

The State and Fate of Himalayan Glaciers

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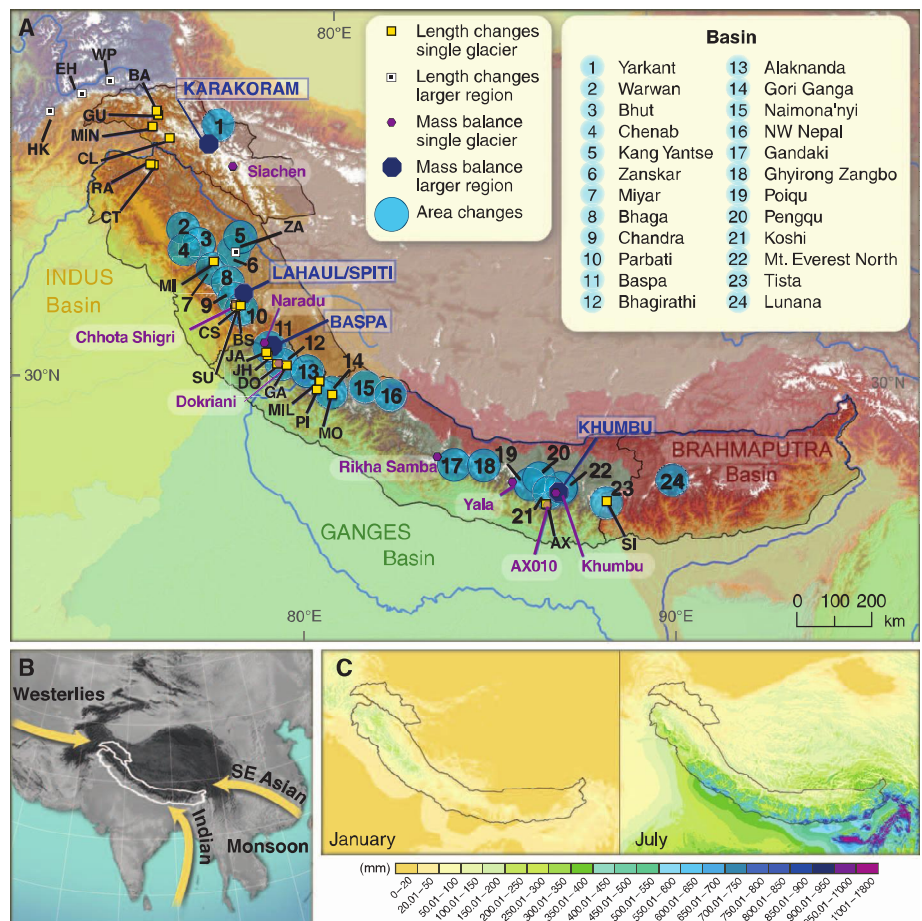
Himalayan glaciers are a focus of public and scientific debate. Prevailing uncertainties are of major concern because some projections of their future have serious implications for water resources. Most Himalayan glaciers are losing mass at rates similar to glaciers elsewhere, except for emerging indications of stability or mass gain in the Karakoram. A poor understanding of the processes affecting them, combined with the diversity of climatic conditions and the extremes of topographical relief within the region, makes projections speculative. Nevertheless, it is unlikely that dramatic changes in total runoff will occur soon, although continuing shrinkage outside the Karakoram will increase the seasonality of runoff, affect irrigation and hydropower, and alter hazards.

Almost 800 million people live in the catchments of the Indus, Ganges, and Brahmaputra rivers and rely to varying extents (in particular during dry seasons and in mountain valleys) on the water released from glaciers (1, 2) that constitute the most extensive glacier cover outside Alaska and the Arctic (3). Published estimates of glacier coverage for the Himalaya and Karakoram (H-K), mostly based on historic data, vary between 43,178 km² and 49,650 km² (table S1). Our best estimate for H-K, as defined in fig. S1 (4), mainly based on mapping using recent satellite images (4) is ~40,800 km² (Himalaya, ~22,800 km²; Karakoram, ~18,000 km²) (table S2). Glacier volume cannot be measured directly over regional scales but must be modeled. Empirical estimates are highly uncertain and range from about 2300 km³, taking the slope-dependent ice thickness into account, to ~3600 to ~6500 km³ based on volume-area scaling (4) (table S2).

Glaciers are natural buffers of hydrological seasonality, releasing meltwater during summer and early autumn in particular. They represent a local water resource in the mountains but also influence runoff into lowland rivers, recharge river-fed aquifers, and contribute to global sea-level change (1, 5). Regional climates are heterogeneous, and the socioeconomic importance of glacier meltwater varies over the H-K. It is a major source of stream flow in parts of the H-K having little summer precipitation, especially the Karakoram

and northwestern Himalaya, but is less important in monsoon-dominated regions with abundant summer precipitation (3, 5). This spatial variability influences meltwater regimes, in turn affecting the availability of water for hydropower generation, agriculture, and ecosystems (6). Glacier change also alters risks due to glacial hazards, not least from glacial lake outburst floods (GLOFs) (7).

Recent controversy about future Himalayan glacier change, largely fueled by an erroneous statement in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (8), has exposed major gaps in our knowledge of the behavior of the region's glaciers: Annual amounts of ice and snow melt along with its seasonal and spatial variability, as well as the contributions of precipitation to discharge, are all uncertain (1, 6). These gaps are due to insufficient numbers of in situ measurements, for which remote sensing only partially substitutes. There are few high-elevation weather stations and no long-term field measurement programs on glaciers, and information about current ice extent is nonuniform and unsatisfactory in places (4). This can be attributed to the remote location of glaciers, the rugged terrain, and a complex political situation, all of which make physical access difficult. Here, we review the state of knowledge about key characteristics, current extent, and changes of H-K glaciers since the mid-19th century. We also discuss projections of possible future changes, summarize important implications for water resources and natural hazards, and close by



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Fig. 1. (A) Map of the Karakoram and Himalaya showing the major river basins and the locations of measured rates of change in area and of a sample of glacier length change and mass budget measurements (4) (tables S3, S5, and S6). (B) Main wind systems. (C) Mean precipitation in January and July. [Source: (9)]

sketching a framework for integrated cryosphere research needed to fill the most critical gaps.

Regional Variations of Himalayan Climate

The climate in H-K is strongly influenced by the varying dominance of the Asian monsoon and winds from the west (9, 10). The westerlies are a more important moisture source in the northwest: about two-thirds of the high-altitude snowfall in the Karakoram is due to westerly cyclones, mainly in winter, whereas in the southeast more than 80% is provided by the summer monsoon (10). The mountains block transfer of most moisture to the Tibetan plateau; hence, precipitation decreases sharply northward in both the monsoonal and the westerly regimes (Fig. 1). The mean elevation of H-K glaciers, a rough proxy for the equilibrium line altitude (ELA), is ~5360 m above sea level (asl), with the highest values in the central (~5600 m) and the lowest in the western Himalaya (~5150 m) (table S2). The ELA is lower where accumulation is greater, requiring more ablation and higher temperatures to yield an annual mass budget of zero.

Little is known about the regional horizontal and vertical distribution of precipitation, especially at high elevations. Short records suggest precipitation of 1600 to 1800 mm year⁻¹ in the southwestern Karakoram near 5000 m asl (11). Himalayan precipitation records show little or no trend with time (12), whereas winter precipitation has increased in the Karakoram (13, 14). Weather-station data indicate recent warming in the Himalaya but not in the Karakoram (13, 15). Nearly all stations are far below the lower limit of glaciers, and some are affected by progressive urbanization, so that it is uncertain whether these trends are also valid for the glaciers. At the highest long-term weather station in the Himalaya, Tingri (4300 m asl), north of Mount Everest, mean annual air temperature (MAAT) increased by ~0.03 K year⁻¹ during 1959 to 2007, with greater warming in winter than in summer (16). This warming rate may be greater than the global average. In contrast, the MAAT in the Karakoram decreased—a global anomaly—mainly due to the decrease of summer temperatures (13, 14).

Characteristics of Himalayan Glaciers

Most glaciers in the eastern and central Himalaya belong to the “summer-accumulation type,” gaining mass mainly from summer-monsoon snowfall (17), whereas winter accumulation is more important in the northwest (18) (Fig. 1). The very steep and rugged terrain above the glaciers leads to considerable accumulation by snow avalanching in H-K, especially for Karakoram glaciers, complicating the definition of accumulation areas and the calculation of responses to climatic changes (19–21). Many glaciers in H-K have heavily debris-covered tongues, a further consequence of the steep rocky terrain and avalanche activity. Debris cover, along with seasonal snow (22), complicates delineation of the glaciers, and different measures and definitions of the numer-

ous tributaries of the larger glaciers make length and area determination difficult. The large proportion of low-elevation glacier area (fig. S2) in the western Himalaya may in part be a result of extensive debris cover. Our best estimate of total debris cover in H-K is ~10% (4). This percentage is important, because thick debris, which retards surface melting, is concentrated on the low-lying tongues where most melting is expected (23). However, many completely debris-covered glacier tongues have very low flow velocities or are stagnant (23, 24) and are thus subject to additional melt processes, such as the development of thermokarst lakes from melt ponds (25). The flow speed of such glacier tongues is also controlled by the extent of the accumulation area and thus by the ice flux to the tongue.

In Bhutan, glaciers with large accumulation areas reach velocities of 100 to 200 m year⁻¹, decreasing gradually toward their termini, whereas those with small and steep accumulation areas have speeds >50 m year⁻¹ only in the zones beneath their rock-ice headwalls (26) (Fig. 2B). In contrast to this rather homogeneous regional pattern, which is typical for the central and eastern Himalaya (23) (fig. S5), glacier speeds in the Karakoram vary greatly in time and space (Fig. 2A). Glaciers in close proximity, in similar topographic settings, and with similar sizes and shapes have very different speeds at a given time, which points to a range of dynamical sensitivities and instabilities (27). Particularly in the Karakoram, many glaciers surge for reasons that are not directly related to climate (27, 28). However, there is evidence that recent surges are favored by high-altitude warming (18). The number of glacier surges has almost doubled since 1990, which might be linked to positive mass budgets in this region in the recent period (29).

General Changes in Himalayan Glaciers

Length changes (22, 30) (tables S3 and S4) measured for more than 100 glaciers in H-K suggest that most Himalayan glaciers have been retreating since the mid-19th century (Fig. 3C), except for 1920 to 1940, when about half the records show stationary or advancing tongues (30). Some large glaciers have advanced or been stable recently in the northwestern Himalaya and in the Karakoram (19, 21) (Fig. 3C and table S4). In the eastern Hindu Kush, west of the Karakoram, 25% of the glaciers were stable or advancing during 1976 to 2007 (31). North of the Karakoram, in the Wakhan Pamir, however, glaciers were retreating during a similar period (32).

Area changes (table S5) have been measured for several thousand glaciers in H-K. Area change data from the Karakoram exist only for the

Yarkant basin north of the main ridge, where the loss rate was ~0.1% year⁻¹ between 1962 and 1999 (33). Small high-altitude glaciers in the Transhimalaya of Ladakh had a shrinkage rate of ~0.4% year⁻¹ from 1969 to 2010 (34). In the Indian Himalaya, shrinkage rates are regionally variable: ~0.2 to ~0.7% year⁻¹, 1960s to 2001–2004 [11 Indian catchments, (35)]; 0.12 ± 0.07% year⁻¹, 1968 to 2007 [Garhwal Himalaya, (36)]; ~0.3% year⁻¹, 1963 to 1993 [Bhutan, (37)]; and ~0.3 to 0.6% year⁻¹, ~1970 to ~2005 [Tibet, (38)]. There is also a clear tendency for area loss in Nepal (39) (table S5). Where measured, the

Glacial Response to Climate Change

Glaciers develop where mass gain (e.g., by snowfall and avalanches) exceeds mass loss (e.g., by melting and calving). Lower temperatures and greater snowfall favor mass gain (accumulation); conversely, higher temperatures favor mass loss (ablation). The sum of accumulation and ablation over any period is the mass budget. Mass is transferred by glacier flow from the accumulation area, at high elevation, to the ablation area at low elevation. The steeper the glacier, the faster the flow. If ablation dominates over several years, the mass flux is reduced and the glacier starts to retreat. Conversely, if net annual accumulation (positive balance) dominates for a long time, the glacier increases flow speed and eventually advances. Because the response of the terminus to a change in climate is delayed by flow dynamics, current changes in terminus position are integrated reactions to past climate changes. Glacier response times vary; the larger and slower (flatter) the glacier, the longer the delay under equal climatic conditions. Length and area changes are thus harder to interpret in climatic terms than are mass changes, but the latter are harder to measure.

debris-covered area has increased [e.g., (36)], indicating increasing debris production, reduced glacial transport capacity, or negative mass balances. Most studies investigating more than one time period show faster shrinkage rates in later periods. Notwithstanding the variability and the uncertainties, a consistent picture emerges of net area loss in recent decades in most parts of the Himalaya (Fig. 3B and fig. S4). Indications of positive mass budget suggest that net area gain is likely at least in the more humid parts of the Karakoram (19, 29).

Measurements of the annual mass budget are relatively few and short-term. The longest series spans only 10 years (Fig. 3A and table S6). One geodetic (multiannual) measurement covers 1962 to 2007 (20). All budgets are negative on average with only a few positive years. Typical values vary from ~0.32 m year⁻¹ water equivalent (w.e.) (Dokriani Glacier, 1992 to 2000) to ~0.67 ± 0.40 m year⁻¹ w.e. (Chhota Shigri Glacier, 2002 to 2010) (40) to ~1.60 m year⁻¹ w.e. (Hamtah Glacier, 2001 to 2006) (table S6). A space-borne geodetic assessment for 1999 to 2004 in Lahaul/Spiti (Western Himalaya) revealed substantial mass loss on several heavily debris-covered tongues (41). In the Mount Everest region, such glaciers had an average budget of ~0.32 ± 0.08 m year⁻¹ w.e.

(1970 to 2007) (20) (fig. S5). The only source of information for the Karakoram based on in situ data indicates an average budget of $-0.51 \text{ m year}^{-1}$ w.e. for Siachen Glacier (1986 to 1991) (42), whereas a slight mass gain was observed for the Karakoram for the early 21st century based on a geodetic estimate (43). These measurements suggest that the mass budget over large parts of the Himalaya has been negative over the past five decades, that the rate of loss increased after roughly 1995 (Fig. 3), but also that the spatiotemporal variability is high (44). The region-wide loss rate is close to the global mean (45). Gravimetric measurements (46) indicate mass loss in the Himalaya and also possible mass gain in the Karakoram from 2002 to 2006, with a decrease thereafter. A more recent gravimetric study (47) is basically in line with this finding but shows considerably lower mass loss for the whole of High Mountain Asia (-4 ± 20 versus $-47 \pm 12 \text{ Gt year}^{-1}$) and only $-5 \pm 6 \text{ Gt year}^{-1}$ for the H-K from 2003 to 2010. The difference has been attributed mainly to different estimates of the groundwater depletion (47). The lower estimate could also be a sign of slight mass gain in the central Karakoram and moderate loss in the Himalaya during this period. It is beyond the scope of this contribution to discuss satellite gravimetry methods. However, it has to be noted that interpretation of Gravity Recovery and Climate Experiment (GRACE) satellite measurements in terms of glacier mass changes for a complex, large, and tectonically very active mountain range such as H-K, in close vicinity to a zone of substantial groundwater depletion in northern India, implies substantial uncertainties. These gravimetrically derived results need to be contrasted with existing mass budget data that show all negative values in the Himalaya outside the Karakoram (Fig. 3A)

Monsoon-affected glaciers are more sensitive to temperature change than winter-accumulation-type glaciers (48) because the temperature increase directly reduces solid precipitation (i.e., snow accumulation) and extends the melting period. Without a snow cover in summer, surface albedo is much lower and melt is further increased. In the Karakoram and northwestern Himalaya, glaciers that extend to higher elevations show irregular behavior and have retreated less rapidly or even advanced in recent years (the so-called Karakoram anomaly) (19, 29) (tables S3 and S4). This is readily understandable for avalanche-fed glaciers where the extent of the accumulation area changes only slightly when the ELA is rising (21). Observed strong surface lowering of heavily debris-covered glaciers can be explained by their low elevations, by enhanced melting on exposed ice cliffs and beneath surface ponds (25), and maybe also by collapse of englacial conduits (for nearly stagnant ice). Dust and black soot, which increased melt on some Tibetan glaciers (49), are also likely to influence H-K glaciers, but this requires further investigation.

Persistence of Himalayan glaciers

The statement that most H-K glaciers will likely disappear by 2035 is wrong (8), as shown by sim-

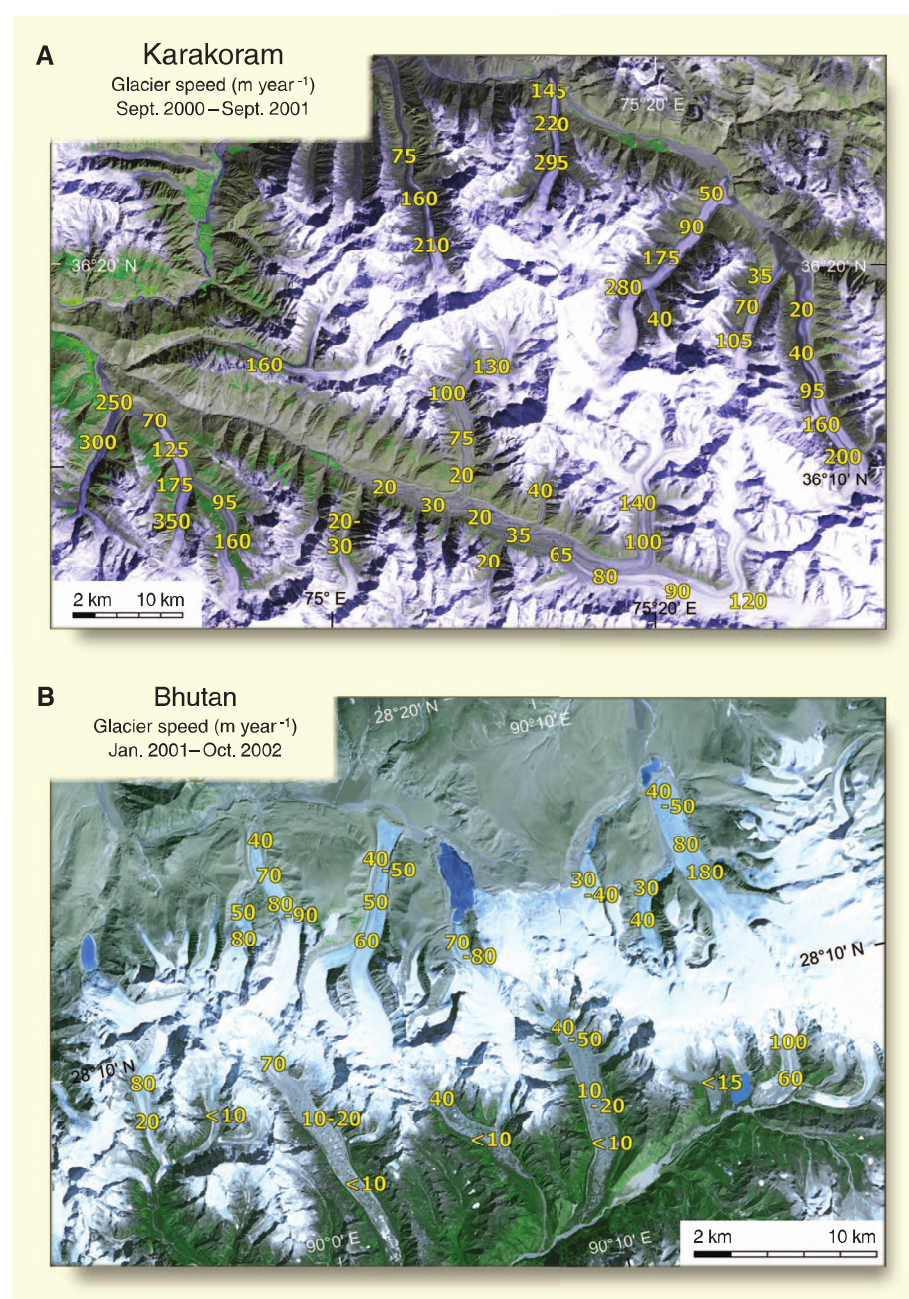


Fig. 2. (A) Representative horizontal speeds from Landsat data of October 2000 and October 2001 on glaciers in the Karakoram. Speeds vary greatly even for nearby and otherwise similar glaciers due to a large temporal variability in glacier dynamics, among other reasons because of glacier surges. **(B)** Representative horizontal surface displacements measured from repeat Advanced Spaceborne Thermal Emission and Reflection Radiometer satellite data of January 2001 and October 2002 on glaciers in Bhutan. The northern glaciers are debris-free, flow faster, and sustain their flow through their entire length, whereas the southbound glaciers have extensive debris cover on tongues that are nearly stagnant (for full measurements, see fig. S3).

ple but physically robust modeling (50). More realistic projections (5), relying on degree-day modeling but reporting the H-K glaciers only as part of High Mountain Asia, are consistent with the simpler model in suggesting moderate mass loss over the 21st century. The only published study on catchment scale (Langtang Valley, Nepal) predicts somewhat higher mass loss (75% by 2088) (51), although melt processes beneath the extensive debris cover were only roughly

addressed. Future changes of monsoon intensity will have an important effect on Himalayan glaciers, but current climate projections do not even agree on the sign of change, thus introducing further uncertainties (6). Nevertheless, all models project mass losses in coming decades that are substantial for most parts of the Himalaya, but consistently fall well short of complete region-wide glacier disappearance even by 2100. Information about total ice volume is essential

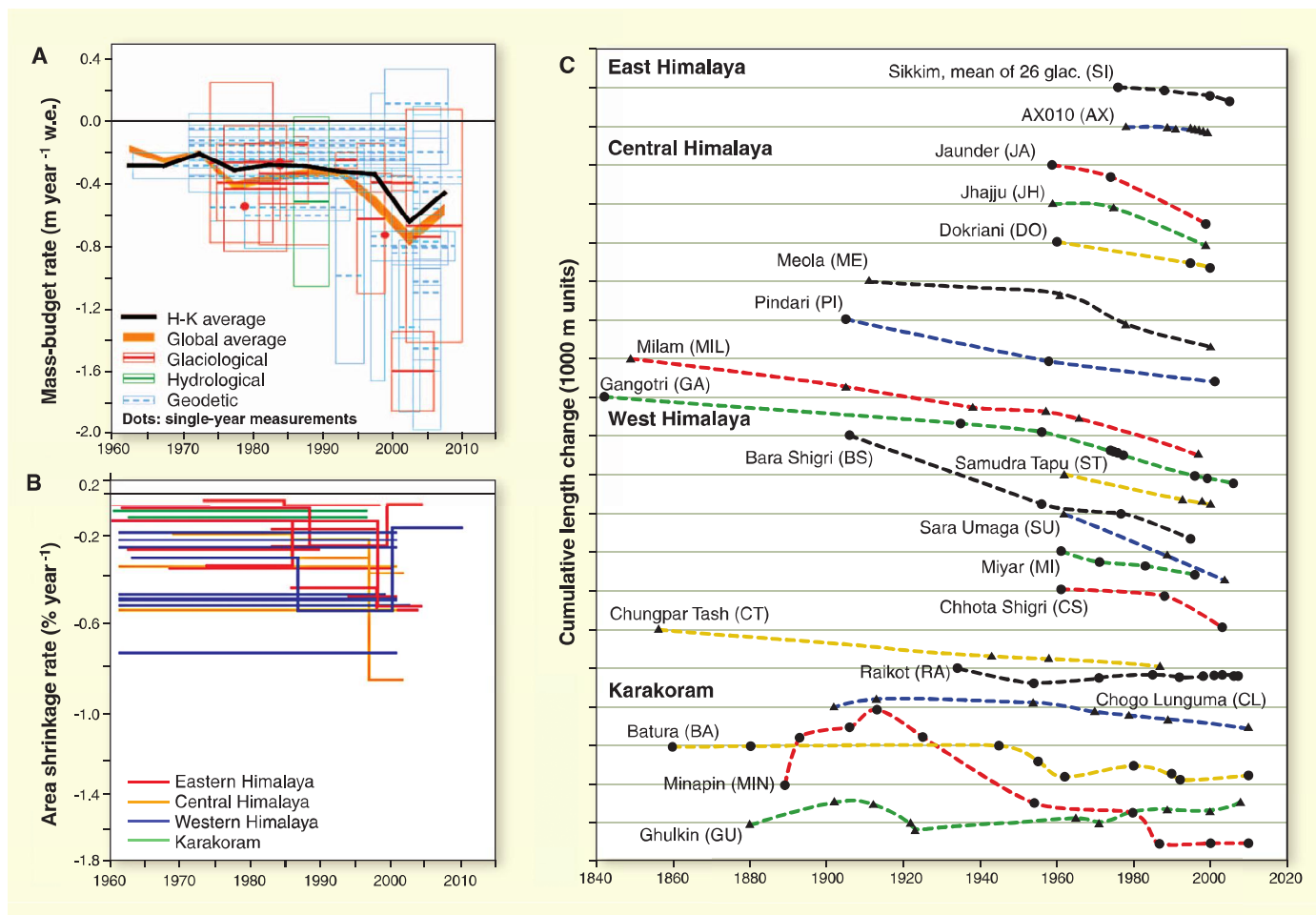


Fig. 3. Measured rates of change in mass budget (A) and area (B) and of a sample of cumulative length change measurements (C). For locations, see Fig. 1; for sources, see tables S3, S5, and S6. (A) Glaciological measurements are those made annually in situ; geodetic measurements, mostly multiannual, compare a later surface elevation (mostly derived from photogrammetric surveys) to an earlier one. Each budget is drawn as a thick horizontal line contained in a

± 1 standard deviation box (± 1 standard error for geodetic measurements). (B) Area shrinkage in recent decades. No statistically significant difference between the regions can be discerned. Uncertainties appear to be high but are as yet poorly assessed. (C) The glacier retreat since the mid-19th century is obvious in the Himalaya, with the exception of the glaciers at Nanga Parbat in the northwest (RA, CL). Glaciers in the Karakoram show complex behavior.

for predictions, but only very few measurements exist (4). Percentage changes in glacier volume are very likely to exceed percentage area changes, because a large part of the H-K ice is located in the low-lying and flat (and thus thick) tongues of the largest valley glaciers. Projections for the Karakoram glaciers will remain impractical until the reasons for their observed anomalous behavior, including their propensity to surge, are better understood (27, 29). The evidence of stability or even mass gain in the Karakoram, which may be ascribable to increased winter precipitation and reduced summer temperature, was recently confirmed by direct measurement (43).

Impacts of Glacier Changes in the Himalaya

Glacier change affects the hydrological cycle. A negative annual mass budget yields a surplus of runoff from glacier ice, whereas a positive budget yields a deficit of runoff because snow has gone into storage on the glacier. When glacier ice (as opposed to winter snow) is lost in the long term,

the annual hydrograph evolves toward that of an equivalent glacier-free catchment. The relative importance of this loss of glacier ice necessarily decreases downstream, but it differs fundamentally under different precipitation regimes (2). The runoff contribution from glacier imbalance is relatively minor in the wetter monsoonal catchments of the Ganges and Brahmaputra but more substantial in the drier westerly dominated headwaters of the Indus (1, 2) (table S7).

Projections of the diminishing contribution of seasonal snow to annual runoff indicate reduced maximum flows in spring and an increase by over 30% of the glacier contribution to total runoff (52). Runoff in strongly glaciated catchments, especially in the Karakoram, will likely not decrease due to deglaciation before the end of the 21st century (53). Currently, gauging stations in the extensively glaciated Hunza basin (Karakoram) show reduced runoff, consistent with climate records (14) and indications of a positive mass budget for glaciers in the Karakoram (29, 43, 46).

Rough predictions of runoff for the Langtang Valley (Nepal) suggest that total discharge might even increase during the next decades (51). However, this is mainly attributable to a projected increase in precipitation; the contribution of glaciers to discharge may decrease after ~2040. Unlike in regions with winter-accumulation-type glaciers, where an earlier peak of spring snowmelt is expected, the monsoon-influenced Himalaya will maintain peak discharge in summer even with strongly reduced glacier sizes (1, 2). Runoff from less glaciated catchments will probably decrease, especially in the central and eastern Himalaya, as glaciers continue to shrink (53). In the absence of a clear trend in glacier shrinkage in the Karakoram and parts of the northwestern Himalaya, constituting important parts of the Indus catchment, we would not expect large changes in the discharge of the Indus River during the next decades. A corollary of the confirmation of the Karakoram anomaly is that the contribution of Karakoram glaciers to sea-level rise has been overestimated (43).

A further serious implication of glacier recession is the development of moraine-dammed glacial lakes (54) that, if their dams breach, can drain catastrophically (7). In the central and eastern Himalaya, both south and north of the main ridge, lake growth has been observed in recent decades, with much larger absolute growth rates in the east, while in the drier northwest, total lake area decreased (54, 55). Lakes in contact with glacier ice efficiently transmit thermal energy to the ice front, accelerating melting, and also induce calving, accelerating retreat (56). In the H-K, growth of moraine-dammed lakes and disintegration of glacier tongues have been found to stem mostly from tongue stagnation and the rapid expansion of supraglacial lakes over a period of typically 50 years. The process may start when average surface slopes of glacier tongues become smaller than 2° (57). The associated thermokarst processes can be self-enhancing and irreversible, so that pond and lake development may lead to glacier shrinkage independently of climatic factors. Advancing glaciers may also cause threats if they dam tributary valleys, turning them into new lake basins (58). The risk related to glacial lakes in the H-K, in contrast to some other mountain regions such as the Alps or Andes, is characterized by the particularly large lake volumes and associated long outburst flood reaches rather than by a high population concentration close to the lakes (7).

Perspectives

Most glaciers in H-K have retreated and lost mass since the mid-19th century. Loss rates have probably accelerated in recent decades, but the observed tendencies are not regionally uniform. In the Karakoram and parts of the northwestern Himalaya, many of the observed large glaciers have oscillated or surged since the beginning of the last century, with indications of positive mass balances for the 1990s and the beginning of the 21st century (19, 29, 43, 46). This Karakoram anomaly stands out as a phenomenon that deserves further investigation to clarify the relation between climate forcing and glacier responses in the region, taking due account of the distinctive behavior of its many surge-type and dynamically variable glaciers.

The leading uncertainties about the state and fate of H-K glaciers relate to the contribution of glaciers to runoff (51), the projection of glacier changes (50), the variability of glacier changes within the region (44), the influence of debris cover on glacier melt (20, 23), the role of ice and snow avalanches in the glacier mass budget (21), and the magnitude of past glacier changes as revealed from comparisons with maps (22). These uncertainties can be mainly attributed to deficient information (for example, about total glacier area and mass); lack of measurements, both of climatic forcing agents and of the glaciers themselves (mass budgets and length changes); and the use of unsuitable or uncertain data, such as imagery with extensive seasonal snow or maps drawn from such imagery. Nonpublication of existing data makes these problems worse.

To close the knowledge gaps, the most useful steps will be to release a regionally complete, up-to-date, and accurate glacier inventory conforming to international standards and including the most important topographic parameters; to continue to develop and refine remote-sensing methods for the estimation of glacier changes, including length, area, and volume changes, as well as gravimetric measurement of mass changes; to fill critical gaps in the climatic and hydrologic station network and establish transects from the lowlands in the south to the Tibetan Plateau, similar to that already established north and south of Mount Everest; to continue existing mass-budget measurements on reference glaciers and to establish new programs to cover more climate zones and glacier types in a more representative way, particularly in the Karakoram; to measure the thickness of selected glaciers as a basis for calibrating recently developed methods for modeling of subglacial topography [e.g., (59)] and hence glacier volume; and to strengthen modeling efforts, in particular for climate projections, future glacier evolution, GLOFs, and glacier runoff. Field and remote-sensing-based investigations should consider the needs of these models when designing and performing investigations. Finally, we recommend the continuation and extension of coordinated transboundary research on climate, cryosphere, and their impacts, including the exchange of all relevant data.

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Supplementary Materials

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