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Glacier Change, Concentration, and Elevation Effects in the Karakoram Himalaya, Upper Indus Basin

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This paper seeks to explain evidence of distinctive late- and post-Little Ice Age glacier change in the Karakoram Himalaya and a recent, seemingly anomalous, expansion. Attention is directed to processes that support and concentrate glacier mass, including an all-year accumulation regime, avalanche nourishment, and effects related to elevation. Glacier basins have exceptional elevation ranges, and rockwalls make up the larger part of their area. However, more than 80% of the ice cover is concentrated between 4000 and 5500 m elevation. Classification into Turkestan-, Mustagh-, and Alpine-type glaciers is revisited to help identify controls over mass balance. Estimates of changes based on snowlines, equilibrium line altitudes, and accumulation area ratio are shown to be problematic. Extensive debris covers in ablation zone areas protect glacier tongues. They are relatively insensitive to climate change, and their importance for water supply has been exaggerated compared to clean and thinly covered ablation zone ice. Recent changes include shifts in seasonal temperatures, snowfall, and snow cover at high elevations. Understanding their significance involves rarely investigated conditions at higher elevations that lack monitoring programs.

Keywords: *Avalanche nourishment; glacier classification; ELA; AAR; rockwalls; debris-covered glaciers; elevation effects.*

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Introduction

In recent decades the consequences of climate change for Himalayan glaciers has become of great concern. Glaciers in much of High Asia appear to be declining, some at globally extreme rates (Ageta 2001; Oerlemanns 2001). It had been widely reported that the Indus basin is threatened with severe losses. However, emerging evidence suggests that such reports were, at best, exaggerated (Raina 2009; Armstrong 2010).

Several inquiries have concluded that the behavior of Karakoram glaciers differs from those in the rest of the Himalaya and from the more intensively studied European and North American glaciers (Mayewski and Jeschke 1979; Kick 1989; Shroder et al 1993). If so, it suggests conditions exist that distinguish Karakoram glacier environments. Here attention is directed to high-altitude snowfall and nourishment regimes, glacier typology, and "verticality," especially the role of rockwalls, avalanches, and related conditions above 4000 m elevation—hitherto rather neglected concerns. What can reasonably be deduced about the distribution of terrain and conditions in Karakoram glacier basins from cartographic and satellite imagery is examined as well as how these factors relate to available high-elevation snowfall data. These reveal a distinctive combination of conditions that lead to a strong spatial concentration and intensification of glacier nourishment. They explain and add to the significance of what have been termed "Turkestan"- and "Mustagh"-type glaciers that prevail in the Karakoram. Certain differences emerge, compared with other High Asian mountains, which may explain the seemingly anomalous response to global climate change.

However, it is important, first, to be aware of glacier change in the region and that it involves a far from simple picture of advances and retreats: Current knowledge is limited by the fact that most reports are of changes in termini, sometimes ice-tongue thicknesses at their lowest elevations. One must be cautious in inferring what this can tell us about the vast glacier areas up above.

Glacier changes in the last 150 years

The perennial snow and ice cover of the trans-Himalayan upper Indus Basin is about 20,000 km^2. The greatest share is in the Karakoram Himalaya. Along its main axis the cover exceeds 70%, and the largest glaciers are found here. Most drain to the Indus, and some to the Yarkand River in China's Sinjiang Province. Although the number of Karakoram glaciers may exceed 7000, the 15 largest comprise about half the glacierized area (Yao 2007).

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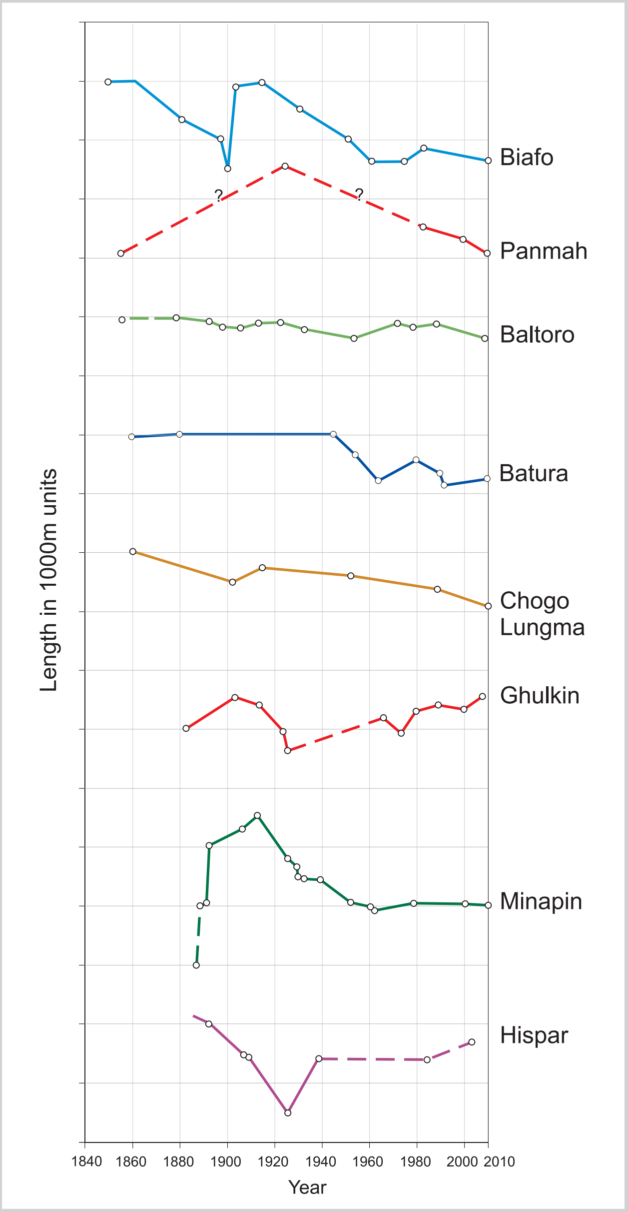
FIGURE 1 Terminus changes of selected Karakoram glaciers (after Mason 1930; Mayewski and Jensche 1979; Zhang, 1984; Goudie et al 1984; Hewitt et al 1989).



Karakoram glaciers have declined by 5% or more since the early 20th century, mainly between the 1920s and 1960s. However, losses slowed in the 1970s (Mayewski and Jensche 1979), and some glaciers underwent modest advances, as elsewhere in the region (Kotlyakov 1997). Retreat again prevailed from the mid-1980s through the 1990s, but without dramatic losses. Since the late 1990s we have reports of glaciers stabilizing and, in the high Karakoram, advancing (Hewitt 2005; Immerzeel et al 2009). Total snow cover has been increasing in the high Karakoram (Naz et al 2009).

A complicated picture emerges from glaciers whose terminus fluctuations can be reconstructed (Figure 1). Developments seem almost chaotic from the mid-19th through the early 20th centuries. Large, often rapid, advances and retreats occurred, more or less out of phase with one another. From the 1930s through the 1990s, a net retreat affected most of them, with minor reversals in the 1970s. Thus, by 2010 none were close to their maximum extent of the last 130–150 years, with the possible exception of Ghulkin. More surprising, however, except for Chogo Lungma, they were *not* at their farthest reported retreat. Meanwhile, Ghulkin is one of dozens of glaciers that have undergone advance in recent years (Scherler et al 2011).

These glaciers do differ in size and other characteristics. Disparities remain even among those of similar areas and lengths, for example, Biafo and Baltoro, or Batura and Chogo Lungma, or Ghulkin and Minapin. However, all Karakoram assessments have been for such diverse sets because we have no standardized records (Mason 1930; Mercer 1975; Goudie et al 1984; Zhang 1984; Shroder and Bishop 2010).

Various enquiries conclude that the behavior of Karakoram glaciers differs from the rest of the Himalaya and the more intensively studied European and North American glaciers (Mayewski and Jeschke 1979; Kick 1989; Shroder et al 1993). If so, this suggests conditions that distinguish Karakoram glacier environments. Here attention is directed to the high-altitude snowfall and nourishment regimes, glacier typology, and "verticality," especially the role of rockwalls and related conditions above 4000 m elevation—hitherto rather neglected concerns.

Snowfall regimes and inputs to glaciers

The Karakoram used to be assigned to the Semiarid Himalaya. As late as the 1970s maps showed very low precipitation based on valley weather station records. Explorers and mountaineers reported heavy snowfall at high elevations, and, after the mid-1960s, gauging stations confirmed water yields indicative of more humid conditions. In the 1970s, Chinese glaciologists first showed that, to sustain Batura Glacier, upper basin snowfall had to be 1000–2000 mm water equivalent (w.e.), and measured 1034 mm (w.e.) in a year at 4840 m elevation (Batura Investigations Group 1979).

Avalanche-fed glaciers prevail in the Karakoram, making measurements impossible except on a few glaciers with extensive, high-altitude accumulation basins. Biafo Glacier (35°55″N; 75°40″E) is one, and observations there in the 1980s provide the only relatively comprehensive data yet available (Hewitt et al 1989; Wake 1989). The sites were between 4800 and 5800 m on Biafo and nearby Hispar and Khurdopin Glaciers (Figure 2). Snow pits and drill cores were used to establish vertical profiles and retrieve samples for snow density and water equivalents, chemistry, and isotope analyses (Wake 1987).

FIGURE 2 The Biafo accumulation zone looking north to Lukpe Lawo Peak (6593 m) and Khurdopin Pass (5790 m). Headwaters of Hispar Glacier are to the left side of the photograph. (Photo by Kenneth Hewitt, 2002)

Measured averages at all sites exceed 1000 mm (w.e.) annually, some over 2000 mm (Figure 3). Maximum precipitation was shown to occur above 4800 elevation in the accumulation zone. Various qualifications need to be made. The highest values, at 5520 m on upper Khurdopin Glacier, probably involve "over-catch" of snow carried across the watershed by prevailing westerly and southerly winds. Lower values at Shark Col could reflect upwardly declining precipitation, but the site is more exposed and may undergo wind stripping (Wake 1987: 71).

Seasonal incidence and sources of snow are critical concerns. In these records just more than half the snowfall occurs in winter, slightly less than that in summer. The latter is, however, much greater than for low-elevation weather stations, which causes underestimation of summer inputs to the glaciers (Archer and Fowler 2004; Quincey et al 2009). Chemical signatures show winter snowfall coming largely from westerly sources: the Atlantic Ocean and Mediterranean and Caspian Seas. In late spring and early summer, frontal storms may draw Arabian Sea moisture into the Karakoram (Wake 1989). However, all mid- to late-summer snow samples had significant amounts with a monsoon signature (Wake 1987).

Two key features of glacier nourishment are shown: a distinctive seasonal regime and orographic concentration, both relatively favorable to glacier development. The regime is intermediate between the "winter accumulation" of the Caucasus and European Alps and "summer accumulation" in the Greater Himalaya (Ageta 2001). Given a "year-round ablation type" recognized for the inner tropics (Benn and Evans 1998: 86), the Karakoram defines a fourth, *year-round accumulation type* (with summer ablation). Although accumulation resembles the "Inner Tropics" type of Kaser and Osmaston (2002: 25), the ablation regime is "Mid Latitude" and distinctly different from their "Outer Tropics" type.

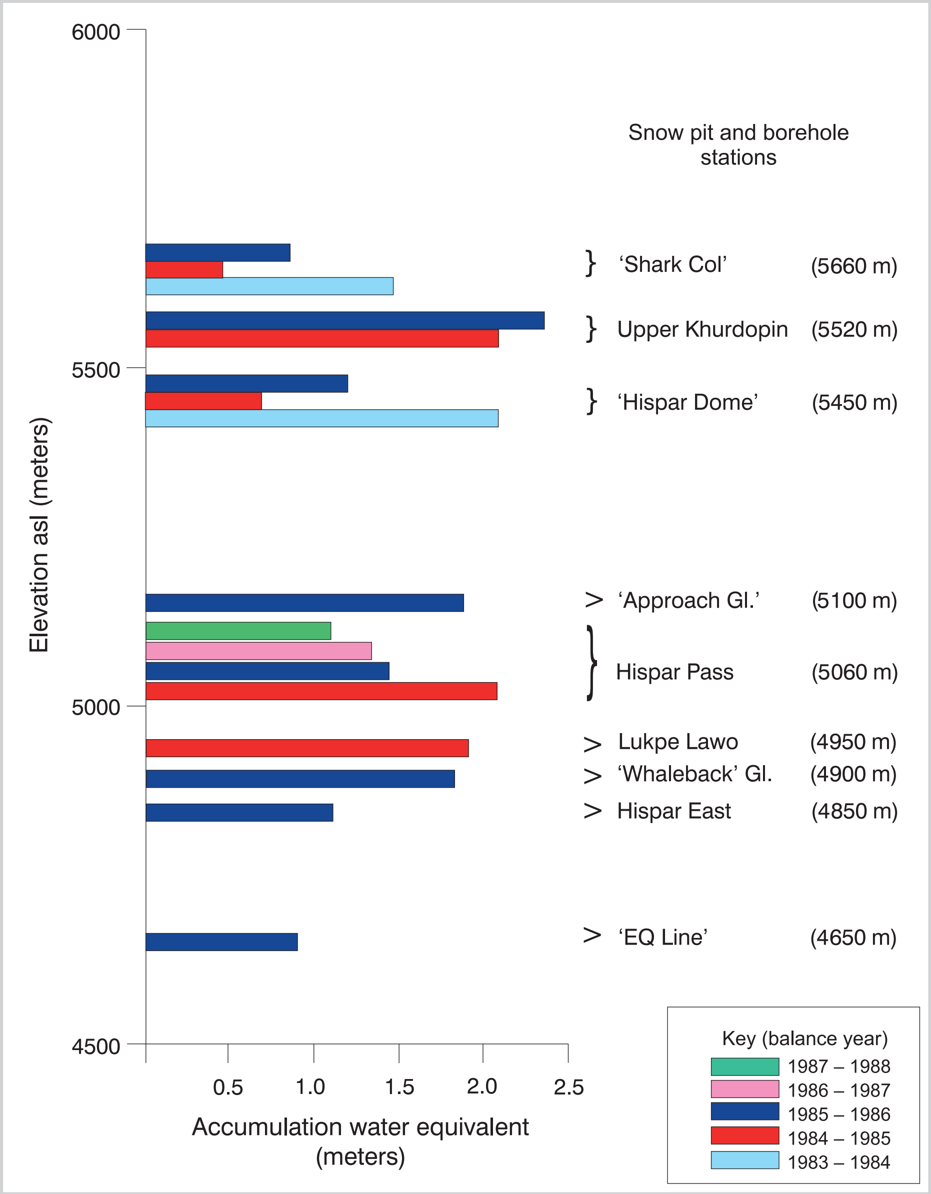
Maximum precipitation occurs almost 2000 m higher than in, say, the Nepal Himalaya, entirely as snowfall, and displays no dramatic decline at the highest elevations. The ice cover, size, and low-elevation reach of glaciers continues to increase with height. Glaciers surrounding massifs culminating at 7500–8000 m are more extensive than those between 6500 and 7000 m. The highest massif of K2 (8610 m) and Gasherbrum (8068 m) produces the largest glaciers, including Siachen (76 km) and Baltoro (62 km).

Mass balance calculations for Biafo, using concurrent measurements of ablation, movement, and glacier thickness, showed an approximate balance with the accumulation data (Hewitt et al 1989). However, Biafo is atypical of Karakoram glaciers. Avalanches nourish most glaciers mainly or wholly, and many lack an accumulation zone as normally understood. This must be addressed indirectly.

Glacier nourishment and typologies

More than a century ago, distinctive glacier types were recognized from High Asian experience. Avalanche-fed

FIGURE 3 Accumulation zone snowfall in the Central Karakoram, as measured at Biafo Glacier (after Wake 1987, 1989; Hewitt et al 1989).



glaciers were called "Turkestan" or "Lawinen" (= avalanche) type (Klebelsberg 1925–26). Oestreich (1911) referred specifically to a "Mustagh type," also largely avalanche nourished but with extensive, deeply incised ice streams above the snowline. Since the extended discussions by Visser and Visser-Hooft (1938) and von Wissmann (1959), little interest has been expressed in this, and only incidentally in English-language studies (Mercer 1975; Shroder and Bishop 2010). Yet the classes identify distinctive features, especially glacier nourishment.

Four basic types can be recognized:

1. The "Turkestan" or Avalanche type: glaciers fed more or less entirely by snow and ice avalanches. Main ice streams commence near the snow line, often well below it, and there is no "accumulation zone" as normally understood (Figure 4).
2. The "Mustagh" type: also predominantly avalanche fed, but with ice streams commencing in the accumulation zone, some firn area, sometimes an identifiable firn limit (Figure 5).

FIGURE 4 Upper source areas of Charakusa Glacier, south-central Karakoram, a Turkestan-type glacier, showing avalanche nourishment from rockwalls and icefalls of disconnected tributaries. (Photo by Kenneth Hewitt, 2005)

FIGURE 5 Upper Panmah Glacier, a Mustagh type in the Central Karakoram. It shows the deeply incised main ice stream originating within an accumulation zone surrounded by steep rockwalls and tributary icefalls. Elevation range from foreground ablation zone to distant peaks is about 2500 m. (Photo by Kenneth Hewitt, 2009)

TABLE 1 Revised classification for the Karakoram valley glaciers with examples discussed in the text.

Nourishment type	"Caldron" type	"Ice stream" type, narrow, incised
Turkestan type	Hinarche, Surgin, Masherbrum, Kukuar	Charakusa, Karambar, Hasanabad, Toltar
Mustagh type	Kutiah, Skamri, Khurdopin, Kondus	Baltoro, Batura, N. Shukpa, Panmah, Hispar, Chogo Lungma
Alpine type	Chiantar, Sarpo Laggo	Siachen, Biafo, Rimo

3. The "Alpine" type: predominantly snow fed, with extensive accumulation zone and relatively well-defined firn limit (Figure 2).
4. The "Wind-Fed" type: not previously considered or investigated, it is added for completeness. Small ice masses are involved, but innumerable at higher elevations and in some of the lesser ranges.

Hitherto, measurable boundaries between the types were not specified. Here the Turkestan type is taken to have less than 20% of its area above the snowline. One might prefer "zero," but actual snowlines are complicated by rugged terrain, orientation, shading, and prevailing and local wind action, whereas upper glacier areas are smothered by avalanche cones and aprons. For the Mustagh type, areas above the snowline are at least 20%, but less than 50%, of the lower cutoff for the Alpine type.

Morphological criteria have also been applied. The Mustagh type was subdivided into *Firnkessel* (= firn caldron) and *Firnstrom* (= firn stream) types (von Wissmann 1959). However, the terminology is confusing. "Firn" infers a significant role for direct snowfall when

FIGURE 6 Long profiles of the main ice streams of Baltoro (top left), Biafo (bottom left) and Toltar-Baltar Glaciers, representing the three glacier types.

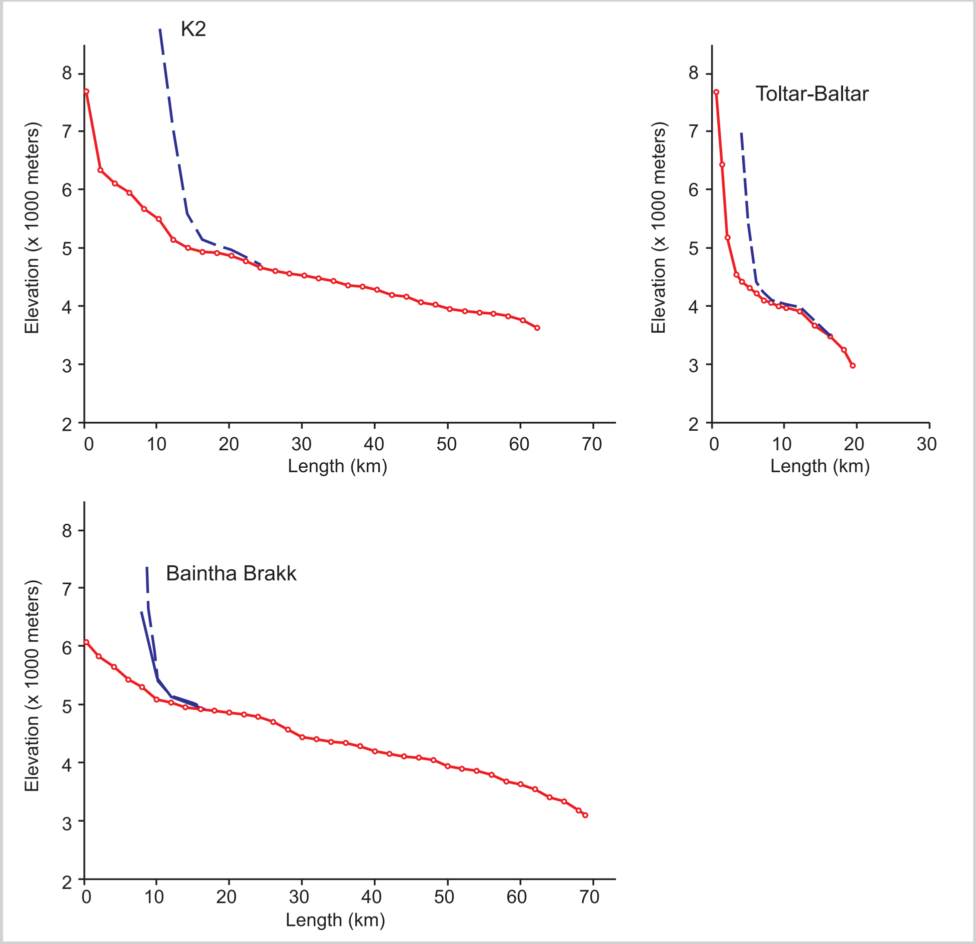


TABLE 2 Principal environmental zones and their areas for three glacier basins of Turkestan-, Mustagh-, and Alpine-type.

	Biafo Glacier	Baltoro Glacier	Toltar-Baltar Glacier
Characteristics			
Latitude and longitude	(35°55′N; 75°40′E)	(35°46′N; 76°15′E)	(36°27′N; 74°24′E)
Glacier type	Alpine	Mustagh	Turkestan
Dimensions and zones			
Length (km)	68	62	17
Elevation range (m)	4215	5010	4779
1. Basin area (km^2)	855	1400	202
2. Perennial snow and ice (km^2)	630 (74%)	990 (70%)	156 (77%)
3. Total glacier (km^2)	470 (55)	538 (38.5)	84 (42)
Main glacier	460 (54)	530 (38)	72 (36)
4. Source zone (km^2)	500 (58)	720 (51)	75 (37)
Firn basins	330 (39)	250 (18)	3 (1.5)
5. Ablation zone (km^2)	130 (15)	280 (20)	69 (34)
a. Clean-dusty ice	100 (12)	185 (13)	37 (18)
b. Heavy debris	30 (4)	95 (10)	32 (16)
6. Ice- and seasonally snow-free (km^2)	220 (26)	510 (37)	46 (23)
7. Rockwalls (km^2)	380 (44)	975 (69)	114 (56)
a. Above snowlines (avalanched)	170 (20)	470 (34)	71 (35.5)
b. Below snowlines	210 (25)	500 (36)	43 (21)

avalanche nourishment is more important, and, in these glaciers, firn is often mixed with and disturbed by avalanched material. It makes more sense to call Biafo a “Firnstream” glacier, as von Wissmann (1959) does, but it is more logical to refer to it as an Alpine type (Visser and Visser-Hooft 1938). Meanwhile, the incised “stream” and “caldron” forms occur with all classes, not just the Mustagh type. Turkestan-type glaciers have extensive, deeply incised, narrow ice streams, if entirely in the ablation zone.

No unique division combines morphology and nourishment, and the typology is revised here to reflect this (Table 1). More usefully, the classes help identify key aspects of glacier maintenance, notably the critical roles of elevation and steepness (Kerr 1993).

Elevation range and distribution of ice masses

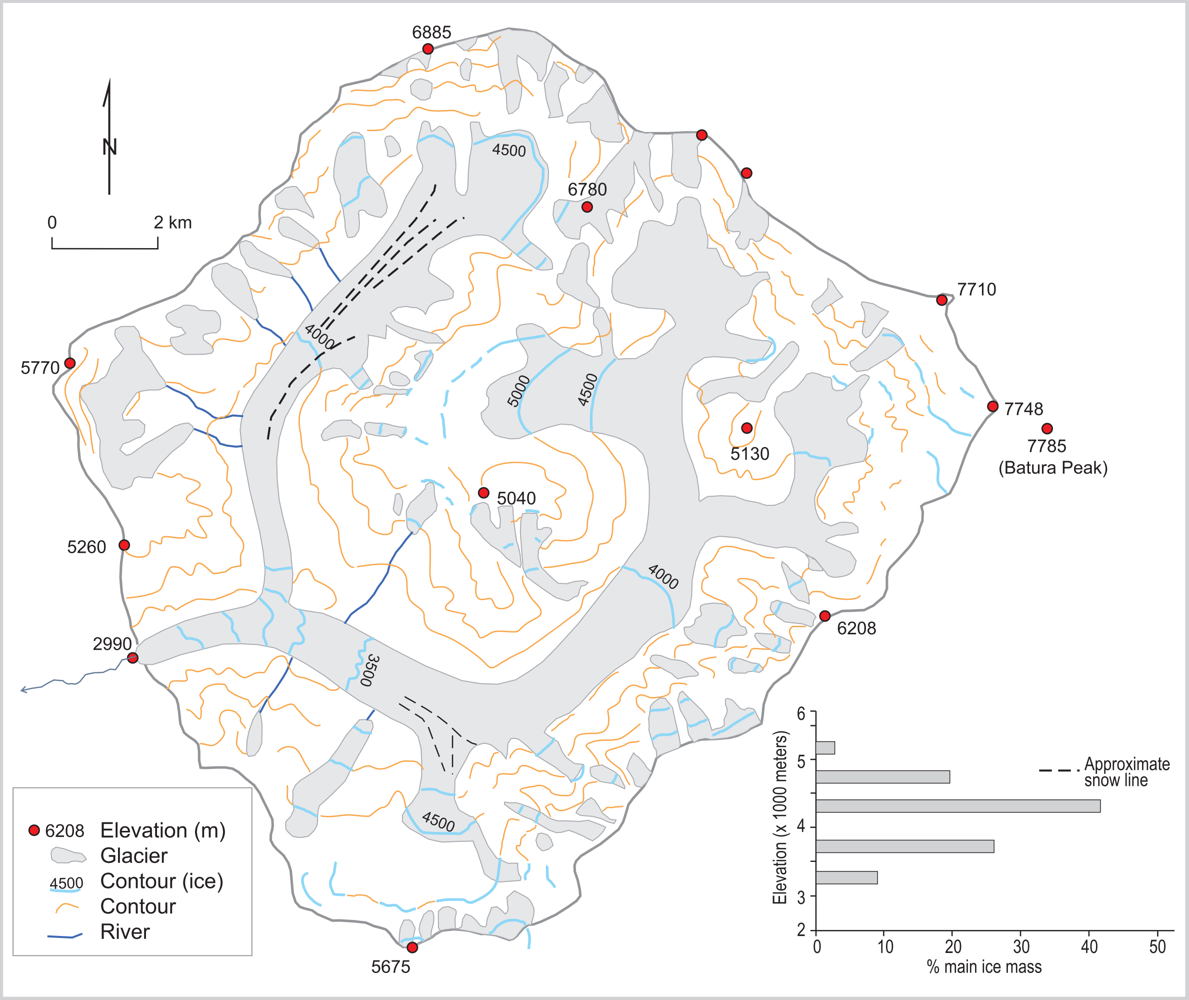
The entire Karakoram glacial zone spans about 6300 m vertically, from K2 (8610 m) to the lowest termini, which, in the Hunza valley, reach down to 2300 m (Hewitt 2006). The highest elevations are matched in other parts of the Himalaya, but glaciers are smaller and few descend as low. Five of the larger Karakoram glaciers span 5000 m, and 34 more than 3000 m.

The importance of elevation range also depends on the altitudinal distribution of ice. Long profiles of larger glaciers emphasize two features (Figure 6). About 60–80% of vertical descent occurs in less than 10% of length, mainly in the upper basin, and the extensive midsections are of relatively gentle gradient. However, this reflects but differs in key aspects from the vertical distribution of basin conditions involved in glacierization and glacier systems (Table 2).

The areas and zones of interest are the following:

1. *Basin area*, above and draining to main glacier terminus.
2. *Perennial snow and ice cover* above snowline and glacier ice below it.
3. *Glacier cover*:
    a. The main continuous, connected ice stream.
    b. Ice of disconnected tributaries.
4. *Source zone* of main connected ice mass above snowline:
    a. Conventional accumulation zone (firn basins and ice streams).
    b. Steep rockwalls (the same as 7a).

FIGURE 7 The Toltar-Baltar Glacier, to show the organization of a Turkestan-type glacier system. Data from the 1:100,000 map (1995). "Hunza Karakorum" Deutschen Alpenverein, Munich, and 2006 and 2009 late summer satellite imagery. (Map by Pam Schaus)



5. *Ablation zone* of the main connected ice mass:
   a. Clean, dusty, dirt-veneered ice surface.
   b. Heavy supraglacial debris.
6. *Snow- and ice-free (off-ice) areas* (below the snowline and not glacierized).
7. *Steep rockwalls*, slopes generally in excess of a 35° angle:
   a. In the perennial snow and ice zone.
   b. In the zone seasonally free of snow and ice or below 4800 m.

Distributions differ markedly by glacier type. The profile for Biafo Glacier is not unlike valley glaciers familiar to researchers elsewhere. The perennial snow and ice cover of Baltoro Glacier is about 990 km^2, or 70% of the basin area, but almost half is *not* "glacier." Careful examination of satellite imagery shows glacier ice is generally absent at slopes steeper than about 20° including icefalls. Cones and aprons of avalanche snow rarely exceed 30°. However, about 70% of the entire basin is steeper than this, and almost 50% of the perennial snow zone. Glacier ice is absent from much of the upper basin, where rockwalls prevail. Less than half of the connected glacier system is accumulation zone.

The main Baltar-Toltar Glacier covers a third of its basin, a typical Turkestan-type with almost no accumulation zone (Figure 7). The main ice streams commence below rockwalls at about 4800 m on south-facing slopes, and 4500 m on north-facing, and snowlines or firn limits are obliterated by avalanches.

The importance of rockwalls above the snowline can hardly be overstated (Table 3). They make up over 60% of source zones for Mustagh-type glaciers and over 70% of basin areas. In a majority of glaciers, maximum snowfall, as determined at Biafo, occurs where slopes are too steep for it to stay in place, and avalanches funnel snow more or less quickly to the glaciers below.

That the glacierized area is overwhelmingly concentrated within a quite narrow elevation range is clear. Half of Biafo's area is between 4500 and 5500 m elevation (Hewitt 2005). Over 60% of Baltoro's and Toltar-Baltar's occurs between

TABLE 3 Rockwalls as a proportion of areas above the snowline, and for basins as a whole. The slopes in rockwall areas are generally steeper than 35° and large parts exceed 55°.

Glacier type and glacier	Rockwalls (% SI area)	Rockwalls (% basin area)
Alpine		
Biafo	28	44
Chiantar	28	40
Siachen	42	49
Sarpo Laggo	39	47
Mean	*37*	*45*
Mustagh		
N. Shukpa	68	71
N. Gasherb'm	59	70
Baltoro	48	69
Panmah	69	73
Batura	53	60
Khurdopin	73	81
Hispar	54	62
Chogo Lungma	60	71
Kutiah	70	73
Skamri	53	86
Kondus-Kab.	67	74
Virjerab	62	77
Ghondoghoro	71	76
Braldu (Sh.)	84	60
Mean	*64*	*71*
Turkestan		
Charakusa	55	72
Karambar	66	76
Hinarche	50	86
Surgin	61	58
Masherbrum	53	74
Hasanabad	80	84
Kukuar	53	63
Toltar-Baltar	46	56
Mean	*58*	*71*
All glacier types		
Mean total	*56*	*69*

4200 and 5000 m, as with most larger glaciers. However, basin organization highlights the importance of steep, mainly rockwall areas. The bulk of the ice cover originates in, or is fed from, the highest and steepest parts.

Mass balance parameters

It is has long been recognized that avalanche nourishment complicates mass balance terms (Meier 1962; Kasser 1967), but it is rarely investigated. Difficult or impossible to measure, such glaciers are avoided in systematic monitoring (WGMS 2009). In other contexts, indirect estimates of mass balance and its changes have utilized equilibrium line altitudes (ELAs), and the ratio of accumulation zone to whole glacier area (AAR) (Cogley and McIntyre 2003). Snowlines, or firn limits on glaciers, are widely seen as fair approximations to ELAs, and year-to-year AARs are understood to reflect mass balance changes (Dyurgerov and Meier 2000).

In the Karakoram, however, despite more than 150 years of snowline height reports (von Wissmann 1959), they are of doubtful value for establishing ELAs. In Turkestan-, and Mustagh-type glaciers, as described, the heaviest snowfall moves rapidly from extensive, steep upper basin areas into the relatively small midbasin, glacierized areas. "Accumulation" undergoes a huge downward shift compared to snowfall, and it is likely that ELAs—where net annual additions balance ablation losses—are hundreds of meters *below* snowlines. In traveling below the snowlines, avalanche inputs create complicated overlaps or mosaics of "accumulation" and ablation, and over elevation ranges exceeding the totals for the best-monitored glaciers (Figure 8). Snow avalanches are of prime importance, but icefalls, and ice avalanches from countless small, steep, disconnected ice masses, may play large and complicated roles.

Similar problems arise for AARs. In any year a complete spectrum exists for different glaciers (Table 4). However, they do differ systematically with nourishment classes, providing a way to define and distinguish them.

The fact that measurements are lacking raises questions about any estimates of mass balance, climate, and glacier change based on snowlines. It seems likely that avalanches, wind action, and summer snowfall will render measureable year-to-year shifts very erratic and complex. Processes that intervene between climate and glaciers to redistribute and concentrate ice mass seem to compromise standard methods. In the absence of measurements a useful "concentration factor" is the ratio of conventional accumulation zones to total contributing area (Table 4). It is 2 to 5 times larger in Mustagh types than Alpine types, and 5 to 15 times in Turkestan types.

Avalanching also causes rapid, direct transport of glacier inputs to warmer elevations, and their immediate conversion to much denser material, accelerating the transformation to glacier ice. Avalanching and icefalls

FIGURE 8 Upper Barpu Glacier, a Turkestan type with extended zone of avalanche inputs to glacier surface below the snowline, from 4900 m in the foreground to 4200 m in the distance. Additional inputs to all-year snow deposits continue out of sight down to 3700 m. (Photo by Kenneth Hewitt, 1987)

carry relatively cold, high-altitude ("Polar") snowfall, to the warmer ("Sub-Polar" or "Temperate") environments of main ice streams. This is an important if not decisive factor in the thermally complex nature of the glaciers, perhaps in the instabilities observed as large fluctuations in movement rates on a wide spectrum of temporal and spatial scales (Batura Investigations Group 1979; Quincey et al 2009). Then there is the exceptional incidence of surging glaciers, all known ones being predominantly avalanche fed (Hewitt 2007; Shroder and Bishop 2010).

Debris-covered glaciers

The prevalence of debris-covered ice has been seen to explain unusual climatic responses in the Karakoram (Kick 1989; Shroder and Bishop 2010). It is important in glacial and geomorphologic processes, and in why many glaciers penetrate into warmer, lower elevations and will persist there longer when mass balance is negative. However, it hardly seems to be a differentiating factor for Karakoram glaciers, being equally or more prevalent elsewhere in the Himalaya and Hindu Kush (Nakawo et al 2000). Rather, with respect to climate response, for water conservation and supply, its importance has been exaggerated. Research shows it slows responses and can make termini fairly insensitive to climate change (Scherler et al 2011). Greatly reduced ablation in these areas means they make the smaller contributions to rivers, with or without glacier change.

The term "debris-covered glaciers" can be misleading. Less than a quarter of Karakoram glaciers are heavily covered—barely a third of their ablation zone areas (Table 5). Moreover, figures from satellite images are likely to overestimate the "thick," ablation-suppressing cover. It has been found that as much as 20% can be less than 3 cm thick, the cutoff between debris-reduced and enhanced ablation (Khan 1989; Mattson and Gardner 1989). More critical in responses to climate change and especially for water supply are the larger areas of mid-to-upper ablation zones with clean, dusty, or dirt-veneered ice. Here the largest ablation losses and water yields occur, generally between about 3800 m and 4800 m elevation. These areas, unlike debris-covered ice, are very sensitive to summer weather and, hence, to climate change (Hewitt 2005). It is entirely possible that this is one—

TABLE 4 The accumulation area ratio (AAR) offers a way to differentiate selected glaciers by nourishment types. The ratio of the conventional accumulation zone, to all upper basin areas contributing to the main glacier serves to define a 'Concentration' factor (see text).

Glacier type and glacier	AAR	"Concentration" factor
Alpine		
Biafo	0.70	1.5
Chiantar	0.66	1.6
Siachen	0.56	2.0
Sarpo Laggo	0.53	2.2
Mustagh		
N. Shukpa	0.49	5.0
N. Gasherb'm	0.48	4.4
Baltoro	0.47	2.9
Panmah	0.37	5.3
Batura	0.34	4.4
Khurdopin	0.32	9.5
Hispar	0.29	5.1
Chogo Lungma	0.29	6.2
Kutiah	0.29	9.3
Skamri	0.29	4.9
Kondus-Kab.	0.29	8.2
Virjerab	0.28	6.7
Ghondoghoro	0.24	13.4
Charakusa	0.21	6.3
Braldu (Sh.)	0.21	4.2
Turkestan		
Karambar	0.19	10.0
Hinarche	0.15	10.0
Surgin	0.12	22.0
Masherbrum	0.11	15.0
Hasanabad	0.10	36.0
Kukuar	0.07	16.3
Toltar-Baltar	0.04	25.0

perhaps the greatest—factor differentiating the Karakoram and other mountain ranges, whether in terms of "naturally" generated or artificial particulates, especially soot. Their amounts may well change as a result of climatic and related land-cover changes, industrial and transportation emissions, and human land-use changes, or in relation to sunshine hours in ablation seasons whose length is critical to their concentration on ice and snow surfaces.

Concluding remarks

In the Karakoram, high mountain processes serve to concentrate climatic conditions for glacierization, notably:

1. Processes that enhance and concentrate snowfall: an orographic condition that generates maximum

TABLE 5 Relative proportions of heavy debris cover for main glacier area, and for ablation zone. Areas were determined from inspection of satellite imagery where no clean ice was visible at the surface, and likely to overestimate 'thick' ablation-reducing covers (see text).

Glacier type and glacier	Debris covered (% main glacier area)	Debris covered (% ablation zone)
Alpine		
Biafo	7	23
Chiantar	4	12
Siachen	17	38
Sarpo Laggo	7	14
Mean	*9*	*22*
Mustagh		
N. Shukpa	10	18
N. Gasherb'm	10	19
Baltoro	18	34
Gharesa	7	13
Panmah	27	43
Batura	32	48
Khurdopin	31	46
Hispar	15	46
Chogo Lungma	34	47
Kutiah	21	30
Skamri	17	25
Kondus-Kab.	29	41
Virjerab	16	30
Ghondoghoro	19	24
Braldu (Sh.)	19	31
Mean	*20*	*33*
Turkestan		
Charakusa	21	26
Karambar	25	31
Hinarche	20	23
Surgin	38	43
Masherbrum	37	44
Hasanabad	62	70
Kukuar	18	19
Toltar-Baltar	44	46
Mean	*33*	*38*
All glacier types		
Mean total	*22*	*32*

precipitation in glacier source areas. Inputs of 1000–2000 mm (w.e.) are an order of magnitude greater than at valley weather stations and comparable to "maritime" glaciers, despite the extreme continentality. An all-year accumulation regime magnifies the effect.

2. Avalanche concentration: a terrain or ruggedness effect in glacier source areas, of which 60–90% are steep rockwalls. Snowfall, rapidly concentrated down slope, is deposited near or below snowlines, accelerating transformation to glacier ice.
3. Ablation buffering: ice tongues at lower elevations, where temperatures are higher and the ablation season longer, are protected by heavy debris covers.
4. Areas with the greatest ablation losses and water yield: these occur where debris covers are thin or absent but have short ablation seasons and respond sensitively to summer weather. On the one hand, increases in "thin" debris cover here are likely to increase ablation. On the other hand, if ablation seasons get shorter or cloudiness and summer precipitation increase, their impact on ablation will diminish.

These are all effects related to altitude and elevation range, in summary, *elevation* or *verticality* effects. Since they apply to other High Asian mountains, only some of them, their intensity or a particular combination, may distinguish the Karakoram. The sheer extent and sustained high elevations of the main Karakoram seem critical, combined with the all-year accumulation regime. Both help to buffer glaciers against "warming," and, with high-altitude precipitation occurring as snowfall in summer and winter, they may benefit from increased moisture transport from warmer oceans. Various investigations report cooler summers recently and greater summer cloudiness and snow covers (Fowler and Archer 2006; Naz et al 2009; Scherler et al 2011). These can also reduce average ablation rates or numbers of "ablation days" and seem especially sensitive to the direction of future climate change.

Compared with other areas, and past predictions for the upper Indus, these observations seem good news. Yet glacier expansion is not without its perils. Historically the greater hazards in upper Indus valleys come from advancing glaciers, especially during the Little Ice Age (Kreutzmann 1994; chapter 7 of Grove 1988). Among the worst, large ice dams and outburst floods have involved some recently advancing glaciers (Hewitt and Liu 2010). However, planning and decisions that assume the opposite of what is happening may pose greater risks, a result of our limited understanding of the glaciers and inadequate monitoring of their environments.

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