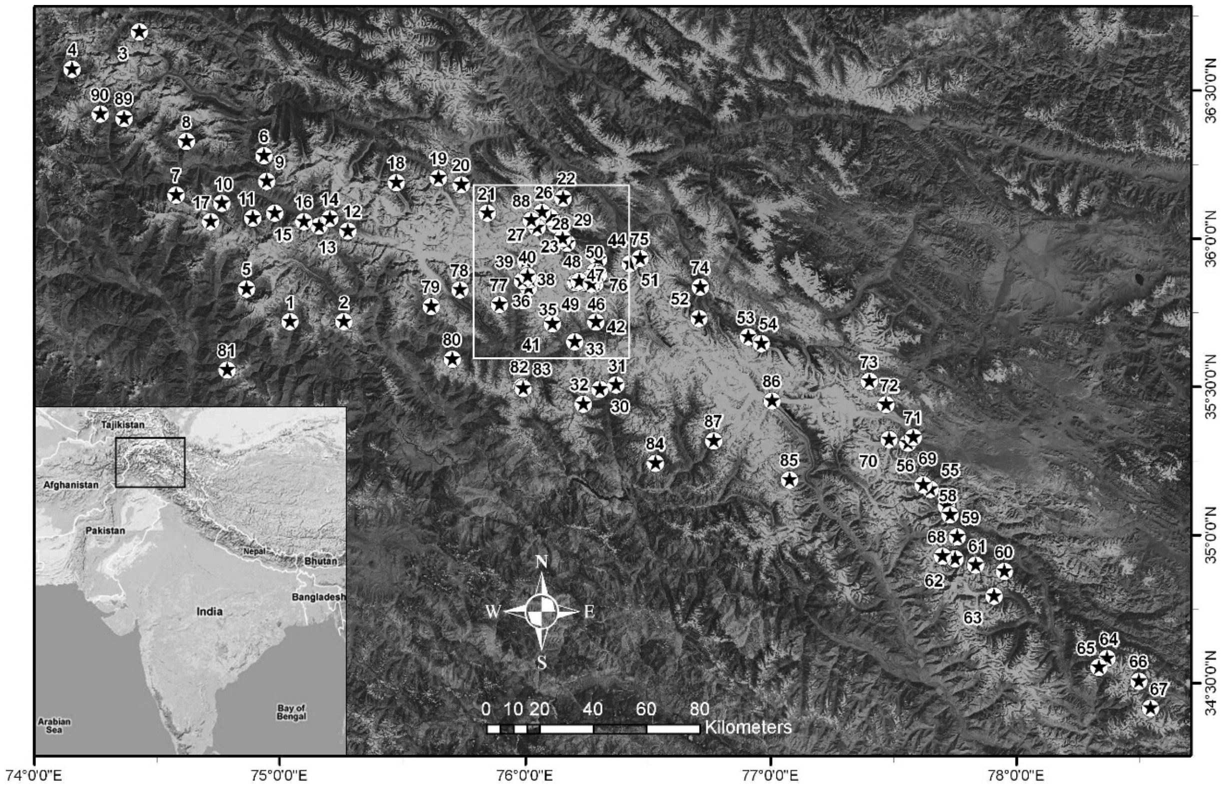

FIGURE 1. Location of Karakoram surge-type glaciers identified in this study. Inset map shows general location of study area. White box shows region covered by Figure 2. Numbers refer to glaciers shown in other figures and listed in Table 1.

identifiable in satellite imagery and persist long after a surge has terminated, making the identification of surge-type glaciers possible even during their quiescent phase (Meier and Post, 1969). Some of the other features (e.g., terminus steepening) may also occur on glaciers which are advancing in response to favorable climate conditions unrelated to surging, so it is important to distinguish between these glacier types. This is achieved by considering the magnitude and rapidity of the change in a given glacier compared to those surrounding it. Where changes are large (e.g., terminus advance of kilometers), occur over a short time period (e.g., a year), and occur out of phase with adjacent glaciers with similar physical characteristics (e.g., area, length, orientation), this increases confidence that a glacier surge has occurred. In this study we carried out systematic visual interpretation of repeat satellite images of every glacier in the Karakoram since ~1969, with all locations being imaged at least three times. To indicate the likelihood that a particular glacier is surge-type, we classified all glaciers that displayed features associated with surging into one of the following four categories (after Copland et al., 2003):

Index 1. Confirmed. Rapid terminus advance is observed (out of phase with surrounding glaciers), with many distinct surge features such as looped moraines.

TABLE 2

List of satellite imagery used in this study.

Sensor/data set	Resolution	Acquisition date (dd/mm/yyyy), UTC time (hh:mm:ss), and image ID (where applicable)
DISP/Keyhole	~3–9 m	30/07/1969 (DS1107-1104DA005 and DS1107-1104DA006); 28/09/1969 (DS1052-1088DF177 and DS1052-1088DF180); 16/09/1971 (DS1115-1088DF202, DS1115-1088DF203 and DS1115-1088DF204); 23/11/1973 (DZB1207-500045L007001); 08/06/1979 (DZB1215-500431L007001); 22/06/1980 (DZB1216-500018L010001); 16/09/1980 (DZB1216-500361L006001)
Landsat GeoCover circa 1975 (MSS)	60 m	10/09/1976 (Path 158, Row 36); 17/02/1977 (Path 156, Row 35); 09/03/1977 (Path 158, Row 35); 02/08/1977 (Path 160, Row 35); 18/07/1978 (Path 159, Row 35); 15/07/1979 (Path 161, Row 35);
Landsat GeoCover circa 1990 (TM)	28.5 m	Tiles N-43-30 and N-43-35
Landsat GeoCover circa 2000 (ETM+)	30 m	Tiles N-43-30 and N-43-35
Landsat 5 (TM)	28.5 m	29/06/1990 (Path 148, Row 35)
Landsat 7 (ETM+)	15 and 30 m	04/09/2000 (Path 148, Row 35); 18/05/2001 (Path 148, Row 35)
JERS-1	18.3 × 24.2 m	22/09/1993 (05:48:00), 16/09/1995 (05:57:00)
ASTER	15 m	11/09/2000 (06:07:52); 29/08/2001 (05:59:54 and 06:00:03); 30/09/2001 (05:58:33 and 05:58:42); 03/10/2002 (05:53:56 and 05:54:04); 20/09/2003 (05:52:18 and 05:52:27); 29/10/2003 (05:58:54); 13/09/2004 (05:58:17); 15/09/2004 (05:46:04); 05/11/2005 (05:45:45 and 05:45:54); 17/06/2006 (05:46:09 and 05:46:18); 26/07/2006 (05:52:31 and 05:52:40); 12/09/2006 (05:52:21 and 05:52:30); 28/09/2006 (05:52:11); 30/10/2006 (05:52:04); 27/06/2007 (05:52:52 and 05:53:01)

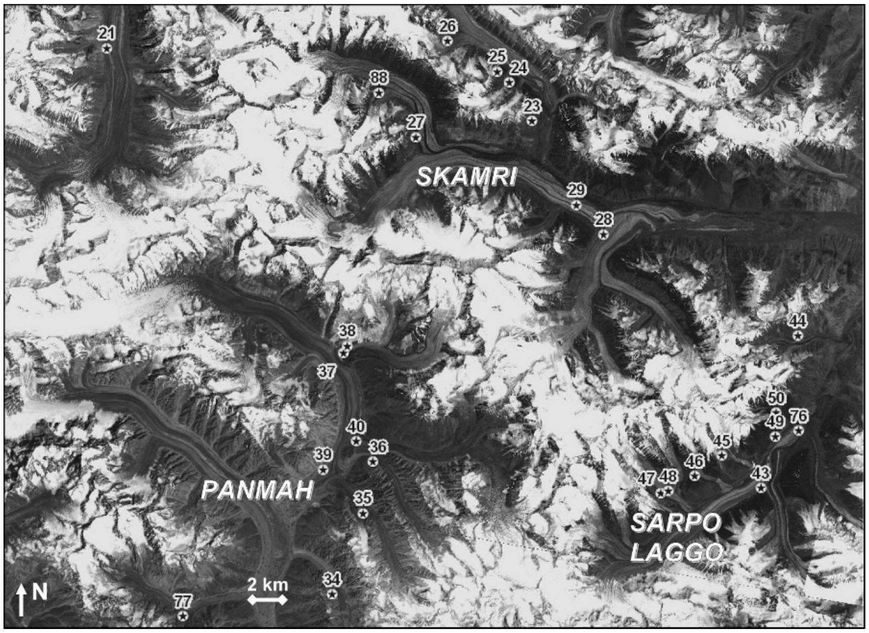

FIGURE 2. Main cluster of Karakoram surge-type glaciers (base image: ASTER, 26 July 2006). Numbers refer to glaciers listed in Table 1.

Index 2. Likely. Rapid terminus advance is not observed (or difficult to identify), but several distinct surge features are present such as looped moraines.

Index 3. Possible. A few surge features are present, but active phase is not observed.

Index 4. Non-surge. No surge features are present.

Following the scheme used in previous studies (e.g., Hewitt, 1998; Barrand and Murray, 2006), surges of tributaries are identified and counted separately if they occur independently from the main glacier into which they flow. The list of surge-type glaciers provided here is considered to be a minimum estimate as some of the features described above are not always easily identifiable in satellite imagery (e.g., strandlines), and some glaciers observed in their surge phase contained no features indicative of previous surges prior to their current activity. In addition, some field observations of surges occurred on glaciers that would not have been classified as surge-type based on satellite observations alone. Hayden (1907), for example, reported the 9.7 km advance of Hassanabad Glacier in 1904–1905, yet there were few surface features indicative of that surge in any of the satellite imagery reviewed here.

The Karakoram is generally poorly mapped due to its remoteness and political instability across several countries, with many of the glaciers either being unnamed or having several different names. The glacier names used in this paper are derived from previous studies (e.g., Hewitt, 1969, 1998, 2007; Barrand and Murray, 2006), the Global Land Ice Measurements from Space (GLIMS) database (http://www.glims.org), and published maps (Lanzhou Institute of Glaciology and Geocryology, no date; Government of Pakistan, 1995; PZA, 2004). Where a glacier has more than one known name, all of the names are provided in Table 1.

SATELLITE IMAGERY

Tiles of satellite imagery of the entire Karakoram were systematically visually examined for indications of surge activity described above. Wherever possible, late summer imagery was used to coincide with the period of minimum surface snow cover. The satellite data fell into three main age categories:

1970s Imagery

The primary source of early data consisted of the Landsat GeoCover circa 1975 series, which comprises Landsat 2 and 3 Multispectral Scanner (MSS) scenes with a ground resolution of 60 m. These data were downloaded as individual orthorectified frames from the Global Land Cover Facility (GLCF; http://www.landcover.org), and ranged in acquisition date from 1976 to 1979 (Table 2). To supplement the Landsat data, a total of 11 Declassified Intelligence Satellite Photography (DISP) scenes were ordered from the U.S. Geological Survey (Table 2). These panchromatic images ranged in date between 1969 and 1980, with ground resolutions of 3–9 m (McDonald, 1995). High-resolution scans of these photos were georectified in ESRI ArcGIS 9.1 against Landsat GeoCover circa 2000 imagery using an average of ~20 tie points and root mean-squared error (RMSE) of <30 m per scene.

1990s Imagery

Data centered on 1990 were mainly derived from the Landsat GeoCover circa 1990 data set, which consists of a global set of orthorectified tiles (each 5° latitude by 5° longitude) of multispectral Landsat 4 and 5 imagery. The acquisition dates of the individual scenes that make up the tiles are not provided, although the entire global data set was produced with scenes from 1989–1993. These data were downloaded from GLCF, together with a Landsat 5 scene from 1990 (Table 2). Two additional Japanese Earth Resources Satellite-1 images of the eastern Karakoram and Baltoro regions from September 1993 and 1995, respectively, were downloaded from the Japanese Aerospace Exploration Agency (http://www.eorc.jaxa.jp/en/imgdata/index.html).

2000 and Later Imagery

Imagery centered on the year 2000 mainly came from the Landsat GeoCover circa 2000 data set, which contains imagery collected between 1997 and 2000 (Table 2). These data were already orthorectified and were acquired by the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor and downloaded from GLCF. Two additional Landsat 7 ETM+ scenes were used from 2000 and 2001, which provided panchromatic coverage at a resolution of 15 m that was better than the 30 m resolution

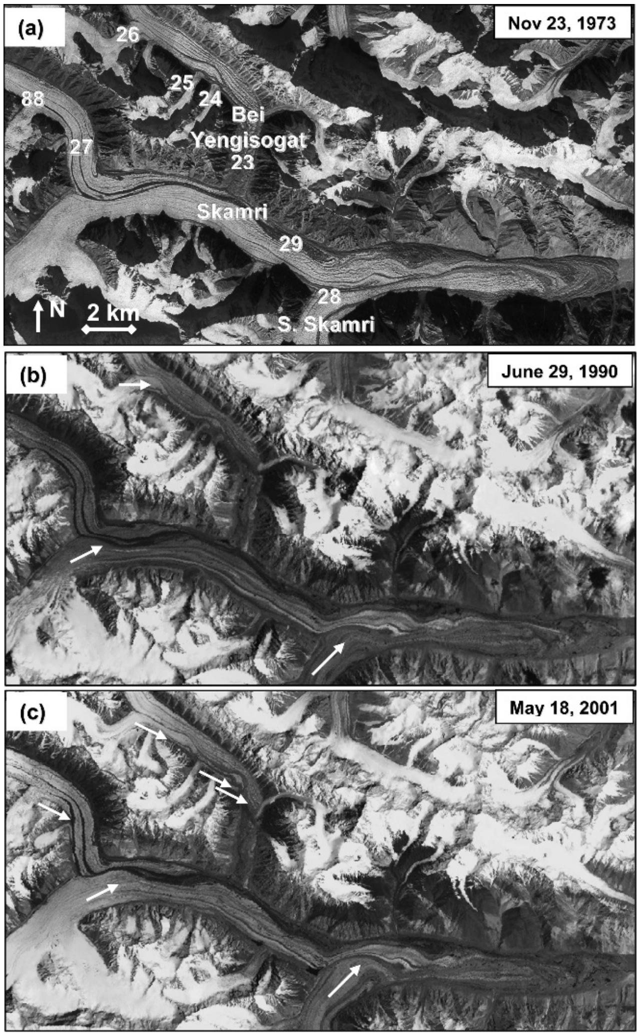

FIGURE 3. Temporal sequence of glacier surges in Skamri Basin, 1973–2001. Numbers refer to descriptions in Table 1; satellite image details provided in Table 2. Arrows in (b) and (c) indicate significant changes since the previous image.

available with the multispectral GeoCover data. ASTER Level 1B scenes were ordered from the NASA Earth Observing System to provide coverage over the period 2001–2007 (Table 2). Each ASTER scene covers a footprint of ~60 × 60 km, while each Landsat scene covers an area of ~185 × 185 km, so many ASTER scenes were required to obtain good regional coverage.

Results

The majority of glaciers in the Karakoram were classified as Index 4, with no evidence of being surge-type. However, a total of 90 glaciers were identified as surge-type, of which 50 had not previously been described in detail (Table 1, Fig. 1). There was a large range in the size of surge-type glaciers, with their lengths varying from <4 km (Glacier 85) to >50 km (Glacier 12 = Hispar Glacier). Out of the 90 glaciers identified as surge-type, 51 were observed in the active phase of the surge cycle and were classified as Index 1. A total of 21 were classified as Index 2 (likely surge-type), and 18 were classified as Index 3 (possibly surge-type). This comprises one of the largest clusters of mid-latitude (<45°N) surge-type glaciers in the world, with perhaps only the Pamirs (to the north of the Karakoram) containing more. Kotlyakov et al. (2008) stated that there are at least 55 glaciers with indicators of surging characteristics in the Pamirs, with '*signs of current periodic activity*' on 215 more. Outside of Asia, other mid-latitude glacier surges have typically been observed as single isolated events within mountain ranges where few, if any, other glaciers surge (e.g., Glaciar Horcones Inferior in the Argentinean Andes (Milana, 2007) and Vernagtferner, in the Austrian Alps (Hoinkes, 1969)). This contrasts with higher latitude regions in the northern hemisphere, where many surge-type glaciers have been identified in clusters in locations such as the Russian High Arctic (Grant et al., 2009), Canadian High Arctic (Copland et al., 2003), Svalbard (Jiskoot et al., 2000), East Greenland (Jiskoot et al., 2003), and Alaska-Yukon (Post, 1969).

Many of the glaciers identified in this study as surge-type were also identified as such in the map of Kotlyakov (1997), although several others that he described as surge-type, even under his most definite surge category, were not classified as surge-type here. These glaciers displayed little to no evidence of surging in the satellite imagery that we analyzed, and no reference could be found to them in extensive literature searches. This disparity likely reflects the classing of entire drainage basins under one category by Kotlyakov (1997). This reiterates the point made above that our inventory should be interpreted as a minimum estimate of the number of surge-type glaciers in the Karakoram. In Table 1, a glacier surge identified as 'new' means that its surge characteristics have never been described in detail in published literature, even though it may have been shown in Kotlyakov's (1997) map.

SURGE PERIODICITY

For glaciers in the Karakoram with long records it is clear that some of them have surged multiple times, such as Karambar Glacier (#4) which surged five times in the past 150 years, and Aktash (#58) which surged four times over the same period (also see Table 1). Some glaciers were also observed to have surged multiple times in the recent satellite record, such as Glacier #45, which surged in both 1977–1990 and 2004–2007, and Bualtar (#10), which surged in both 1986–1987 and 1989–1990 (Hewitt, 1998). These observations suggest that the quiescent period averages ~25–40 years for several glaciers in the Karakoram, although this may be as short as a few years or as long as a century or more. The few direct field observations of surges in this region suggest that the active phase is typically short-lived, ranging from a few days or months to as much as a year or two (e.g., Hayden, 1907; Mason, 1940; Kick, 1958; Gardner and Hewitt, 1990; Hewitt, 1998, 2007). The lack of reliable long-term observational records in this region makes it difficult to draw general conclusions, although it appears that the surge periodicity in the Karakoram more closely approximates the short-lived active phase and multi-decadal quiescent phase common in predominantly temperate locations such as the Pamirs (Kotlyakov et al., 2008) and Alaska-Yukon (Kamb et al., 1985; Eisen et al., 2001), rather than the decadal-long active phase and sometimes century or longer quiescent phase more common on polythermal glaciers in higher latitude locations such as Svalbard (Dowdeswell et al., 1991), East Greenland (Jiskoot and Juhlin, 2009), and the Canadian High Arctic (Copland et al., 2003). This suggests that surges of Karakoram glaciers are more likely to be triggered by changes in their subglacial hydrology, rather than by changes in their basal thermal regime (Murray et al., 2003).

SPATIAL CLUSTERING OF SURGES

The results indicate that within the Karakoram the distribution of surge-type glaciers is non-random, with a particularly large cluster in the Skamri (Yengisogat), Panmah, and Sarpo Laggo

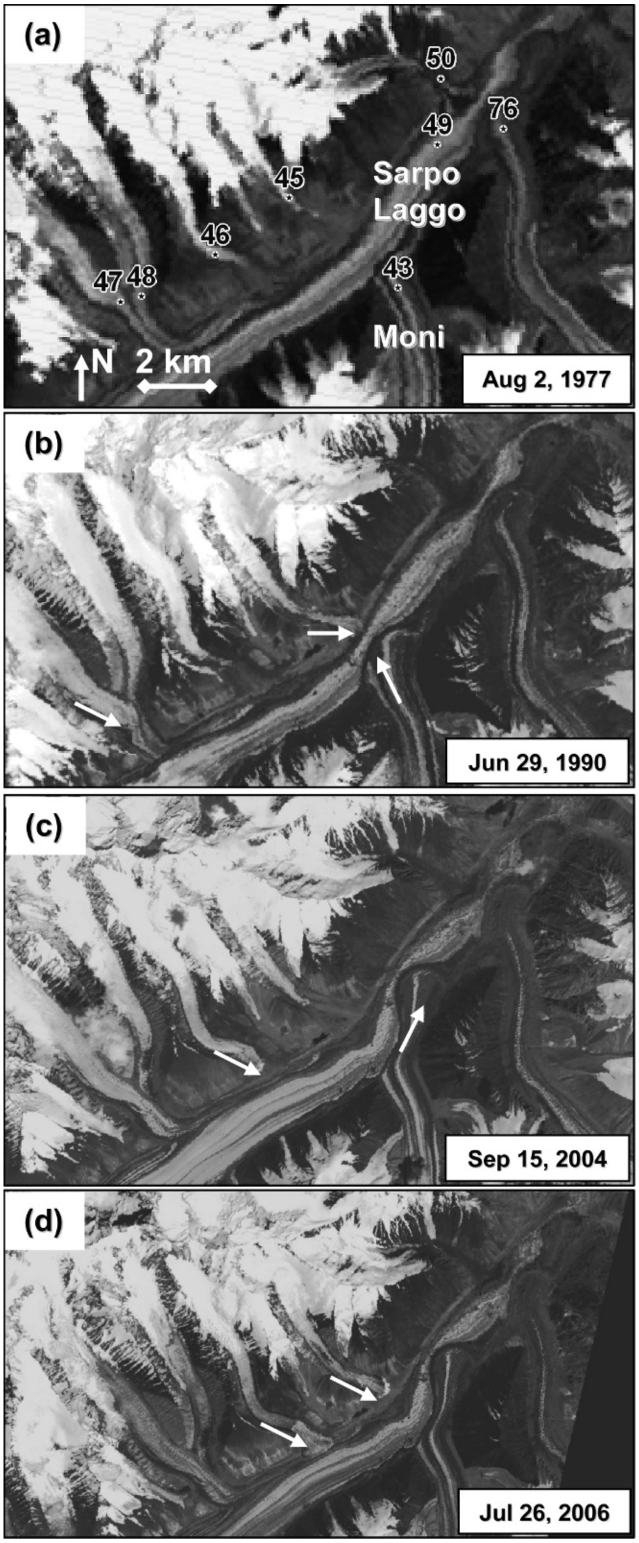

FIGURE 4. Temporal sequence of surges of tributaries of the Sarpo Laggo Glacier. Numbers refer to Table 1; satellite image details provided in Table 2. Arrows indicate the occurrence of surges. Note that Glacier 45 has surged twice.

drainage basins to the north and northwest of Baltoro Glacier (Table 1, Fig. 2). Close to a third of all Karakoram surge-type glaciers are found within these valleys, with almost every large glacier in these areas classified as surge-type. Hewitt (2007) and Copland et al. (2009) have previously discussed the characteristics and strong concentration of surge-type glaciers within the Panmah basin, but the clusters in the Sarpo Laggo and Skamri basins have not previously been described in detail. The surges in these two basins will therefore be presented here.

Skamri Basin

The Skamri Basin contains at least eight surge-type glaciers, with five of them observed to have surged between 1973 and 2001 (Fig. 3, Table 1). Skamri Glacier (#29) is the largest ice mass in this basin, at almost 40 km long, with evidence of surging provided by the extensively deformed and folded moraines along its length. In addition, Skamri Glacier provided the dominant outflow from the basin in 1973 (Fig. 3, a), with clean ice at the terminus extending ~5 km further down-glacier than in 1990. This suggests that Skamri Glacier surged shortly before 1973, although there are no direct observations to date this. By 1990 South Skamri Glacier (#28) had surged and replaced Skamri Glacier as the dominant ice outflow from the basin (Fig. 3, b). Based on feature-tracking of ASTER scenes, Copland et al. (2009) found that South Skamri Glacier was still dominant and active in 2006–2007, with velocities >200 m yr^{-1} across its upper ablation area, although it was not surging at this time. Separately, the upper parts of Skamri Glacier began pinching out the flow from Glacier 27 in 1990, with the flow almost completely cutoff by 2001 (Fig. 3, b and c). The long duration of this change suggests that it relates to the reorganization of ice flow after an earlier surge of Glacier 27 or one of its tributaries. Tributary Glacier 88, for example, surged between 1990 and 2001 (Fig. 3, b and c), and looped moraines on the eastern side of Glacier 27 (visible in Fig. 3, a) suggest that other tributaries also surged in the past.

Two unnamed tributaries (#24 and #25) of Bei Yengisogat Glacier (#23) show interesting surge histories (Table 1, Fig. 3), with a comparison of Landsat and JERS imagery indicating that they both advanced by ~1.2–1.5 km between 1990 and 1995. These glaciers have accumulation basins that are very similar topographically (size, shape, aspect, altitude), but are physically separate. Their termini had a bulbous shape and were in an advanced position in 1990 compared to 1973 (Fig. 3, a and b). Prior to the surges of Glacier 24 and Glacier 25, an up-glacier tributary (#26) of Bei Yengisogat Glacier with a similar aspect surged sometime between 1977 and 1990. It was considered whether this advance triggered the other two downstream, but close analysis suggests that this surge front had not reached the termini of Glacier 24 and Glacier 25 by the time of their surge (Fig. 3, b).

Sarpo Laggo Basin

Sarpo Laggo Glacier (#49) and its tributaries (#43, #45, #46, #47, #48, #50, #76) comprise the largest concentration of surge-type glaciers in the Karakoram (Figs. 2, 4). The surface of Moni Glacier (#43) was relatively undisturbed and uncrevassed in 1973, but had advanced 1.5 km by 1990, distorting medial moraines of Sarpo Laggo Glacier as it pushed into it (Fig. 4, a and b). Furthermore, between 1990 and 2004 the terminus of Moni Glacier advanced by another 1.1 km into Sarpo Laggo Glacier to become the dominant ice mass in the main valley. This produced distinct shear margins and a well-defined medial moraine between the fast moving Moni Glacier and the adjacent more slowly moving Sarpo Laggo Glacier.

Glacier 45, another tributary of Sarpo Laggo Glacier, showed repeated surging over the period of study. Similar to Moni Glacier it had an undisturbed surface in 1977, but by 1990 its terminus had advanced by ~1.1 km to join Sarpo Laggo Glacier (Fig. 4, b). The glacier experienced extensive up-glacier crevassing during this

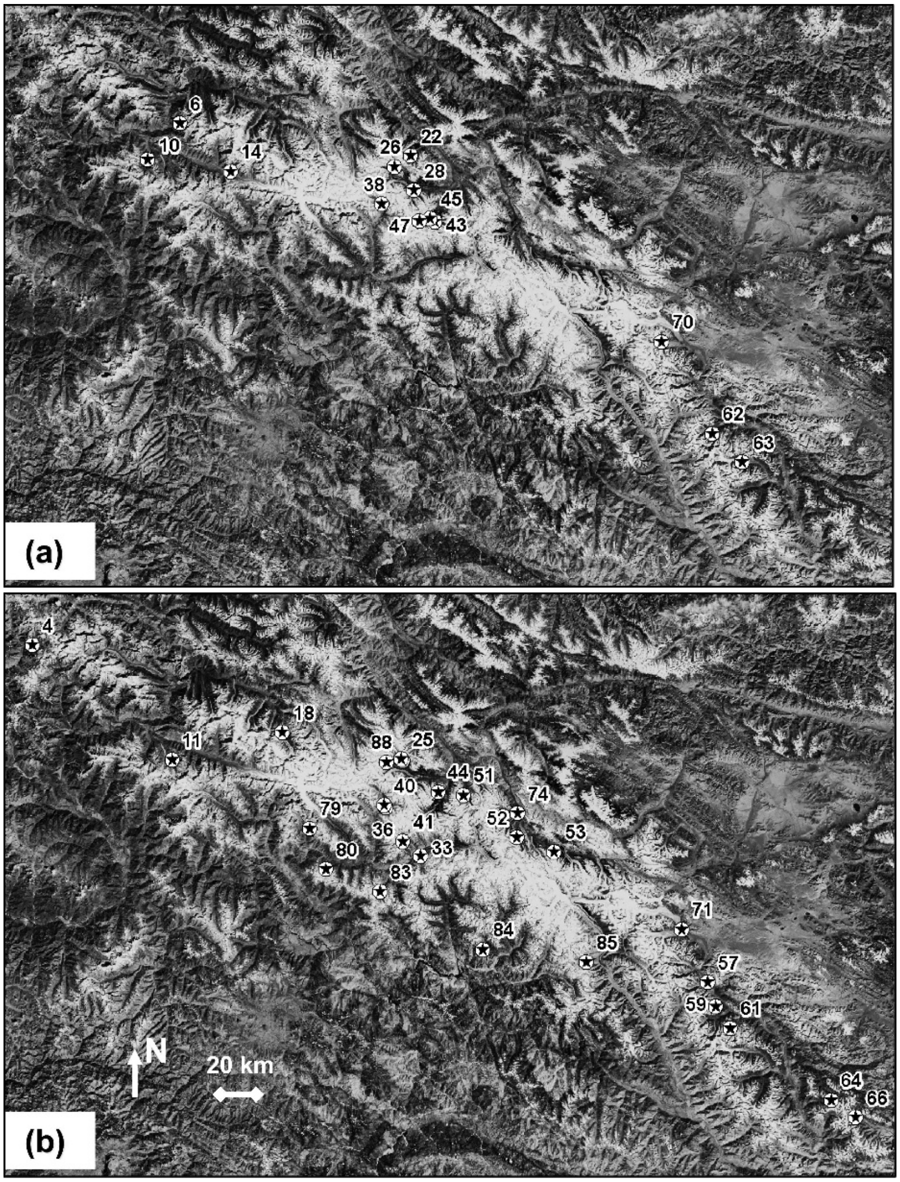

FIGURE 5. (a) Distribution of glacier surges observed during 1976–1990. (b) Distribution of glacier surges observed during 1990–2004. Numbers refer to glaciers listed in Table 1.

surge, and then retreated back to its pre-surge position between 1990 and 2000. However, Glacier 45 surged again between 2004 and 2007 (Fig. 4, c and d) to join Sarpo Laggo Glacier a second time. The adjacent Glacier 46 also surged between 2004 and 2007, pushing into Sarpo Laggo Glacier.

TEMPORAL CLUSTERING OF SURGES

To assess temporal patterns in the frequency of glacier surges the inventory was subset into equal periods centered on 1990, and a count was made of the number of confirmed surges (Index 1 in Table 1) that occurred in the 14 years before and after. In particular, three Landsat 5 images were used as the 1990 base scenes, and compared against the 1976–1980 Landsat 2/3 and DISP scenes, and the 2000–2004 Landsat 7 and ASTER scenes (Table 2). By subsetting the imagery in this way we ensured that differences in the repeat imaging of a region over time did not bias the results. In addition, issues with differences in the ability to detect surges between different image sources were considered to be insignificant as clear-sky imagery of the entire study region was available for all periods, and the observed changes occurred over a much larger scale than that of the imagery. In addition, the old DISP imagery (e.g., Fig. 3, a) provided similar or better resolution than the more recent Landsat and ASTER imagery (e.g., Fig. 3, c). Additional information from published articles was used to supplement and confirm the surges identified from the satellite imagery. Any surges which occurred over the year 1990 itself were excluded from this analysis.

Overall, a total of 39 glacier surges occurred during the study period that met the requirements outlined above (Table 1); a total of 13 occurred during 1976–1990 (Fig. 5, a), while 26 occurred during 1990–2004 (Fig. 5, b). This large recent increase was also noted by Hewitt (1998), who described an apparent increase in the incidence of glacier surging in the Karakoram since the early 1990s (albeit on a smaller scale), arguing that the glaciers in this region may be unusually sensitive to climate change due to the potentially large impact of changes in monsoon conditions. This point was further expanded by Hewitt (2005), who reported an increase in glacier surging and widespread expansion of non-surging glaciers in the Karakoram in the late 1990s. In a further detailed study that focused just on surging glaciers, Hewitt (2007) found that 13 surges had occurred since 1985 in the Karakoram and that "s*ince*

1985, more surges have been recorded than in any comparable period in the records since the 1850s" (Hewitt, 2007, p.181). The present study is in line with these earlier results, but increases the number of glaciers known to have surged recently.

Discussion and Conclusions

One of the most interesting findings from our inventory is that there has been a marked increase in the recent occurrence of glacier surging in the Karakoram. This contrasts with the expectation that the incidence of surging across a large region with many surge-type glaciers would occur randomly if there was no change in forcing, meaning that long-term (decadal +) variations in surging would likely be small. 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. One potential source of changes in forcing comes from changes in valley geometry over time, whereby surges in one glacier can trigger surges in others in a connected drainage network. For example, Kotlyakov et al. (2008) discussed how the surges of several large glaciers in the Pamirs (e.g., Sugran, Oktyabr'sky) are strongly controlled by interactions between trunk and tributary glaciers, with an advance in one having the ability to cause damming in another and subsequent surge(s) once the blockage is released. This issue has been previously discussed in the Karakoram by Hewitt (2007) in relation to the exceptionally high concentration of tributary glacier surges of Panmah Glacier. However, a comparison between Figure 5, a and b, indicates that the location of glacier surges in 1976–1990 vs. 1990–2004 is well distributed across our study area, with only limited clustering in particular basins. This suggests that forcing due to changes in valley geometry alone cannot explain the recent increase in surging.

Several previous studies have discussed how glacier mass balance plays an important role in defining the frequency at which a particular glacier will surge (Harrison and Post, 2003). For example, studies at Variegated Glacier, Alaska (Eisen et al., 2001), and Medvezhiy Glacier, Russia (Dyurgerov et al., 1985), indicate that a specific cumulative snowfall is necessary to trigger a surge. For Variegated Glacier, this amounts to an ice-equivalent snowfall of 43.5 ± 1.2 m in its accumulation area between each of its last four surges, meaning that a more positive mass balance results in a shorter period between subsequent surges (Eisen et al., 2001). In Svalbard, Dowdeswell et al. (1995) demonstrated that a marked reduction in the occurrence of glacier surging (from 18 to 5) between 1936 and 1990 was related to a marked decrease in glacier mass balance over the same period. In the European Alps, Vernagtferner surged repeatedly during the 1600s–1800s with a periodicity of ~80 years, but did not surge again as expected at the start of the 20th century, most likely due to strongly negative mass balance conditions (Hoinkes, 1969). However, the glacier did undergo a rapid terminus advance/surge in the late 1970s and early 1980s after a period of positive mass balance since 1954 (Braun, 1995; Escher-Vetter et al., 2009). The relationship between mass balance and surge periodicity does not hold true for all surge-type glaciers, however, as studies in Iceland have found little connection between these factors (Björnsson et al., 2003).

Climate records from the Karakoram are generally patchy, although data from the few available stations indicate that there was a significant increase in winter, summer, and annual precipitation in the Karakoram over the period 1961–1999 (Archer and Fowler, 2004). Similarly, ERA-40 climate reanalysis data presented by Quincey et al. (2009; their Fig. 8, b) showed a mean annual precipitation of 2.58 mm day^{-1} for the period 1980–1989, compared to 2.83 mm day^{-1} (~10% higher) for the period 1991–2000. In terms of temperature changes, Archer and Fowler (2004) found a general decrease in mean summer temperatures since the early 1960s due mainly to increased summer cloudiness, but winter warming. Taken together, these changes are favorable for positive glacier mass balance, a point supported by the recent stability and expansion of many non-surge glaciers in this region (Hewitt, 2005; Pecci and Smiraglia, 2000; Mayer et al., 2006), including increases in surface velocity (Quincey et al., 2009). The recent increase in glacier surging therefore appears to be a response to positive mass balances over the Karakoram over the past few decades, and is in line with the many other glaciological indicators of recent changes in this area. Hewitt (2007) argued that recent increases in glacier surging in the Panmah basin were related to warming and increased melting at high altitudes in the Karakoram, but the evidence presented here suggests that increases in snowfall are the more likely cause. This is in line with studies in other areas that have found direct relationships between changes in glacier mass balance and surge periodicity (Dyurgerov et al., 1985; Dowdeswell et al., 1995; Eisen et al., 2001).

To conclude, it is evident that glacier surging is more extensive than previously reported in the Karakoram and that the number of glacier surges has increased recently. To provide an analysis of why a particular glacier surges, or why there is a particular concentration of surge-type glaciers in the Karakoram, is beyond the scope of this study. For detailed analysis of the mechanisms that cause a glacier to surge, a comprehensive inventory of the physical characteristics (e.g., length, area, elevation, aspect) of all glaciers in the Karakoram is required, which motivates work currently being undertaken by projects such as GLIMS. The inventory presented here will also improve efforts to assess the causes of glacier fluctuations in this region, as terminus variations on surging glaciers should be largely excluded from assessments of glacier responses to climate change (Yde and Paasche, 2010).

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