The State and Fate of Himalayan Glaciers

T. Bolch,[1,2]* A. Kulkarni,[3] A. Kääb,[4] C. Huggel,[1,5] F. Paul,[1] J. G. Cogley,[6] H. Frey,[1,5] J. S. Kargel,[7] K. Fujita,[8] M. Scheel,[1,5] S. Bajracharya,[9] M. Stoffel[5,10]

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 km^2 and 49,650 km^2 (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 km^2 (Himalaya, ~22,800 km^2; Karakoram, ~18,000 km^2) (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 km^3, taking the slope-dependent ice thickness into account, to ~3600 to ~6500 km^3 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

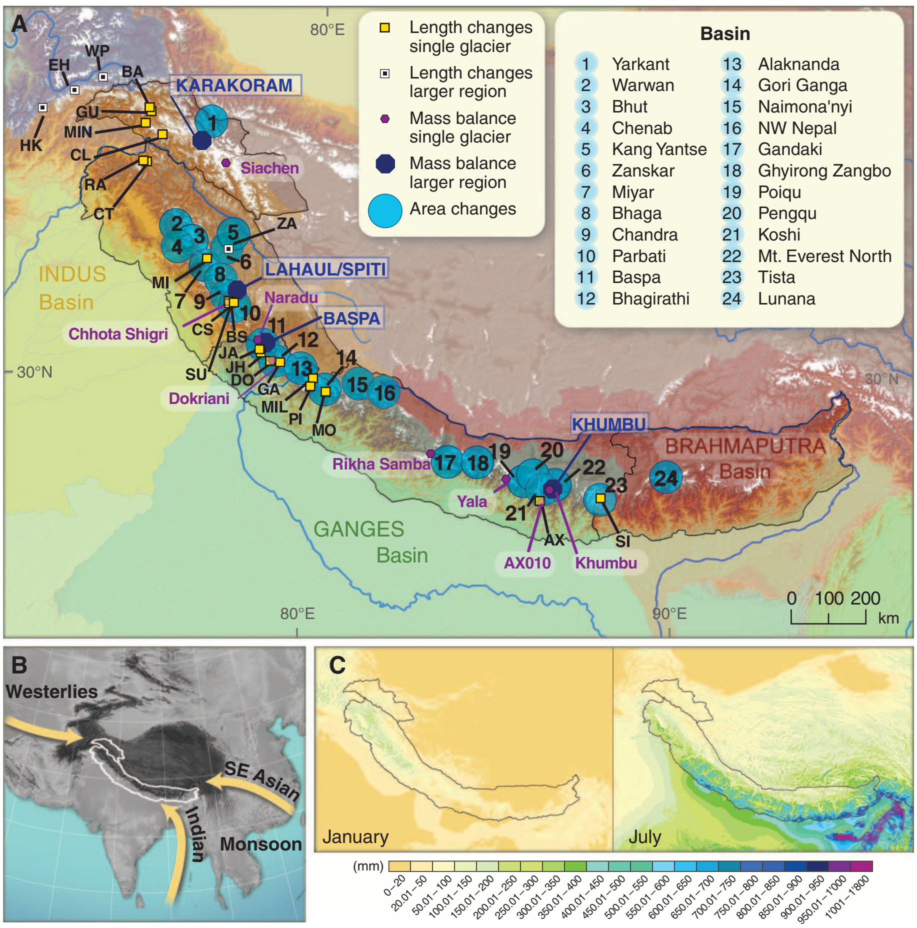

Fig. 1. (**A**) Map of the Karakoram and Himalaya showing the major river basins and the locations of measured rates of change in area and of a sample of glacier length change and mass budget measurements (*4*) (tables S3, S5, and S6). (**B**) Main wind systems. (**C**) Mean precipitation in January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

[1]Department of Geography, University of Zurich, 8057 Zürich Switzerland. [2]Institute for Cartography, Technische Universität Dresden, 01069 Dresden, Germany. [3]Divecha Center for Climate Change, Indian Institute of Science, Bangalore 560 012, India. [4]Department of Geosciences, University of Oslo, 0316 Oslo, Norway. [5]Institute for Environmental Sciences, University of Geneva, 1227 Geneva, Switzerland. [6]Department of Geography, Trent University, Peterborough, Ontario, Canada K9J 7B8. [7]Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721, USA. [8]Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan. [9]International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal. [10]Institute of Geological Sciences, University of Bern, 3012 Bern, Switzerland.

*To whom correspondence should be addressed. E-mail: tobias.bolch@geo.uzh.ch

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 numerous 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*).

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.

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 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 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 ± 12 Gt year^{-1}) and only –5 ± 6 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.

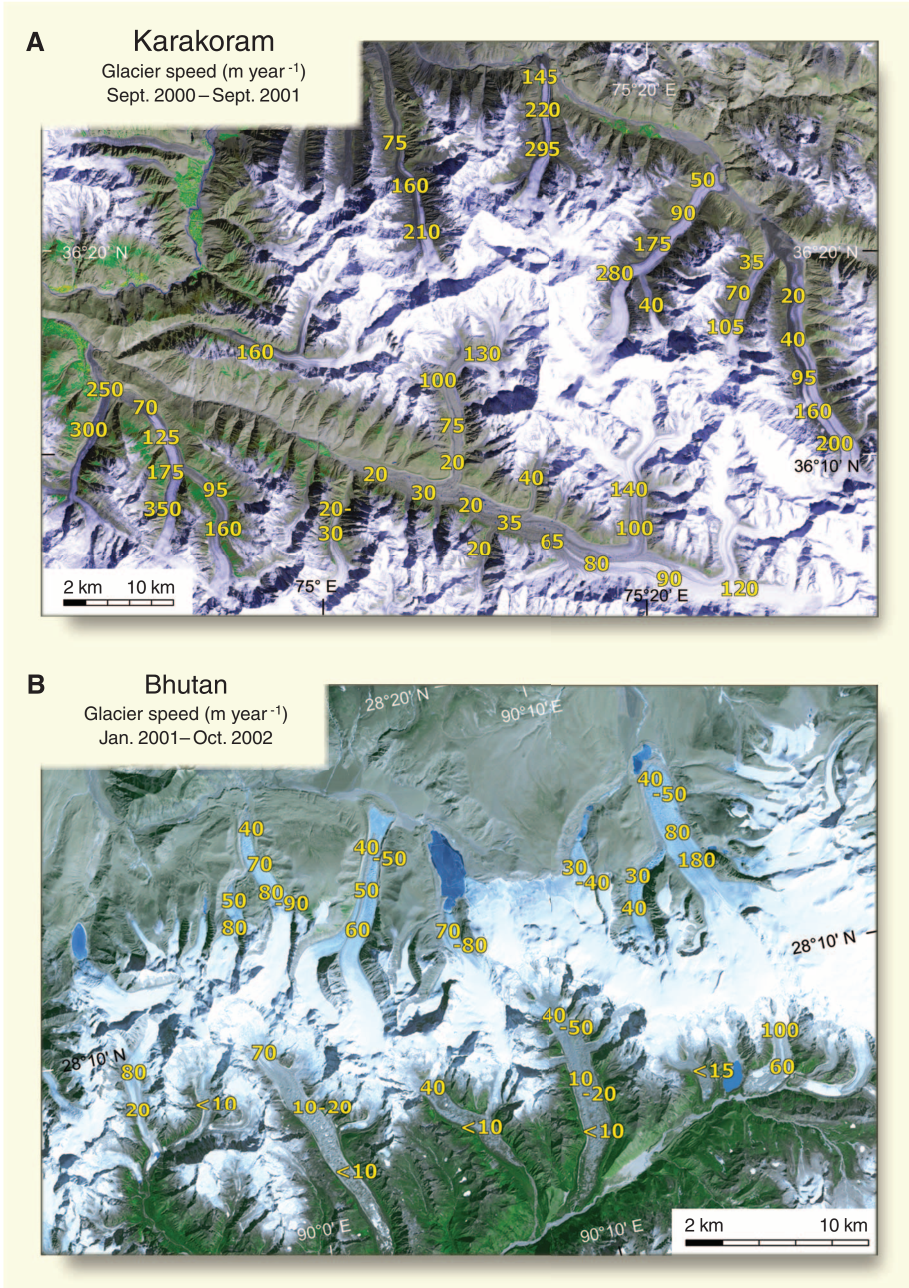

Fig. 2. (**A**) Representative horizontal speeds from Landsat data of October 2000 and October 2001 on glaciers in the Karakoram. Speeds vary greatly even for nearby and otherwise similar glaciers due to a large temporal variability in glacier dynamics, among other reasons because of glacier surges. (**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).

Persistence of Himalayan glaciers

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

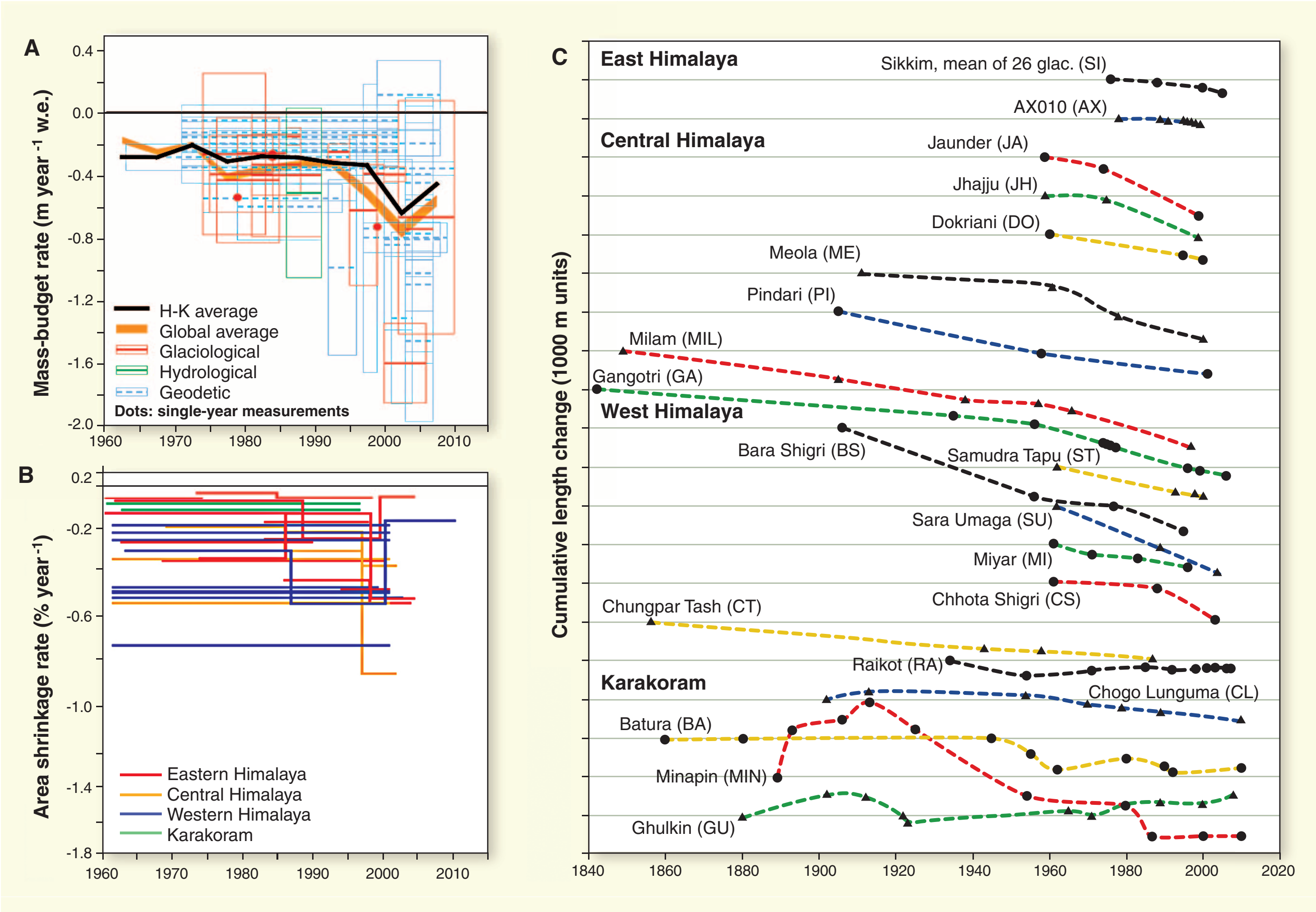

Fig. 3. Measured rates of change in mass budget (A) and area (B) and of a sample of cumulative length change measurements (C). For locations, see Fig. 1; for sources, see tables S3, S5, and S6. (**A**) Glaciological measurements are those made annually in situ; geodetic measurements, mostly multiannual, 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.

References and Notes

1. W. W. Immerzeel, L. P. van Beek, M. F. Bierkens, *Science* **328**, 1382 (2010).
2. G. Kaser, M. Grosshauser, B. Marzeion, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 20223 (2010).
3. M. B. Dyurgerov, M. F. Meier, "Glaciers and the Changing Earth System: A 2004 Snapshot" Occasional Paper **58**. (2005).
4. Methods and discussion are available as supplementary materials on *Science* Online.
5. V. Radić, R. Hock, *J. Geophys. Res.* **115**, (F1), F01010 (2010).
6. E. J. Moors *et al*., *Environ. Sci. Policy* **14**, 758 (2011).
7. S. Richardson, J. Reynolds, *Quat. Int.* **65–66**, 31 (2000).
8. J. G. Cogley, J. S. Kargel, G. Kaser, C. J. van der Veen, *Science* **327**, 522 (2010).
9. J. Böhner, *Boreas* **35**, 279 (2006).
10. B. Bookhagen, D. Burbank, *J. Geophys. Res.* **115**, (F3), F03019 (2010).
11. M. Winiger, M. Gumpert, H. Yamout, *Hydrol. Processes* **19**, 2329 (2005).
12. A. Shrestha, C. Wake, J. Dibb, P. Mayewski, *Int. J. Climatol.* **20**, 317 (2000).
13. M. Shekhar, H. Chand, S. Kumar, K. Srinivasan, A. Ganju, *Ann. Glaciol.* **51**, 105 (2010).
14. H. Fowler, D. Archer, *J. Clim.* **19**, 4276 (2006).
15. A. Shrestha, C. Wake, P. Mayewski, J. Dibb, *J. Clim.* **12**, 2775 (1999).
16. X. Yang, T. Zhang, D. Qin, S. Kang, X. Qin, *Arct. Antarct. Alp. Res.* **43**, 147 (2011).
17. Y. Ageta, K. Higuchi, *Geogr. Ann. A* **66**, 249 (1984).
18. D. J. Quincey *et al*., *Geophys. Res. Lett.* **38**, L18504 (2011).
19. K. Hewitt, *Mt. Res. Dev.* **31**, 188 (2011).
20. T. Bolch, T. Pieczonka, D. I. Benn, *The Cryosphere* **5**, 349 (2011).
21. L. Iturrizaga, *Zeit. für Geo.* **55**, (suppl.), 205 (2011).
22. R. Bhambri, T. Bolch, *Prog. Phys. Geogr.* **33**, 672 (2009).
23. D. Scherler, B. Bookhagen, M. R. Strecker, *Nat. Geosci.* **4**, 156 (2011).
24. D. Quincey, A. Luckman, D. I. Benn, *J. Glaciol.* **55**, 596 (2009).
25. A. Sakai, N. Takeuchi, K. Fujita, M. Nakawo, *IAHS Publication* **264**, 119 (2000).
26. A. Kääb, *Remote Sens. Environ.* **94**, 463 (2005).
27. T. Heid, A. Kääb, *The Cryosphere Discuss.* **5**, 3025 (2011).
28. L. Copland *et al*., *Ann. Glaciol.* **50**, 41 (2009).
29. L. Copland *et al*., *Arct. Antarct. Alp. Res.* **43**, 503 (2011).
30. P. A. Mayewski, P. A. Jeschke, *Arct. Alp. Res.* **11**, 267 (1979).
31. M. A. Sarikaya, M. P. Bishop, J. F. Shroder, J. A. Olsenholler, *Remote Sens. Lett.* **3**, 77 (2012).
32. U. K. Haritashya, M. P. Bishop, J. F. Shroder, A. B. G. Bush, H. N. N. Bulley, *Clim. Change* **94**, 5 (2009).
33. S. Liu *et al*., *Ann. Glaciol.* **43**, 91 (2006).
34. S. Schmidt, M. Nüsser, *Arct. Antarct. Alp. Res.* **44**, 107 (2012).
35. A. V. Kulkarni, B. P. Rathore, S. K. Singh, I. M. Bahuguna, *Int. J. Remote Sens.* **32**, 601 (2011).
36. R. Bhambri, T. Bolch, R. K. Chaujar, S. C. Kulshreshtha, *J. Glaciol.* **57**, 543 (2011).
37. Karma, Y. Ageta, N. Naito, S. Iwata, H. Yabuki, *Bull. Glaciol. Res.* **20**, 29 (2003).
38. Y. Nie, Y. Zhang, L. Liu, J. Zhang, *J. Geogr. Sci.* **20**, 667 (2010).
39. S. R. Bajracharya, S. B. Maharjan, F. Shrestha, in *Climate Change, Geophysical Foundations and Ecological Effects*, J. Blanco, H. Kheradmand, Eds. (InTech, Rijeka, Croatia, 2011).
40. M. F. Azam *et al*., *J. Glaciol.* **58**, 315 (2012).
41. E. Berthier *et al*., *Remote Sens. Environ.* **108**, 327 (2007).
42. M. R. Bhutiyani, *J. Glaciol.* **45**, 112 (1999).
43. J. Gardelle, E. Berthier, Y. Arnaud, *Nat. Geosci.* (2012); 10.1038/ngeo1450.
44. K. Fujita, T. Nuimura, *Proc. Natl. Acad. Sci. U.S.A.* **108**, 14011 (2011).
45. M. Zemp, M. Hoelzle, W. Haeberli, *Ann. Glaciol.* **50**, 101 (2009).
46. K. Matsuo, K. Heki, *Earth Planet. Sci. Lett.* **290**, 30 (2010).
47. T. Jacob, J. Wahr, W. T. Pfeffer, S. Swenson, *Nature* **482**, 514 (2012).
48. K. Fujita, *Earth Planet. Sci. Lett.* **276**, 14 (2008).
49. B. Xu *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **106**, 22114 (2009).
50. J. G. Cogley, *Ann. Glaciol.* **52**, 69 (2011).
51. W. W. Immerzeel, L. P. H. Beek, M. Konz, A. B. Shrestha, M. F. P. Bierkens, *Clim. Change* **110**, 721 (2012).
52. T. P. Barnett, J. C. Adam, D. P. Lettenmaier, *Nature* **438**, 303 (2005).
53. H. G. Rees, D. N. Collins, *Hydrol. Processes* **20**, 2157 (2006).
54. J. Gardelle, Y. Arnaud, E. Berthier, *Global Planet. Change* **75**, 47 (2011).
55. W. Xin, S. Liu, W. Gou, J. Xu, *Mt. Res. Dev.* **28**, 310 (2008).
56. A. Sakai, K. Nishimura, T. Kadota, N. Takeuchi, *J. Glaciol.* **55**, 909 (2009).
57. A. Sakai, K. Fujita, *J. Glaciol.* **56**, 177 (2010).
58. K. Hewitt, J. Liu, *Physical Geography* **31**, 528 (2010).
59. D. Farinotti, M. Huss, A. Bauder, M. Funk, M. Truffer, *J. Glaciol.* **55**, 422 (2009).

Acknowledgments: This work has been supported by the European Union FP7 project HighNoon (grant 22708), the European Space Agency projects Glaciers_cci (4000101778/10/I-AM) and GlobGlacier (21088/07/I-EC), and the Global Land Ice Measurements from Space (GLIMS) initiative. J.S.K. acknowledges the support of NASA and T.B. the support of Deutsche Forschungsgemeinschaft (DFG). This review has benefited greatly from discussions with E. Berthier, M. Bishop, U. Haritashya, D. Quincey, A. Racoviteanu, J. Wahr, and M. Zemp. Glacier inventory data for Shyok Basin was provided by R. Bhambri.

Supplementary Materials

www.sciencemag.org/cgi/content/full/336/6079/310/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S5
Tables S1 to S7
References (*60–113*)

10.1126/science.1215828

Supplementary Text

1. Current knowledge about glacier area and volume in the Himalaya and Karakoram

Definitions of the H-K region vary, the chosen boundaries often being somewhat arbitrary. Peripheral mountain ranges, such as the Hindu Raj range in the northwest or Hengduan Shan in the east, are variously included or excluded. These variations hinder direct comparison of estimates of total glacier area and volume for the region, especially when the boundaries are not displayed. We subdivided the entire H-K region into the Karakoram, and the western, central and eastern Himalaya (Fig. 1 and S1). We hereby refer to (*60*) and (*61*) for a more detailed description and further information about the nature of the mountains and possible subdivisions.

The completeness and reference date of the data sets on which inventories are based vary strongly, both between and within inventories. For example, the first publicly available glacier inventory in the H-K was completed by the International Centre for Integrated Mountain Development (ICIMOD) in 2001 and is based on map data from 1963 to 1982 and satellite imagery from 1999 (*39, 62*). Similarly, the first Chinese glacier inventory was only completed within 23 years of its inception (*63*). These inventories are downloadable from the database of the Global Land Ice Measurements from Space initiative (GLIMS, www.glims.org) (*64*).

In recent publications, the glacier coverage is often quoted from (*3*) as 33,050 km² for the Himalaya and 16,600 km² for the Karakoram. These numbers derive from (*65*) and (*66*), the latter being a global overview based on sources dating back to the 1950s. Hence, the numbers do not represent the recent glacier coverage and their accuracy is nearly impossible to assess.

A complete inventory for the Himalaya and Karakoram has been recently published (*50*). It is compiled from various sources (Chinese Glacier Inventory [CGI]; the older inventory by ICIMOD; and partial inventories of the Geological Survey of India [GSI]) and from newly-digitized glacier outlines for the Indian part of Kashmir, based on analog maps of the Soviet military (reference date: late 1970s; 1:200,000 scale). This inventory counts ~21,000 glaciers covering a total area of ~43,200 km^2 within the H-K region. Inventory dates cover 1968-2003. The author suggests, based on simple mass-budget projections, that up to 20% of the inventoried glaciers might have disappeared by 2010 (*50*). An overview of the discussed numbers for the glacier coverage of the H-K region is compiled in Table S1.

2. New estimates of glacier area, volume, and debris cover

2.1 New glacier inventory

In order to present the most up-to-date number of glacier-covered area in the H-K region, we used the data from the new ICIMOD inventory based on Landsat ETM+ satellite data from around 2008 (*67*), an inventory for northwestern Himalaya generated from Landsat ETM+ satellite data acquired between 2000 and 2002 within the framework of the ESA "GlobGlacier" project (*68, 69*), and data from parts of the Karakorum mapped by R. Bhambri using a Landsat ETM+ scene from 2002. Some remaining gaps mainly situated in Tibet/China were filled with data from the first Chinese Glacier Inventory (*63*) as available from the GLIMS data base (*70*, Fig. S1). Clean-ice glaciers were mapped automatically using band ratio images or the normalized difference snow index (NDSI). Both methods are based on the strong difference in spectral reflectance of ice and snow in the short-wave infrared compared the red or green band and separate ice and snow from other terrain with an appropriate threshold value following (*71–73*). While clean and also polluted ice can be mapped accurately from multispectral data using these methods (*73–75*), the debris-covered portions are still best mapped by manual digitization especially for smaller glaciers (*76, 77*). Further filters (e.g. for noise, surface slope, or vegetation) were in some regions applied to reduce the amount of misclassified pixels and to help to identify debris-covered glaciers (*67, 78, 79*). To map the debris-covered parts accurately by visual methods, ALOS PALSAR coherence images (*69, 80*) were additionally considered. Glacier polygons smaller than 0.05 km² were removed as they are subject to high uncertainties and do not add much to the total area and volume. The contiguous ice masses were split into their drainage basins using the SRTM3 digital elevation model (DEM) either fully manually or with the help of a watershed algorithm (*75*). These outlines were finally visually checked and manually improved if necessary.

The resulting total glacier area from this new assessment is ~40,800 km² (Table S2). Our best estimate of the percentage of debris-covered glacier area, based on measurements over an area of 32,000 km^2, is ~10% (12.6% and 9.6% in the Ganges and Indus basins, respectively) (*67*). This is of the same order as the estimate of ~15% by (*23*) and the inventory for the northwestern Himalaya (*69*).

For all glaciers the minimum, maximum, and mean elevation, as well as mean slope were calculated by fusing the glacier polygons with the void-filled version 4 of the SRTM DEM, available from the Consultative Group on International Agricultural Research (CGIAR, http://srtm.csi.cgiar.org/).

2.2 Glacier volume estimates

Glacier volumes were estimated by two different methods. One is based on the mean slope (α), the elevation range (ΔH) and the mean basal shear stress (τ) according to (*81*). For this approach τ is parameterized in dependence of the elevation range and a constant value of 1.5 bar is applied if ΔH exceeds 1.6 km (*81*). The resultant mass for all glaciers in H-K is in this case less than 2000 km³. In the original approach (*81*), mean slope (α) is calculated as the arc tangent of ΔH and the glacier length. However, as glacier length is not yet available for most of the glaciers in the study region, we here calculated mean slope by averaging for each glacier the slope values of all DEM cells. For glaciers with a constantly inclined surface there is no difference between the two ways of calculation, but for large valley glaciers with flat glacier tongues, the arc tangent calculation gives considerably smaller mean slopes than the DEM approach, which includes all the – mostly steeper – parts of the accumulation region. The DEM approach thus results in higher mean slope values and, hence, in much smaller volumes for large valley glaciers than the arc tangent approach. We thus calculated glacier volumes from the original approach with digitized flow lines (*82*) for a subset of 130 glaciers of different sizes and types in the western and central Himalaya. For this purpose calibrated the model with the thickness data of Dokriani Glacier (*83*), the only published data for the Himalaya besides Chhota Shigri Glacier in western Himalaya (*40*) and Kangwure Glacier in Tibet (*84*). This approach resulted in higher value for the glacier volume than for the mean slope from the DEM cells. The total volume would be about 2330 km³ (Table S2).

The second approach to estimating the glacier volume is the so-called volume-area scaling method (*85*). This method parameterizes glacier volume as a function only of glacier area. The scaling parameters are fitted to a relation between area and mean thickness, but for any given area the measured thicknesses vary widely, and so volume-area scaling is highly uncertain for individual glaciers. This is in particular the case for glaciers with multiple tributaries and avalanche-fed glaciers, both of which are common in the H-K. Moreover, in some of the inventories (CGI and the older ICIMOD inventories) rock outcrops are not mapped, resulting in often much too large glacier areas and hence an overestimation of the volume. Glacier volume resulting by applying several sets of scaling parameters as suggested by different studies (*85-87*) range from ~3600 to ~6500 km³ (Table S2). Previous mass estimates based on older inventory data but the same parameterizations range from ~4000 to

~8000 Gt (which equals ~4450 to 8900 km³) (*50*). The highest value resulting from the scaling parameters by (*87*) are possibly overestimated because (*87*) calibrate their volume-area scaling relationship on centerline mass losses of glaciers in Alaska. However, these values are likely overestimated (*88*). A further shortcoming is that none of the existing and applied scaling parameters were calibrated for Himalayan glaciers. However, all estimates are substantially higher than with the calculation based on (*81*), but clearly well below the estimate of 12,000 Gt (~13,300 km³) presented in the Fourth Assessment Report of the IPCC (*89*). The wide range of the estimates indicates a pressing need for improved modeling approaches and for more in-situ thickness measurements for calibration and validation of the models.

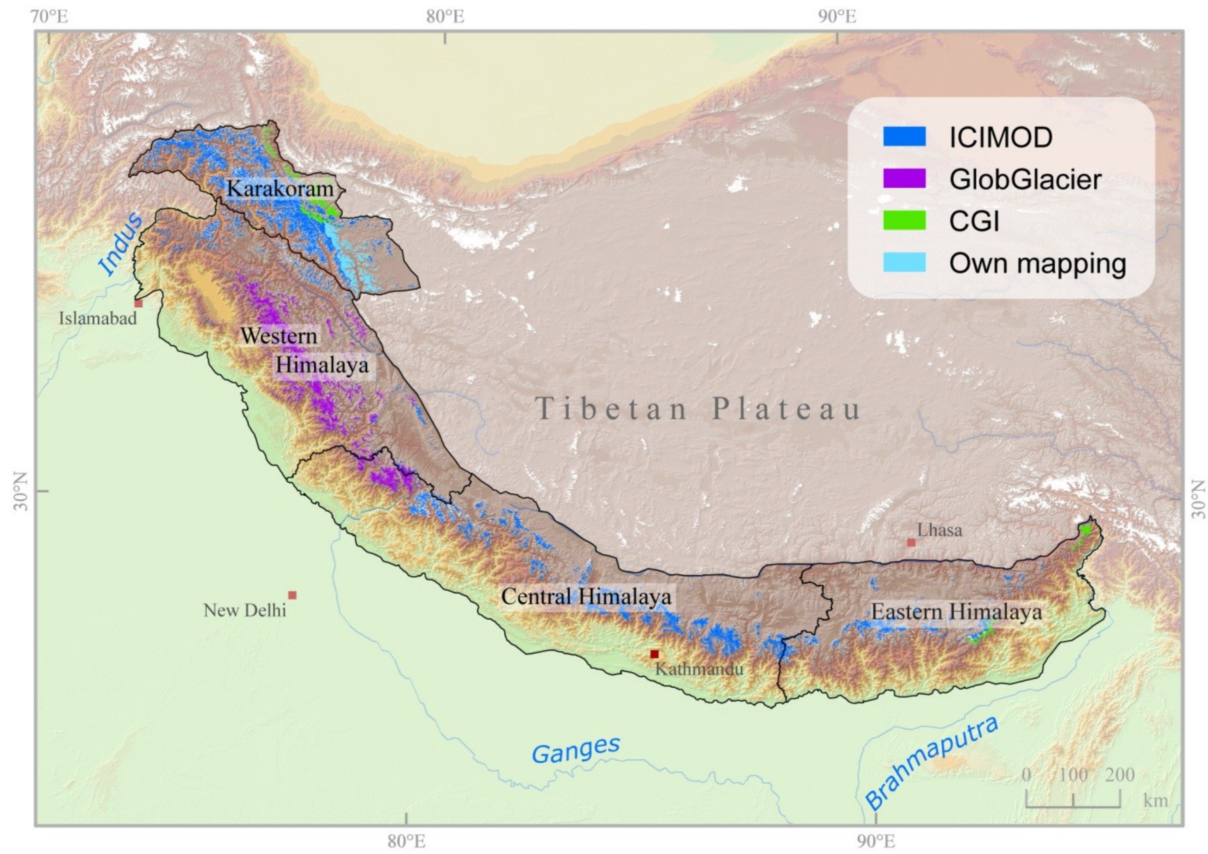

Fig. S1.
Sources of the Glacier Inventory of the Himalaya (ICIMOD (67), GlobGlacier (68, 69), CGI [Chinese Glacier Inventory] (63, 70), Own mapping: R. Bhambri). The figure shows also the subdivision into the four major regions.

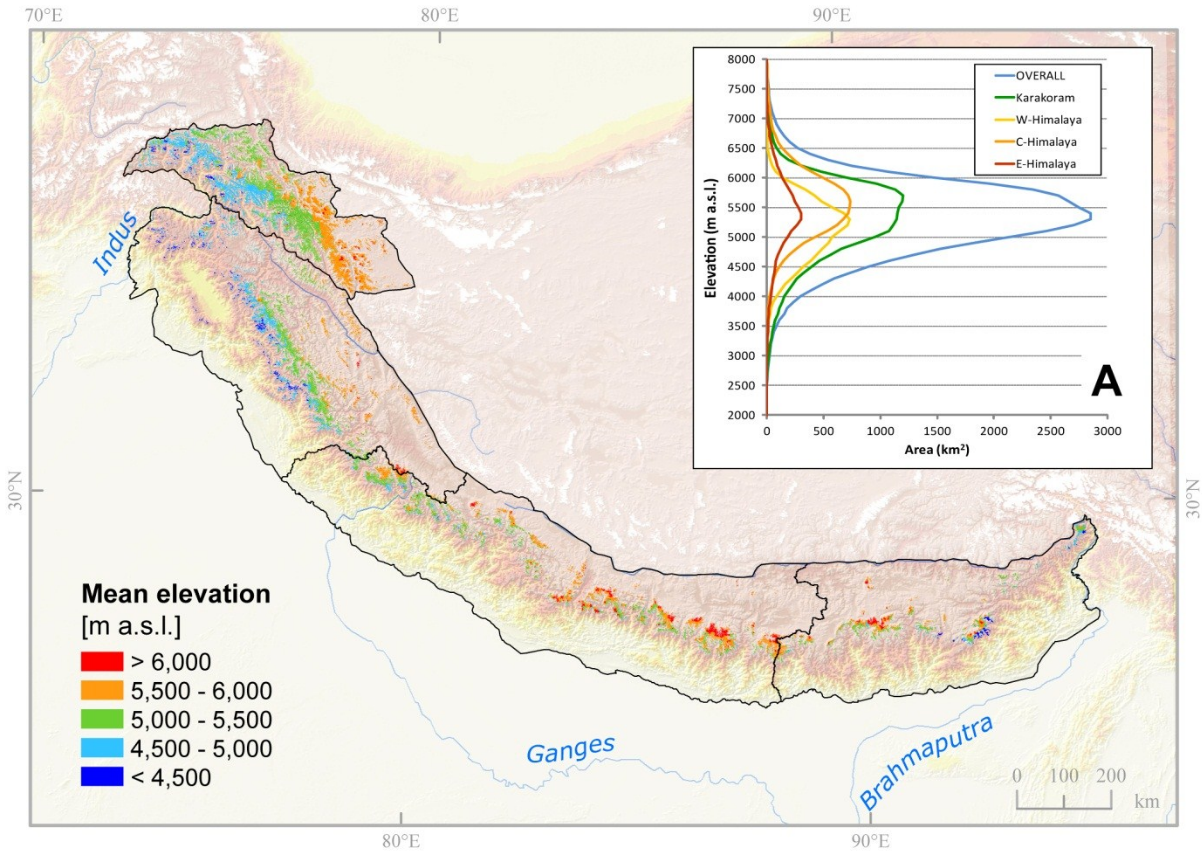

Fig. S2

Mean elevation of the glaciers in H-K. See also Table S2. As found in other mountain ranges, the mean elevations increase downwind, that is, with distance from the source of moisture. The glaciers in the northwest exposed to the westerlies are situated at comparatively low elevation, while the glaciers north or northeast of the main ridge of the Himalaya have a clearly higher mean elevation. A: Area-elevation distribution (hypsometry) for the different regions and for the whole of the H-K. The highest mean elevation of the Central Himalaya is noticeable. This distribution is bimodal: the higher and more explicit peak is probably due to the large area of high elevation glaciers northeast of the main ridge, the lower one due to those windward of the divide. The hypsometry for western Himalaya is strongly skewed towards lower elevations, probably due to high precipitation and possibly to debris cover promoting the survival of low lying glacier tongues.

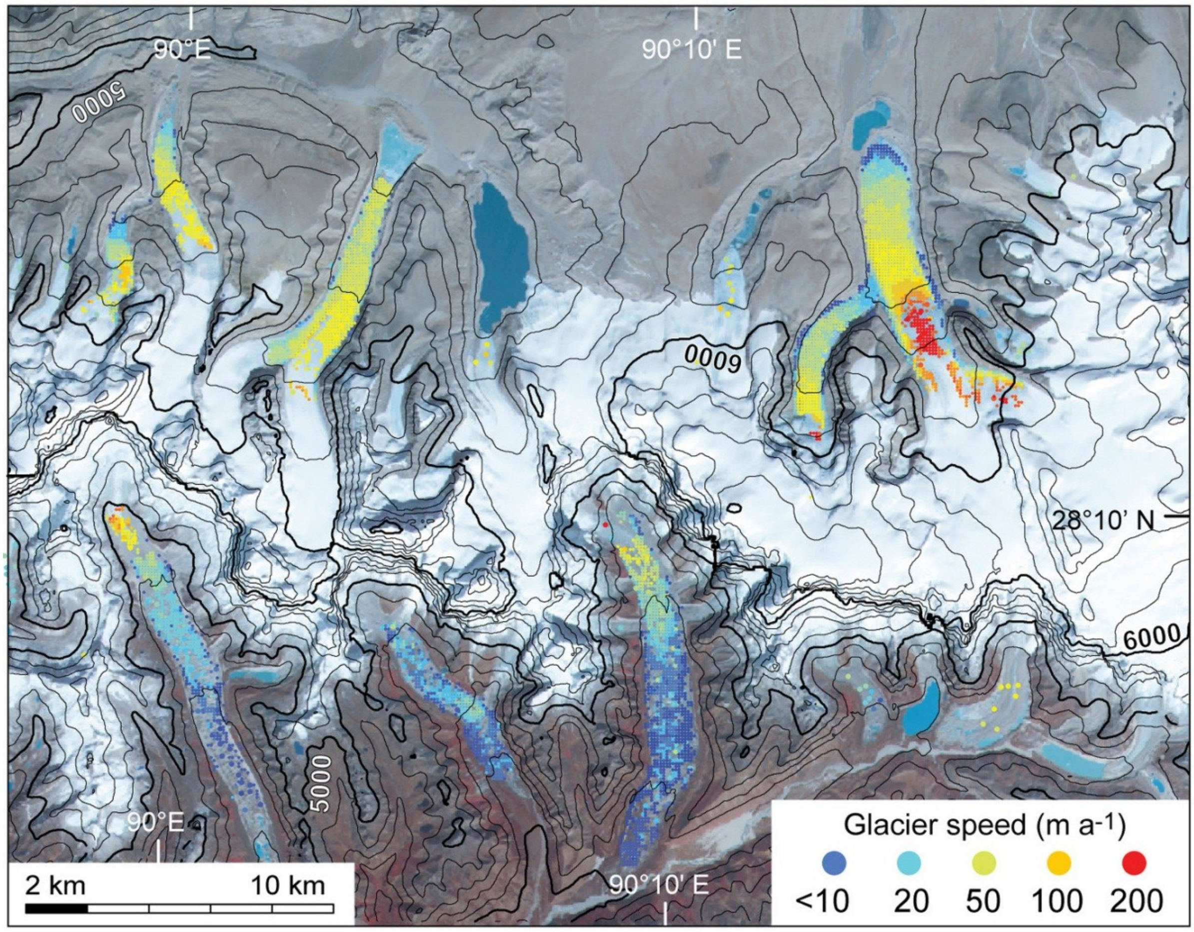

Fig. S3
Average annual horizontal surface speeds from ASTER data of 20 Jan 2001, 20 Nov 2001 and 22 Oct 2002 from normalized cross-correlation between the repeat images. Background image: ASTER channel 321 RGB composite of 20 Nov 2001. 200m-contours from the SRTM-DEM with voids filled using an ASTER DEM of 20 Jan 2001. Raw velocity measurements, with only a threshold on the correlation coefficient applied. Velocities 20 Jan-20 Nov 2001 and 20 Nov 2001-22 Oct 2002 showed no significant differences. More information can be found in (*26*).

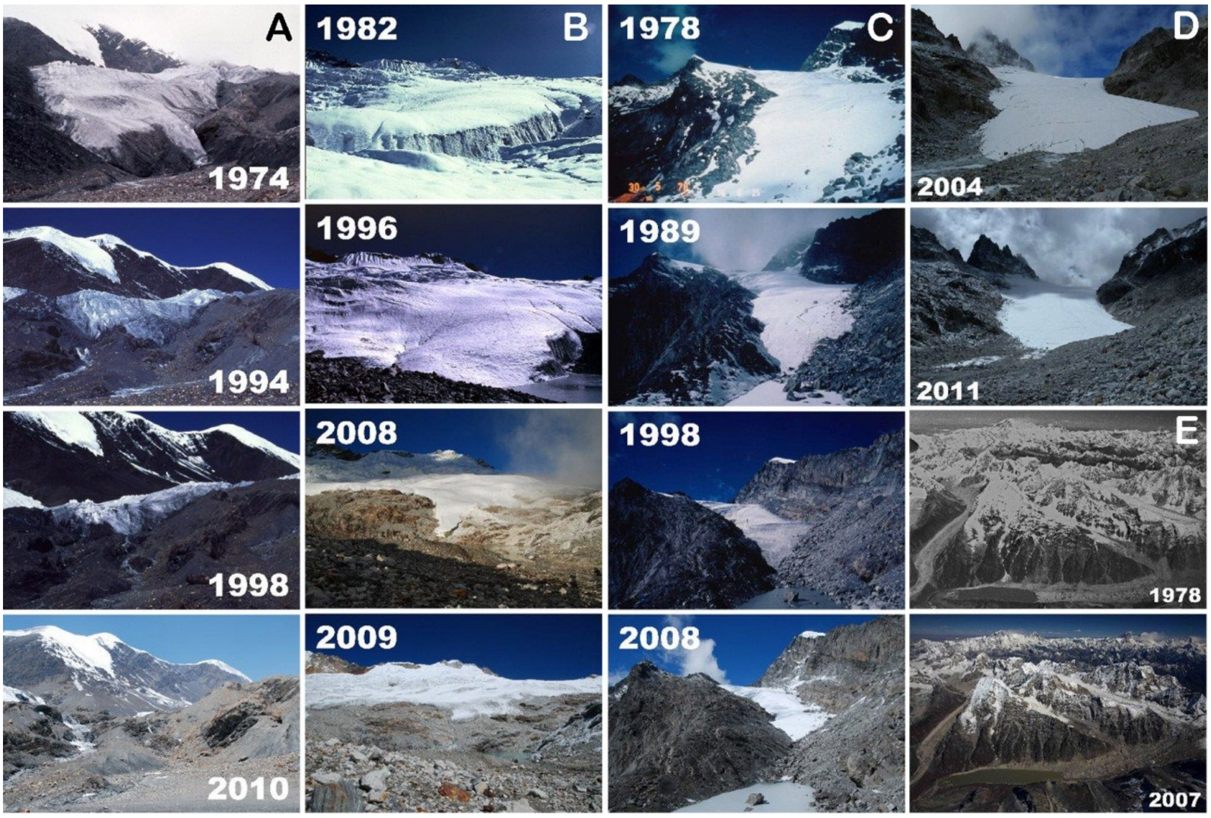

Fig. S4

Multi-temporal photo sequences showing the shrinkage of glaciers and (E) the concomitant development of a large glacial lake; A: Rikha Samba Glacier, Nepal; B: Yala Glacier, Nepal; C: Glacier AX010, Nepal; D: Ganju La Glacier, Bhutan; E: Tsho Rolpa, Nepal; Photos: GEN (Nagoya Univ. and Japanese Society of Snow and Ice), Y. Fujii, Y. Ageta, S. Kohshima, T. Kadota, K. Fujita and the Asahi Shimbun Company.

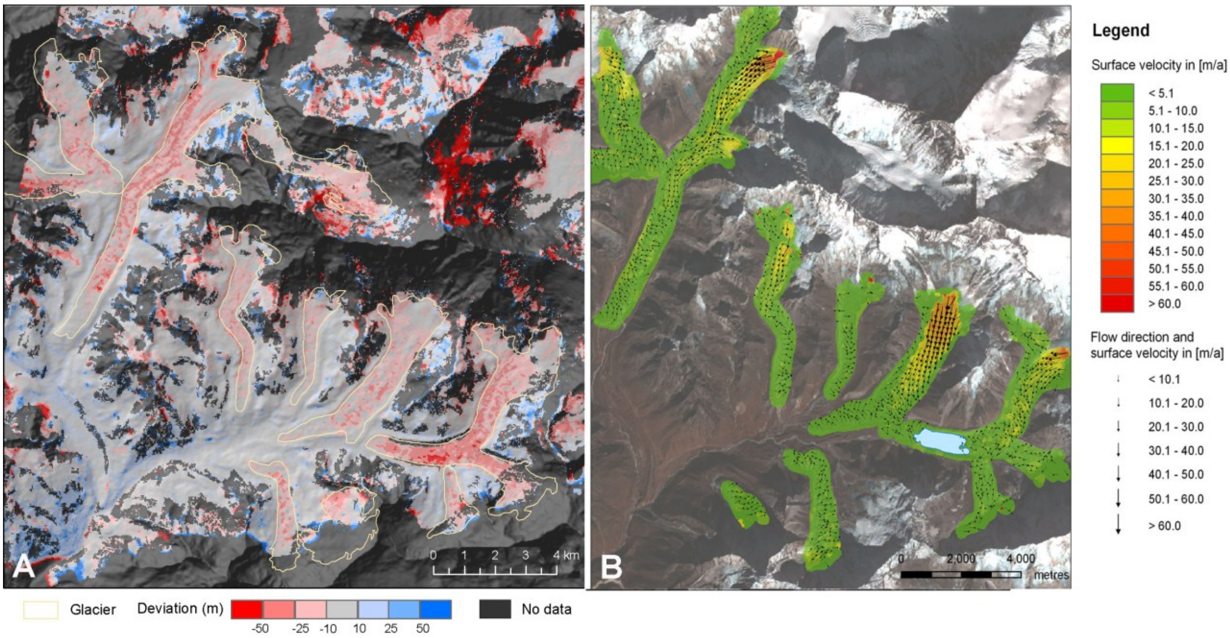

Fig. S5

Glacier elevation change (A) and velocity (B) for the glaciers south of Mt. Everest. Sources: (20, 90). For the location see Fig. 1. Background: shaded ASTER DEM (A) and ASTER RGB 321 composite (B). The elevation change was calculated by differencing of relatively adjusted DEMs based on Corona data (year 1970) and Cartosat-1 data (2007). The glacier velocity is derived using cross-correlation techniques based on ASTER data 20 Dec 2001 and 23 Nov 2003. The lower parts of the tongues show indications of stagnation (green color, undirected arrows, in B) similar to the southbound glaciers in Bhutan (Fig. S3). The red color, indicating mass loss, is clearly prevalent (in A). Only the upper clearly active parts of the glaciers and the distal parts show little or no lowering. The greatest surface lowering was found at Imja Glacier, where a pro-glacial lake has developed since the 1960s. The investigated glaciers, except one where no velocity measurements are available, are all heavily debris covered. More information can be found in (*20, 90, 91*).

Table S1: Published estimates of H-K glacier area. Note that the delineation of the regions varies as no clear boundary exists.

Glacier area Himalaya (km²)	Glacier area Karakoram (km²)	Source
31,530	15,145	(*92*)
33,050	15,400	(3, *65*)
33,050	16,600	(*66*)
21,973	21,205	(*50*)
35,109	n.a.	Qin, 1999 in (*93*)

Table S2: Glacier statistics for the different regions. See section 2.2 for more information.

	Area (km²)	Volume (km³) based on (*81*), adjusted	Volume (km³) based on scaling parameters by			Mean elevation (m a.s.l.)
			(*86*)	(*85*)	(*87*)	
Karakoram	**17,946**	**1259**	**2235**	**2745**	**4024**	**5326**
Western Himalaya	8943	415	515	610	895	5155
Central Himalaya	9940	484	647	770	1128	5600
Eastern Himalaya	3946	172	235	279	408	5395
Himalaya total	**22,829**	**1071**	**1397**	**1659**	**2431**	**5390**
Total	**40,775**	**2330**	**3632**	**4403**	**6455**	**5362**

Table S3: Information about selected glaciers with length measurements. See Fig. 1 for the glacier locations.

Abbr.	Glacier	Region	Period	No. of Measurements	Mean Recession Rate (m a-1)	Method	Reference
SI	Mean of 26 Glaciers	Sikkim (East Himalaya)	1976-2005	4	-12.2	In-situ	(*94*)
AX	AX010	Shorong Himal (Central Himalaya)	1978-1999	8	-7.3	In-situ	*(95, 96)*
CS	Chhota Shigri	Himachal Pradesh (Western Himalaya)	1961-2003	3	-23.3	In-situ	(*22*)
SU	Sara Umga	Himachal Pradesh (Western Himalaya)	1962-2004	3	-41.5	In-situ	(*22*)
BS	Bara Shigri	Himachal Pradesh (Western Himalaya)	1906-1995	4	-30.0	In-situ	(*22*)
MI	Miyar	Himachal Pradesh (Western Himalaya)	1961-1996	4	-17.1	In-situ	(*22*)
ST	Samudra Tapu	Himachal Pradesh (Western Himalaya)	1962-2000	4	-19.5	In-situ, remote sensing	(*97*)
JA	Jaunder	Garhwal Himal (Central Himalaya)	1959-1999	3	-37.7	In-situ	(*22*)
JH	Jhajju	Garhwal Himal (Central Himalaya)	1959-1999	3	-27.0	In-situ	(*22*)
DO	Dokirani	Garhwal Himal (Central Himalaya)	1960-2000	3	-16.4	In-situ	(*22*)
ME	Meola	Garhwal Himal (Central Himalaya)	1911-2000	4	-19.2	In-situ	(*22*)
PI	Pindari	Garhwal Himal (Central Himalaya)	1905-2001	3	-17.0	In-situ	(*22*)
MIL	Milam	Garhwal Himal (Central Himalaya)	1849-2006	7	-18.3	In-situ	(*22, 98*)
GA	Gangotri	Garhwal Himal (Central Himalaya)	1842-2006	10	-13.6	In-situ	(*22*)
CT	Chungpar-Tash	Nanga Parbat (Western Himalaya)	1856-1987	4	-7.3	In-situ	*(95)*
RA	Raikot	Nanga Parbat (Western Himalaya)	1934-2007	10	-2.8	Remote Sensing	(*99*)
CL	Chogo Lungma	Karakoram	1902-2010	7	-4.8	In-situ	*(19, 95)*
MIN	Minapin	Karakoram	1989-2010	10	-12.6	In-situ	*(19, 95)*
GU	Ghulkin	Karakoram	1980-2008	11	+4.3	In-situ	(*19*)
BA	Batura	Karakoram	1860-2010	9	-5.0	In-situ	(*19*)

Table S4: Selected studies with information about length changes for different regions or mountain chains in the Karakoram and surrounding regions. See Fig. 1 for the locations.

Abbr.	Region	No. of Glaciers	Period	Data	Advancing (%)	Stable (%)	Retreating (%)	Reference
WP	Wakhan Pamir	30	1976-2003	MSS, ASTER	0	10	90	(*32*)
HK	Hindu Kush	15	~2000-2007	ASTER	20	7	73	(*23*)
EH	East Hindu Kush	37	1976-2007	MSS,TM ASTER	16	8	76	(*31*)
KA	Karakoram	31	~2001-2006	ASTER	33	25	42	(*23*)
ZA	Greater Himalaya of Zanskar	13	1975/1990-2008	MSS, TM, ETM+, ASTER	16	8	76	(*100*)
ZA	Greater Himalaya of Zanskar	34	1975-1992	MSS, TM	0	32	68	(*101*)
		34	2001-2007	IRS 1C	18	32	50	(*101*)
WH	Western Himalaya	65	2001-2007	ASTER	10	6	84	(*23*)

Table S5: Overview of existing studies of glacier area changes. See Figure 1 for the glacier locations.

No.	Catchment/ Mountains	Region	No. of Glaciers	Initial Area of Glaciers (km²)	Mean Glacier size (km²)	Period	Additional survey	Relative Change (% a-1)	Data source	Reference
1	Yarkant	Karakoram	565	2707	4.8	1962-1999	No	-0.11*	Map, Landsat ETM+	(*33*)
	Warwan	West Himalaya	253	847	3.4	1962-2002	No	-0.52*	Map, IRS LISS-III	(*35*)
3	Bhut	West Himalaya	189	469	2.5	1962-2002	No	-0.26*	Map, IRS LISS-III	(*35*)
4	Chenab	West Himalaya	359	1414	3.9	1962-2001	No	-0.55*	Map, IRS LISS-III	(*102*)
5	Kang Yatze	West Himalaya	121	96.4	1.3	1969-2010	1991, 2002	-0.35*	Corona, SPOT, Landsat, WorldView	(*34*)
6	Zanskar	West Himalaya	671	1023	1,5	1962-2002	No	-0.23*	Map, IRS LISS-III	(*35*)
7	Miyar	West Himalaya	166	568	3.4	1962-2002	No	-0.20*	Map, IRS LISS-III	(*35*)
8	Bhaga	West Himalaya	111	363	3.3	1962-2002	No	-0.75*	Map, IRS LISS-III	(*35*)
9	Chandra	West Himalaya	116	696	6.0	1962-2002	No	-0.51*	Map, IRS LISS-III	(*35*)
10	Parbati	West Himalaya	90	493	5.5	1962-2004	No	-0.50*	Map, IRS LISS-IV	(*35*)
11	Baspa	West Himalaya	19	173	9.1	1962-2001	No	-0.49*	Map, IRS LISS-III	(*103*)
12	Bhagirathi 1	Central Himalaya	13	275	21.2	1968-2006	1990	-0.09 ± 0.07	Corona, ASTER	(*36*)
	Bhagirathi 2	Central Himalaya	212	1345	6.3	1962-2002	No	-0.31*	Map, IRS LISS-III	(*35*)
13	Alaknandra	Central Himalaya	69	325	4.7	1968-2006	1990	-0.15 ± 0.07	Corona, ASTER	(*36*)
14	Gori Ganga	Central Himalaya	41	335	8.2	1962-2002	No	-0.49*	Map, IRS LISS-III	(*35*)
15	Naimona'nyi	West Himalaya	n.n.	84.4	n.n.	1976-2003	1990, 1999	-0.31*	Landsat MSS, TM, ASTER	(*106*)
16	NW Nepal	Central Himalaya	n.n.	n.n.	nn.	1980-2000	No	~-0.8*	Map, Corona, Landsat ETM+	(*107*)
17	Gandaki	Central Himalaya	1071	2030	1.9	~1970-2009	No	-0.91**	Map, Landsat ETM+	(*39*)
	Karnali	Central Himalaya	1361	1739	1.3	~1970-2009	No	-0.29**	Map, Landsat ETM+	(*39*)
18	Ghyirong Zangbo	Central Himalaya	n.n.	418	n.n.	1976-2006	1988	-0.58*	Landsat MSS, TM	(*38*)
19	Poiqu	Central Himalaya	n.n.	304	n.n.	1976-2006	1988	-0.54*	Landsat MSS, TM	(*38*)
20	Pengqu	Central Himalaya	n.n.	2056	n.n.	1976-2006	1988	-0.48*	Landsat MSS, TM	(*38, 108*)
21	Koshi	Central Himalaya	779	1413	1.8	~1970-2009	No	-0.42**	Map, Landsat ETM+	(*39*)
	Dudh Koshi	Central Himalaya	20	92	4.6	1962-2005	1992, 2002	-0.12	Corona, Landsat TM, ASTER	(*104*)
	Dudh Koshi	Central Himalaya	40	404	10.1	1960-1992	No	-015*	Maps	*(105)*
22	Mt. Everest north	Central Himalaya	n.n.	n.n.	n.n.	1974-2008	1990	-0.30*	Map, ASTER	(*108*)
23	Tista	East Himalaya	57	402	7.1	1997-2004	No	-0.36	LISS-III	(*35*)
24	Lunana	East Himalaya	66	147	2.2	1963-1993	No	-0.30*	Map, SPOT	(*37*)

* Uncertainty not given or data is based on medium resolution satellite data or on topographic maps of which the quality was not investigated. **Highly uncertain as data is based on maps and the first date can be estimated only roughly.

Table S6: Glaciers or regions with available measurements of mass budget in the H-K region

a Average mass-budget rate; uncertainty is given only when estimated in the source

b Glac: glaciological (in-situ) measurements; Geod: geodetic (in-situ or remote-sensing) surveys of elevation change multiplied by average density; AAR: mapping of the accumulation-area ratio by remote sensing; Hydr: hydrological method.

Region	Glacier Name	Mass Budget Data estimation (years)	Years of observation (periods)	*B* (m w.e. a^{-1})[a]	Method[b]	Reference
E Himalaya						
	Changme Khangpu	1979-1982	4	-0.16	Glac	(*94*)
C Himalaya						
	AX010	1979; 1996-1999	5	-0.61 ± 0.09	Glac	*(95, 96)*
	AX010	1978-2008	30 (4)	-0.75 ± 0.09	Geod	(*44*)
	Mt. Everest region (62 km²)	1970-2007	37 (2)	-0.32 ± 0.08	Geod	(*20*)
	Khumbu	1962; 1970-2007	37 (4)	-0.27 ± 0.08	Geod	(*20*)
	Yala	1983-2009	26 (2)	-0.58 ± 0.08	Geod	(*44*)
	Rikha Samba	1974-2010	36 (2)	-0.46 ± 0.07	Geod	(*44*)
	Dokriani	1992-2000	6	-0.32	Glac	(*109*)
	Dokriani	1963-1995	32 (1)	-0.32	Geod	(*109*)
	Chorabari	2004-2007	4	-0.74	Glac	(*94*)
	Naradu	2000-2003	3	-0.40	Glac	(*110*)
	Dunagiri	1984-1990	6	-1.04	Glac	(*94*)
	Tipra Bank	1981-1989	6	-0.29	Glac	(*94*)
	Kangwure	1975-2008	33 (1)	-0.20 ± 0.08	Geod	(*84*)
W Himalaya						
	Kolahoi	1984	1	-0.26	Glac	(*111*)
	Shishram	1984	1	-0.29	Glac	(*111*)
	Nehnar	1975-1984	9	-0.54	Glac	(*94*)
	Gara	1974-1982	8	-0.37	Glac	(*94*)
	Gor Garang	1976-1985	9	-0.43	Glac	(*94*)
	Shaune Garang	1981-1991	10	-0.36	Glac	(*94*)
	Chhota Shigri	2002-2010	8	-0.67 ± 0.40	Glac	(*40*)
	Hamtah	2001-2006	6	-1.60	Glac	(*112*)
	Lahaul/Spiti (915 km²)	1999-2004	5 (1)	-0.70 to -0.85	Geod	(*41*)
	Baspa basin (19 glaciers)	2001-2006	4	-0.69	AAR	(*35*)
Karakoram						
	Siachen	1986-1991	5	-0.51	Hydr	(*42*)
	Central Karakoram (5615 km²)	1999-2008	9 (1)	+0.11 ± 0.22	Geod.	(43)

Table S7: Conditions, characteristics, and contributions of the three major H-K river catchments and the contribution of glacier melt water to the overall discharge based on different sources.

No.	Parameter	Indus Basin	Ganges Basin	Brahmaputra Basin	Source
1	Total Area (km^2)	1,081,718	1,016,124	651,335	(*113*)
		1,139,814	1,023,609	527,666	(*2*)
		1,005,786	990,316	525,797	(*1*)
2	Upstream Area (% > 2000 m asl.)	40	14	68	(*1*)
3	Glacier area	8926	16,677	4366	Qin, 1999 in (*113*)
		20,325	12,659	16,118	(*2*)
4	No. of glaciers	5057	6694	4366	Qin, 1999 in (*113*)
5	Ice Volume	850	1971	600	Qin, 1999 in (*113*)
6	Glaciated area (% of total area)	0.8	1.2	0.7	L3 / L1
		1.78	1.24	3.05	(*2*)
7	Glaciated area (% of upstream area >2000 m asl.)	2.2	1.0	3.1	(*1*)
8	Annual precipitation basin (mm)	423	1,035	1,071	(*1*)
9	Upstream precipitation (%)	36	11	40	(*1*)
10	% glacier melt to overall run-off	Up to 50%	~9%	~12%	(*93*)
		>30%	>5%	<10%	(*1*)
		1.40	0.33	0.41	(*2*)
11	% glacier melt to overall run-off (upstream)	11.6	13.8	2.3	(*2*)
12	Population (10^3)	178,483	407,466	118,543	(*113*)
		209,619	477,937	62,421	(*1*)
		211,280	448,980	62,430	(*2*)
13	Net irrigation water Demand	908	716	480	(*1*)

References

1. W. W. Immerzeel, L. P. van Beek, M. F. Bierkens, Climate change will affect the Asian water towers. *Science* **328**, 1382 (2010). doi:10.1126/science.1183188 Medline

2. G. Kaser, M. Grosshauser, B. Marzeion, Contribution potential of glaciers to water availability in different climate regimes. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 20223 (2010). doi:10.1073/pnas.1008162107 Medline

3. M. B. Dyurgerov, M. F. Meier, "Glaciers and the Changing Earth System: A 2004 Snapshot" Occasional Paper **58** (2005).

4. Methods and discussion are available as supplementary materials on *Science* Online.

5. V. Radić, R. Hock, Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data. *J. Geophys. Res.* **115**, (F1), F01010 (2010). doi:10.1029/2009JF001373

6. E. J. Moors et al., Adaptation to changing water resources in the Ganges basin, northern India. *Environ. Sci. Policy* **14**, 758 (2011). doi:10.1016/j.envsci.2011.03.005

7. S. Richardson, J. Reynolds, An overview of glacial hazards in the Himalayas. *Quat. Int.* **65–66**, 31 (2000). doi:10.1016/S1040-6182(99)00035-X

8. J. G. Cogley, J. S. Kargel, G. Kaser, C. J. van der Veen, Tracking the source of glacier misinformation. *Science* **327**, 522 (2010). doi:10.1126/science.327.5965.522-a Medline

9. J. Böhner, General climatic controls and topoclimatic variations in Central and High Asia. *Boreas* **35**, 279 (2006). doi:10.1080/03009480500456073

10. B. Bookhagen, D. Burbank, Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *J. Geophys. Res.* **115**, (F3), F03019 (2010). doi:10.1029/2009JF001426

11. M. Winiger, M. Gumpert, H. Yamout, Karakorum-Hindukush-western Himalaya: assessing high-altitude water resources. *Hydrol. Processes* **19**, 2329 (2005). doi:10.1002/hyp.5887

12. A. Shrestha, C. Wake, J. Dibb, P. Mayewski, Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *Int. J. Climatol.* **20**, 317 (2000). doi:10.1002/(SICI)1097-0088(20000315)20:3<317::AID-JOC476>3.0.CO;2-G

13. M. Shekhar, H. Chand, S. Kumar, K. Srinivasan, A. Ganju, Climate-change studies in the western Himalaya. *Ann. Glaciol.* **51**, 105 (2010). doi:10.3189/172756410791386508

14. H. Fowler, D. Archer, Conflicting signals of climatic change in the Upper Indus Basin. *J. Clim.* **19**, 4276 (2006). doi:10.1175/JCLI3860.1

15. A. Shrestha, C. Wake, P. Mayewski, J. Dibb, Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971–94. *J. Clim.* **12**, 2775 (1999). doi:10.1175/1520-0442(1999)012<2775:MTTITH>2.0.CO;2

16. X. Yang, T. Zhang, D. Qin, S. Kang, X. Qin, Characteristics and changes in air temperature and glacier's response on the north slope of Mt. Qomolangma (Mt. Everest). *Arct. Antarct. Alp. Res.* **43**, 147 (2011). doi:10.1657/1938-4246-43.1.147

17. Y. Ageta, K. Higuchi, Estimation of mass balance components of a summer-accumulation type glacier in the Nepal Himalaya. *Geogr. Ann. A* **66**, 249 (1984). doi:10.2307/520698

18. D. J. Quincey et al., Karakoram glacier surge dynamics. *Geophys. Res. Lett.* **38**, L18504 (2011). doi:10.1029/2011GL049004

19. K. Hewitt, Glacier change, concentration, and elevation effects in the Karakoram Himalaya, Upper Indus Basin. *Mt. Res. Dev.* **31**, 188 (2011). doi:10.1659/MRD-JOURNAL-D-11-00020.1

20. T. Bolch, T. Pieczonka, D. I. Benn, Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. *The Cryosphere* **5**, 349 (2011). doi:10.5194/tc-5-349-2011

21. L. Iturrizaga, Trends in 20th century and recent glacier fluctuations in the Karakoram Mountains. *Zeit. für Geo.* **55** (suppl.), 205 (2011). doi:10.1127/0372-8854/2011/0055S3-0059

22. R. Bhambri, T. Bolch, Glacier mapping: A review with special reference to the Indian Himalayas. *Prog. Phys. Geogr.* **33**, 672 (2009). doi:10.1177/0309133309348112

23. D. Scherler, B. Bookhagen, M. R. Strecker, Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nat. Geosci.* **4**, 156 (2011). doi:10.1038/ngeo1068

24. D. Quincey, A. Luckman, D. I. Benn, Quantification of Everest region glacier velocities between 1992 and 2002, using satellite radar interferometry and feature tracking. *J. Glaciol.* **55**, 596 (2009). doi:10.3189/002214309789470987

25. A. Sakai, N. Takeuchi, K. Fujita, M. Nakawo, *IAHS Publication* **264**, 119 (2000).

26. A. Kääb, Combination of SRTM3 and repeat ASTER data for deriving alpine glacier flow velocities in the Bhutan Himalaya. *Remote Sens. Environ.* **94**, 463 (2005). doi:10.1016/j.rse.2004.11.003

27. T. Heid, A. Kääb, Worldwide widespread decadal-scale decrease of glacier speed revealed using repeat optical satellite images. *The Cryosphere Discuss.* **5**, 3025 (2011). doi:10.5194/tcd-5-3025-2011

28. L. Copland et al., Glacier velocities across the central Karakoram. *Ann. Glaciol.* **50**, 41 (2009). doi:10.3189/172756409789624229

29. L. Copland et al., Expanded and recently increased glacier surging in the Karakoram. *Arct. Antarct. Alp. Res.* **43**, 503 (2011). doi:10.1657/1938-4246-43.4.503

30. P. A. Mayewski, P. A. Jeschke, Himalayan and Trans-Himalayan glacier fluctuations since AD 1812. *Arct. Alp. Res.* **11**, 267 (1979). doi:10.2307/1550417

31. M. A. Sarikaya, M. P. Bishop, J. F. Shroder, J. A. Olsenholler, Space-based observations of Eastern Hindu Kush glaciers between 1976 and 2007, Afghanistan and Pakistan. *Remote Sens. Lett.* **3**, 77 (2012). doi:10.1080/01431161.2010.536181

32. U. K. Haritashya, M. P. Bishop, J. F. Shroder, A. B. G. Bush, H. N. N. Bulley, Space-based assessment of glacier fluctuations in the Wakhan Pamir, Afghanistan. *Clim. Change* **94**, 5 (2009). doi:10.1007/s10584-009-9555-9

33. S. Liu et al., Glacier retreat as a result of climate warming and increased precipitation in the Tarim river basin, northwest China. *Ann. Glaciol.* **43**, 91 (2006). doi:10.3189/172756406781812168

34. S. Schmidt, M. Nüsser, Changes of high altitude glaciers from 1969 to 2010 in the Trans-Himalayan Kang Yatze Massif, Ladakh, Northwest India. *Arct. Antarct. Alp. Res.* **44**, 107 (2012). doi:10.1657/1938-4246-44.1.107

35. A. V. Kulkarni, B. P. Rathore, S. K. Singh, I. M. Bahuguna, Understanding changes in the Himalayan cryosphere using remote sensing techniques. *Int. J. Remote Sens.* **32**, 601 (2011). doi:10.1080/01431161.2010.517802

36. R. Bhambri, T. Bolch, R. K. Chaujar, S. C. Kulshreshtha, Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. *J. Glaciol.* **57**, 543 (2011). doi:10.3189/002214311796905604

37. Karma, Y. Ageta, N. Naito, S. Iwata, H. Yabuki, *Bull. Glaciol. Res.* **20**, 29 (2003). www.seppyo.org/bgr/pdf/20/BGR20P29.pdf

38. Y. Nie, Y. Zhang, L. Liu, J. Zhang, Glacial change in the vicinity of Mt. Qomolangma (Everest), central high Himalayas since 1976. *J. Geogr. Sci.* **20**, 667 (2010). doi:10.1007/s11442-010-0803-8

39. S. R. Bajracharya, S. B. Maharjan, F. Shrestha, in *Climate Change, Geophysical Foundations and Ecological Effects*, J. Blanco, H. Kheradmand, Eds. (InTech, Rijeka, Croatia, 2011).

40. M. F. Azam et al., From balance to imbalance: A shift in the dynamic behaviour of Chhota Shigri glacier, western Himalaya, India. *J. Glaciol.* **58**, 315 (2012). doi:10.3189/2012JoG11J123

41. E. Berthier et al., Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sens. Environ.* **108**, 327 (2007). doi:10.1016/j.rse.2006.11.017

42. M. R. Bhutiyani, Mass-balance studies on Siachen Glacier in the Nubra valley, Karakoram, Himalaya, India. *J. Glaciol.* **45**, 112 (1999).

43. J. Gardelle, E. Berthier, Y. Arnaud, Slight mass gain of Karakoram glaciers in the early 21st century. *Nat. Geosci.* (2012); 10.1038/ngeo1450

44. K. Fujita, T. Nuimura, Spatially heterogeneous wastage of Himalayan glaciers. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 14011 (2011). doi:10.1073/pnas.1106242108 Medline

45. M. Zemp, M. Hoelzle, W. Haeberli, Six decades of glacier mass-balance observations: a review of the worldwide monitoring network. *Ann. Glaciol.* **50**, 101 (2009). doi:10.3189/172756409787769591

46. K. Matsuo, K. Heki, Time-variable ice loss in Asian high mountains from satellite gravimetry. *Earth Planet. Sci. Lett.* **290**, 30 (2010). doi:10.1016/j.epsl.2009.11.053

47. T. Jacob, J. Wahr, W. T. Pfeffer, S. Swenson, Recent contributions of glaciers and ice caps to sea level rise. *Nature* **482**, 514 (2012). doi:10.1038/nature10847 Medline

48. K. Fujita, Effect of precipitation seasonality on climatic sensitivity of glacier mass balance. *Earth Planet. Sci. Lett.* **276**, 14 (2008). doi:10.1016/j.epsl.2008.08.028

49. B. Xu et al., Black soot and the survival of Tibetan glaciers. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 22114 (2009). doi:10.1073/pnas.0910444106 Medline

50. J. G. Cogley, Present and future states of Himalaya and Karakoram glaciers. *Ann. Glaciol.* **52**, 69 (2011). doi:10.3189/172756411799096277

51. W. W. Immerzeel, L. P. H. Beek, M. Konz, A. B. Shrestha, M. F. P. Bierkens, Hydrological response to climate change in a glacierized catchment in the Himalayas. *Clim. Change* **110**, 721 (2012). doi:10.1007/s10584-011-0143-4

52. T. P. Barnett, J. C. Adam, D. P. Lettenmaier, Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**, 303 (2005). doi:10.1038/nature04141 Medline

53. H. G. Rees, D. N. Collins, Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming. *Hydrol. Processes* **20**, 2157 (2006). doi:10.1002/hyp.6209

54. J. Gardelle, Y. Arnaud, E. Berthier, Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global Planet. Change* **75**, 47 (2011). doi:10.1016/j.gloplacha.2010.10.003

55. W. Xin, S. Liu, W. Gou, J. Xu, Assessment and simulation of glacier lake outburst floods for Longbasaba and Pida Lakes, China. *Mt. Res. Dev.* **28**, 310 (2008). doi:10.1659/mrd.0894

56. A. Sakai, K. Nishimura, T. Kadota, N. Takeuchi, Onset of calving at supraglacial lakes on debris-covered glaciers of the Nepal Himalaya. *J. Glaciol.* **55**, 909 (2009). doi:10.3189/002214309790152555

57. A. Sakai, K. Fujita, Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalaya. *J. Glaciol.* **56**, 177 (2010). doi:10.3189/002214310791190785

58. K. Hewitt, J. Liu, Ice-dammed lakes and outburst floods, Karakoram Himalaya: Historical perspectives on emerging threats. *Physical Geography* 31, 528 (2010). doi:10.2747/0272-3646.31.6.528

59. D. Farinotti, M. Huss, A. Bauder, M. Funk, M. Truffer, A method to estimate the ice volume and ice-thickness distribution of alpine glaciers. *J. Glaciol.* **55**, 422 (2009). doi:10.3189/002214309788816759

60. J. F. Shroder, in *Encyclopedia of Snow, Ice and Glaciers*, V. P. Singh, P. Singh, U. K. Haritashya, Eds. (Springer Science+Business Media, Dordrecht, 2011), pp. 510–519.

61. H. Gurung, *Mountains of Asia: A Regional Inventory* (ICIMOD, Kathmandu, Nepal, 1999).

62. P. K. Mool, S. R. Bajracharya, S. P. Joshi, *Inventory of Glaciers, Glacial Lakes, Glacial Lake Outburst Floods: Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region, Nepal* (ICIMOD, Kathmandu , Nepal, 2001).

63. Y. Shi, C. Liu, E. Kang, *Ann. Glaciol.* **50**, 1 (2009).

64. B. Raup et al., The GLIMS geospatial glacier database: A new tool for studying glacier change. *Global Planet. Change* **56**, 101 (2007). doi:10.1016/j.gloplacha.2006.07.018

65. M. B. Dyurgerov, M. F. Meier, "Glaciers and the Changing Earth System: A 2004 Snapshot," Occasional Paper 58 (Institute of Arctic and Alpine Research, Univ. of Colorado, Boulder, 2005).

66. M. Dyurgerov, M. Meier, Mass balance of mountain and subpolar glaciers: A new global assessment for 1961-1990. *Arct. Alp. Res.* **29**, 379 (1997). doi:10.2307/1551986

67. L. Dolgushin, G. Osipova, *Ledniki (Glaciers)* (Mysl' Press, Moscow, 1989).

68. S. R. Bajracharya, B. R. Shrestha, Eds., *The Status of Glaciers in the Hindu Kush-Himalayan Region* (Kathmandu, 2011).

69. F. Paul et al., GlobGlacier: A new ESA project to map the world's glaciers and ice caps from space**.** *EARSeL eProceedings* **8**, 11 (2009); http://folk.uio.no/kaeaeb/publications/earsel_globglacier.pdf.

70. H. Frey, *Compilation and Applications of Glacier Inventories using Satellite Data and Digital Terrain Information* (Zurich, 2011).

71. D. K. Hall, G. A. Riggs, V. V. Salomonson, Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer data. *Remote Sens. Environ.* **54**, 127 (1995). doi:10.1016/0034-4257(95)00137-P

72. A. E. Racoviteanu, F. Paul, B. Raup, S. J. S. Khalsa, R. Armstrong, Challenges and recommendations in mapping of glacier parameters from space: Results of the 2008 Global Land Ice Measurements from Space (GLIMS) Workshop, Boulder, Colorado, USA. *Ann. Glaciol.* **50**, 53 (2010). doi:10.3189/172756410790595804

73. F. Paul, A. Kääb, Perspectives on the production of a glacier inventory from multispectral satellite data in Arctic Canada: Cumberland Peninsula, Baffin Island. *Ann. Glaciol.* **42**, 59 (2005). doi:10.3189/172756405781813087

74. F. Paul, A. Kääb, M. Maisch, T. Kellenberger, W. Haeberli, The new remote-sensing-derived Swiss glacier inventory: I. Methods. *Ann. Glaciol.* **34**, 355 (2002). doi:10.3189/172756402781817941

75. T. Bolch, B. Menounos, R. D. Wheate, Landsat-based inventory of glaciers in western Canada, 1985–2005. *Remote Sens. Environ.* **114**, 127 (2010). doi:10.1016/j.rse.2009.08.015

76. T. Bolch, M. F. Buchroithner, A. Kunert, U. Kamp, in *GeoInformation in Europe*, M. A. Gomarasca, Ed. (Millpress, Netherlands, 2007), pp. 403–410.

77. R. Bhambri, T. Bolch, R. K. Chaujar, Mapping of debris-covered glaciers in the Garhwal Himalayas using ASTER DEMs and thermal data. *Int. J. Remote Sens.* **32**, 8095 (2011). doi:10.1080/01431161.2010.532821

78. T. Bolch, U. Kamp, Glacier mapping in high mountains using DEMs, Landsat and ASTER data. *Grazer Schriften der Geographie und Raumforschung* **41**, 13 (2006).

79. F. Paul, C. Huggel, A. Kääb, Combining satellite multispectral image data and a digital elevation model for mapping debris-covered glaciers. *Remote Sens. Environ.* **89**, 510 (2004). doi:10.1016/j.rse.2003.11.007

80. T. Strozzi, F. Paul, A. Kääb, in *Proceedings of the ESA Living Planet Symposium* 2010, 28 June to 2 July 2010, Bergen, Norway, SP-686, DVD, pp. 4.

81. W. Haeberli, M. Hoelzle, *Ann. Glaciol.* **21**, 206 (1995).

82. F. Paul, A. Linsbauer, Modeling of glacier bed topography from glacier outlines, central branch lines, and a DEM. *Int. J. Geogr. Inf. Sci.* **2012**, 1 (2012). doi:10.1080/13658816.2011.627859

83. J. T. Gergan, D. P. Dobhal, R. Kaushik, *Curr. Sci.* **77**, 169 (1999).

84. L. Ma, L. Tian, J. Pu, P. Wang, Recent area and ice volume change of Kangwure Glacier in the middle of Himalayas. *Chin. Sci. Bull.* **55**, 2088 (2010). doi:10.1007/s11434-010-3211-7

85. D. B. Bahr, M. F. Meier, S. D. Peckham, The physical basis of glacier volume-area scaling. *J. Geophys. Res.* **102** (B9), 20,355 (1997). doi:10.1029/97JB01696

86. J. Chen, A. Ohmura, *IAHS Publication* **193**, 127 (1990).

87. A. A. Arendt et al., Updated estimates of glacier volume changes in the western Chugach Mountains, Alaska, and a comparison of regional extrapolation methods. *J. Geophys. Res.* **111** (F3), F03019 (2006). doi:10.1029/2005JF000436

88. E. Berthier, E. Schiefer, G. K. Clarke, B. Menounos, F. Rémy, Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. *Nat. Geosci.* **3**, 92 (2010). doi:10.1038/ngeo737

89. IPCC, *Climate Change 2007 - The Physical Science Basis; Working Group I: Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, 2007).

90. H. von Wissmann, *Abh. Math. Nat. KI. Akad. Wiss Mainz* **14**, 1103 (1959).

91. M. Eriksson et al., *The Changing Himalayas: Impact of Climate Change on Water Resources and Livelihoods in the Greater Himalayas* (ICIMOD, Kathmandu, Nepal, 2009).

92. V. Raina, "Himalayan Glaciers, a state-of-art review of glacial studies, glacial retreat and climate change," Discussion Paper, Ministry of Environment and Forests, New Delhi, India (2009).

93. World Glacial Monitoring Service, *Fluctuation of Glaciers 2000-2005 (Vol. IX)*, ICSU (FAGS)/IUGG (IACS)/UNEP/UNESCO/WMO (WGMS, Zürich, 2008).

94. K. Fujita, T. Kadota, B. Rana, R. Shresta, Y. Ageta, *Bull. Glaciol. Res.* **18**, 51 (2001).

95. A. V. Kulkarni, S. Dhar, B. P. Rathore, R. K. B. Govindha, R. Kalia, Recession of Samudra Tapu Glacier, Chandra River Basin, Himachal Pradesh. *J. Indian Soc. Remote Sens.* **34**, 39 (2006). doi:10.1007/BF02990745

96. K. B. G. Raj, *Curr. Sci.* **100**, 1420 (2011).

97. S. Schmidt, M. Nüsser, Fluctuations of Raikot Glacier during the past 70 years: a case study from the Nanga Parbat massif, northern Pakistan. *J. Glaciol.* **55**, 949 (2009). doi:10.3189/002214309790794878

98. U. Kamp, M. Byrne, T. Bolch, Glacier fluctuations between 1975 and 2008 in the Greater Himalaya Range of Zanskar, southern Ladakh. *J. Mt. Sci.* **8**, 374 (2011). doi:10.1007/s11629-011-2007-9

99. A. C. Pandey, S. Ghosh, M. S. Nathawat, Evaluating patterns of temporal glacier changes in Greater Himalayan Range, Jammu & Kashmir, India. *Geocarto Int.* **26**, 321 (2011). doi:10.1080/10106049.2011.554611

100. A. V. Kulkarni *et al*., *Curr. Sci.* **92**, 69 (2007).

101. A. V. Kulkarni, S. Alex, Estimation of recent glacial variations in Baspa basin using remote sensing technique. *J. Indian Soc. Remote Sens.* **31**, 81 (2003). doi:10.1007/BF03030775

102. T. Bolch, M. F. Buchroithner, T. Pieczonka, A. Kunert, Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data. *J. Glaciol.* **54**, 592 (2008). doi:10.3189/002214308786570782

103. F. Salerno, E. Buraschi, G. Bruccoleri, G. Tartari, C. Smiraglia, Glacier surface-area changes in Sagarmatha National Park, Nepal, in the second half of the 20th century, by comparison of historical maps. *J. Glaciol.* **54**, 738 (2008). doi:10.3189/002214308786570926

104. Q. Ye, T. Yao, S. Kang, F. Chen, J. Wang, Glacier variations in the Naimona'nyi region, western Himalaya, in the last three decades. *Ann. Glaciol.* **43**, 385 (2006). doi:10.3189/172756406781812032

105. R. Frauenfelder, A. Kääb, in Proc. 33rd Int. Symposium on Remote Sensing of Environment, 4–8 May 2009, Stresa, Italy (2009), Paper 299, 4 pp.

106. Q. Ye et al., Monitoring glacier and supra-glacier lakes from space in Mt. Qomolangma region of the Himalayas on the Tibetan Plateau in China. *J. Mt. Sci.* **6**, 211 (2009). doi:10.1007/s11629-009-1016-4

107. D. Dobhal, J. Gergan, R. J. Thayyen, *Bull. Glaciol. Res.* **25**, 9 (2008).

108. M. Koul, R. Ganjoo, Impact of inter- and intra-annual variation in weather parameters on mass balance and equilibrium line altitude of Naradu Glacier (Himachal Pradesh), NW Himalaya, India. *Clim. Change* **99**, 119 (2010). doi:10.1007/s10584-009-9660-9

109. M. Kaul, *Trans. Inst. Indian Geogr.* **8**, 95 (1986).

110. World Glacial Monitoring Service, *Glacier Mass Balance Bulletin 10 (2006-2007)*, ICSU (FAGS)/ IUGG (IACS)/ UNEP/UNESCO /WMO (WGMS, Zurich, 2008).

111. J. Xu, A. B. Shrestha, R. Vaidya, M. Eriksson, K. Hewitt, "The Melting Himalayas: Regional Challenges and Local Impacts of Climate Change on Mountain Ecosystems and Livelihoods" ICIMOD Technical Paper (ICIMOD, Kathmandu, Nepal, 2007).

112. T. Bolch, M. F. Buchroithner, J. Peters, M. Baessler, S. R. Bajracharya, Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. *Nat. Hazards Earth Syst. Sci.* **8**, 1329 (2008). doi:10.5194/nhess-8-1329-2008

113. T. Pieczonka, T. Bolch, M. Buchroithner, Generation and evaluation of multitemporal digital terrain models of the Mt. Everest area from different optical sensors. *ISPRS J. Photogramm.* **66**, 927 (2011). doi:10.1016/j.isprsjprs.2011.07.003