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The state and fate of Himalayan glaciers

Bolch, Tobias ; Kulkarni, A ; Kääh, Andreas ; Huggel, Christian ; Paul, Frank ; Cogley, J G ; Frey, Holger ; Kargel, J S ; Fujita, K ; Scheel, M ; Bajracharya, S ; Stoffel, Markus

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Supporting Online Material for

The State and Fate of Himalayan Glaciers

T. Bolch*, A. Kulkarni, A. Kääb, C. Huggel, F. Paul, J. G. Cogley, H. Frey, J. S. Kargel, K. Fujita, M. Scheel, S. Bajracharya, M. Stoffel.

*correspondence to: tobias.bolch@geo.uzh.ch

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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 km² 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 Karakoram 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 km², 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.

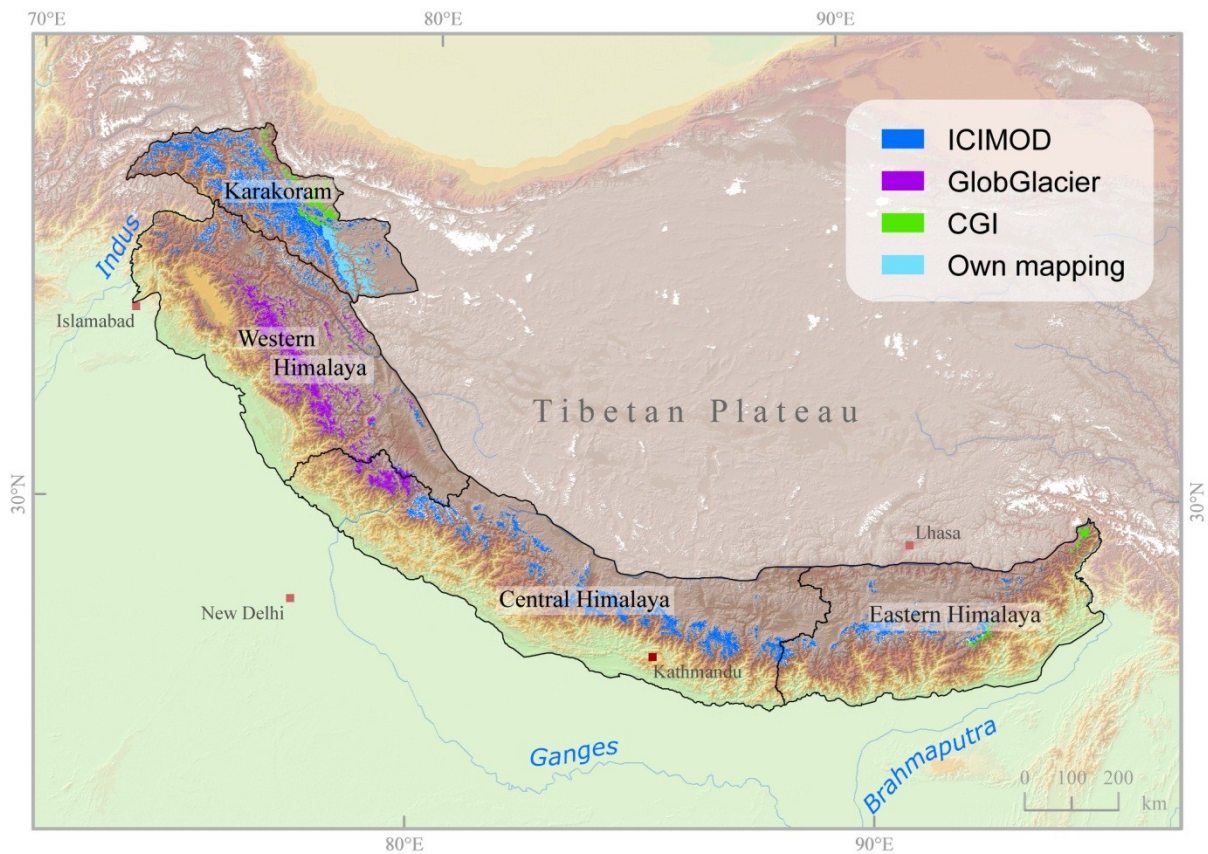


Fig. S1.

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.

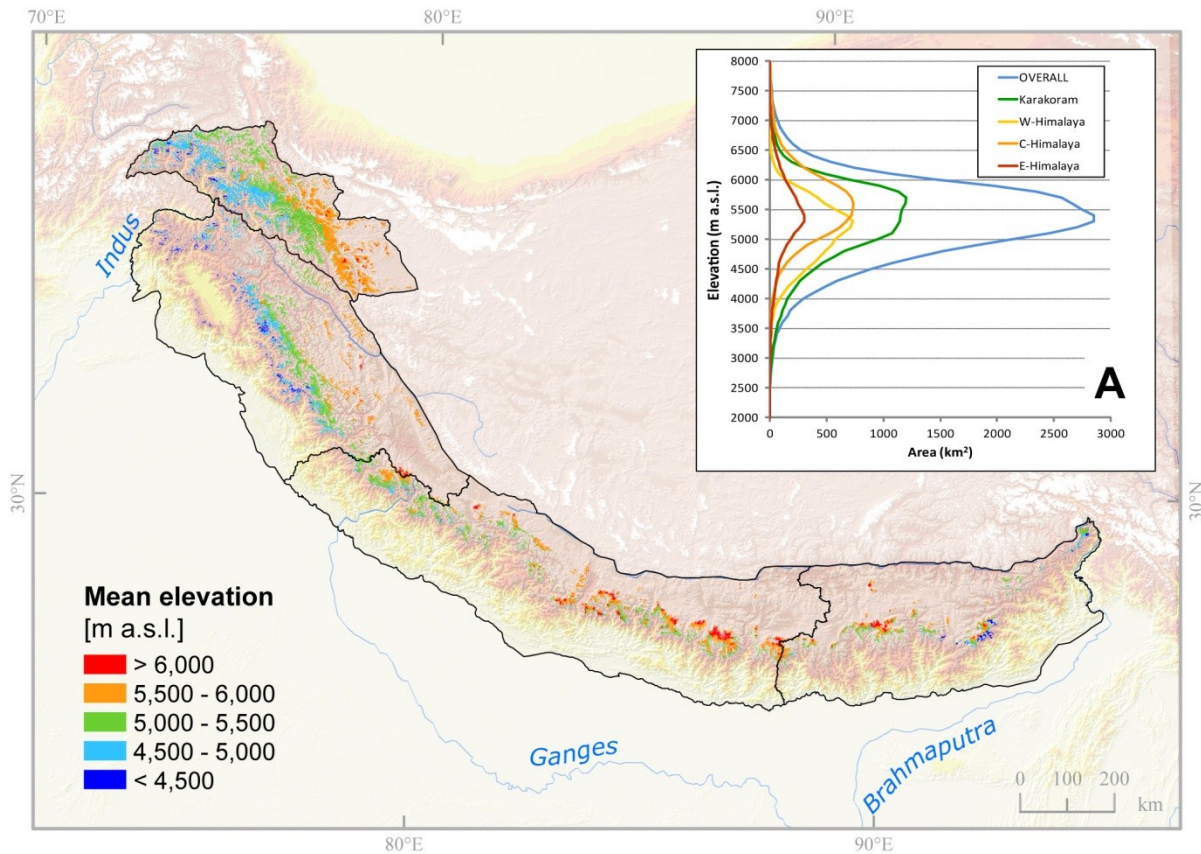


Fig. S2

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.

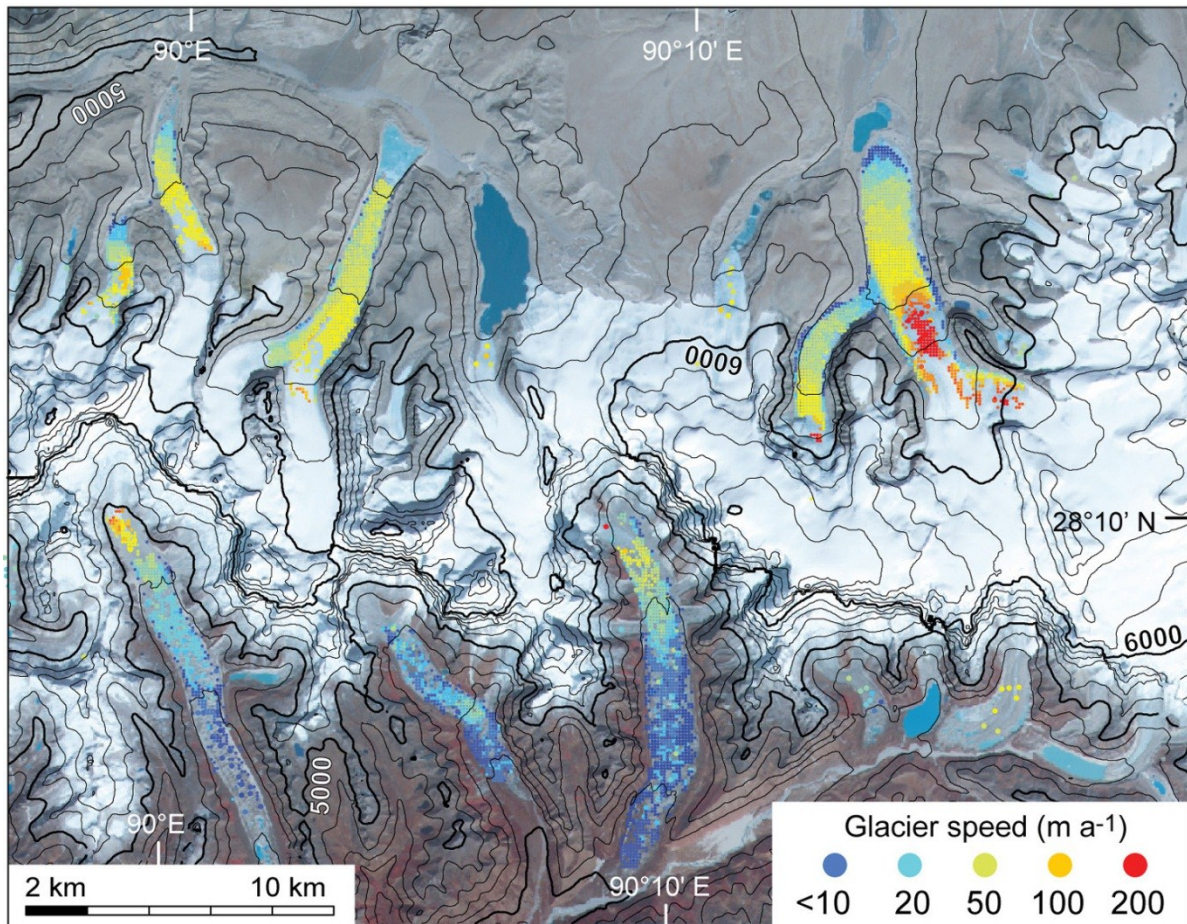


Fig. S3

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).

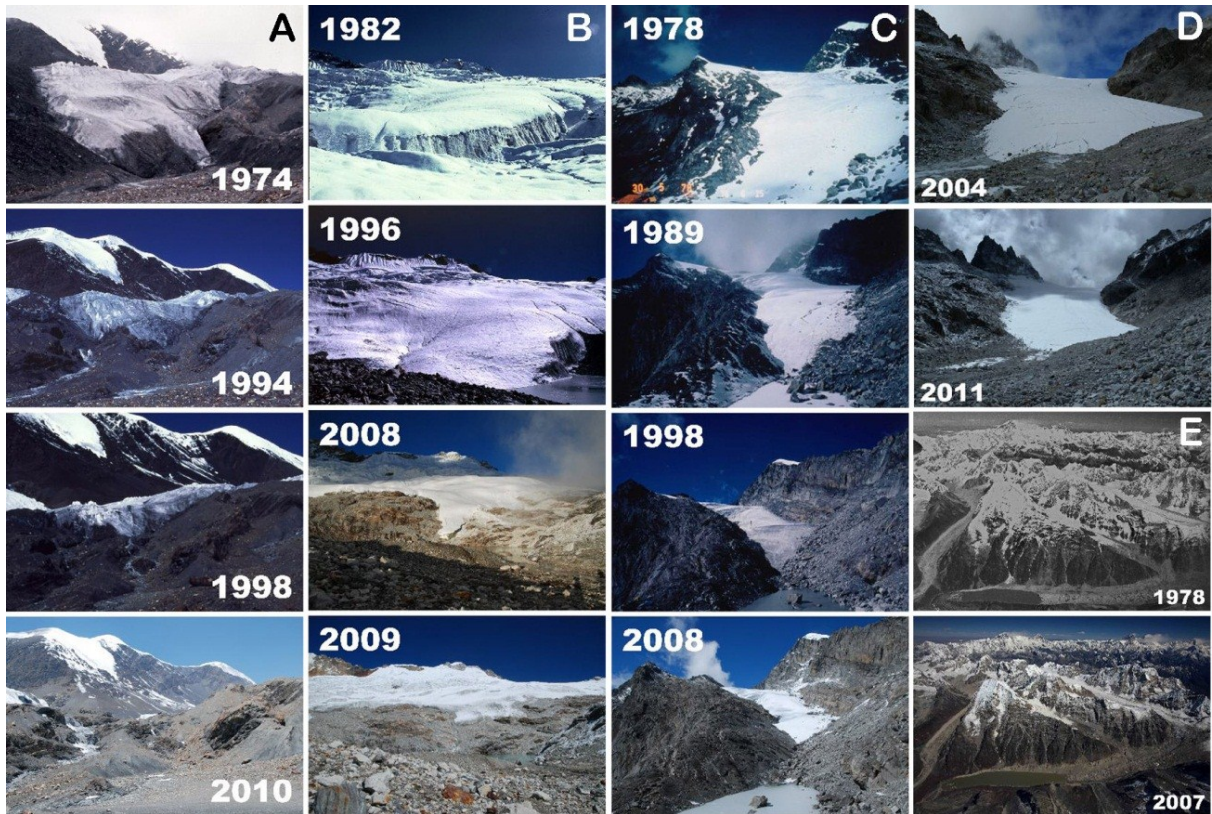


Fig. S4

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.

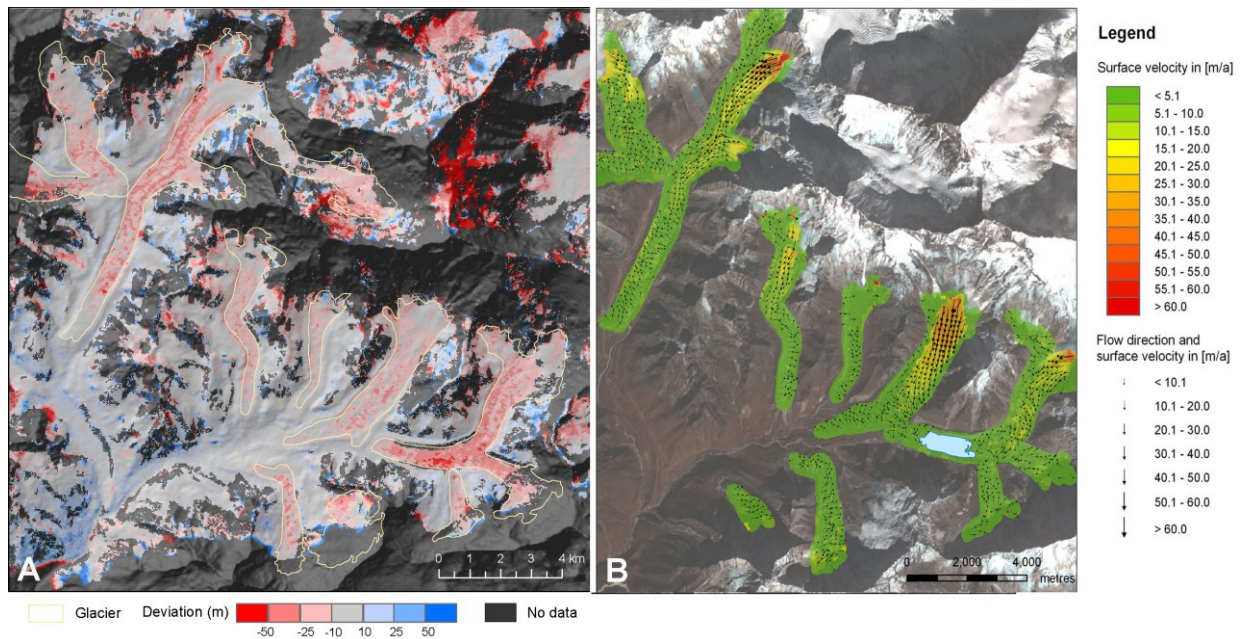


Fig. S5

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 (km ²)	Glacier area Karakoram (km ²)	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 (km ²)	Volume (km ³) based on (81), adjusted	Volume (km ³) 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 Zaskar	13	1975/1990- 2008	MSS, TM, ETM+, ASTER	16	8	76	(100)
ZA	Greater Himalaya of Zaskar	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 (km ²)	Mean Glacier size (km ²)	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	-0.15*	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
<i>E Himalaya</i>						
	Changme Khangpu	1979-1982	4	-0.16	Glac	(94)
<i>C Himalaya</i>						
	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 km ²)	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)
<i>W Himalaya</i>						
	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 km ²)	1999-2004	5 (1)	-0.70 to -0.85	Geod	(41)
	Baspa basin (19 glaciers)	2001-2006	4	-0.69	AAR	(35)
<i>Karakoram</i>						
	Siachen	1986-1991	5	-0.51	Hydr	(42)
	Central Karakoram (5615 km ²)	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)

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